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Effects of plyometric and pneumatic explosive strength training on neuromuscular function and dynamic balance control in 60–70 year old males



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ABSTRACT

The present study compared neuromuscular adaptations to 12 weeks of plyometric (PLY) or pneumatic (PNE) power training and their effects on dynamic balance control. Twenty-two older adults aged 60–70 (PLY $n = 9$, PNE $n = 11$) participated in the study. Measurements were conducted at Pre, 4, 8 and 12 weeks. Dynamic balance was assessed as anterior–posterior center of pressure (COP) displacement in response to sudden perturbations. Explosive isometric knee extension and plantar flexion maximal voluntary contractions (MVCs) were performed. Maximal drop jump performance from optimal dropping height was measured in a sledge ergometer. Increases in knee extensor and ankle plantar flexor torque and muscle activity were higher and occurred sooner in PNE, whereas in drop jumping, PLY showed a clearer increase in optimal drop height (24%, $p < 0.01$) after 8 weeks of training and soleus muscle activity after 12 weeks of training. In spite of these training mode specific adaptations, both groups showed similar improvements in dynamic balance control after 4 weeks of training (PLY 38%, $p < 0.001$; PNE 31%, $p < 0.001$) and no change thereafter. These results show that although power and plyometric training may involve different neural adaptation mechanisms, both training modes can produce similar improvements in dynamic balance control in older individuals. As COP displacement was negatively correlated with rapid knee extension torque in both groups (PLY $r = -0.775$, $p < 0.05$; PNE $r = -0.734$, $p < 0.05$) after training, the results also highlight the importance of targeting rapid force production when training older adults to improve dynamic balance.

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1. Introduction

It is well known that aging causes degeneration of the human neuromuscular system including loss of muscle mass, decreased conduction and contraction velocities and weaker neural activation from central pathways (Harridge et al., 1999; Thom et al., 2007; Vandervoort, 2002; Werner et al., 2012). In aging, rapid force production decreases more than maximal force production (Izquierdo et al., 1999) and its effect on functional muscle capacity may be more crucial, especially in response to sudden balance perturbations (Piirainen et al., 2010). This may be a major contributor to falling accidents and injuries in older adults. The importance of rapid force production suggests that power/explosive strength

training may have beneficial effects on functional performance capacity and balance control.

Power/explosive strength training is often performed using pneumatic devices that primarily involve concentric contractions, often leading to improved strength and power (de Vos et al., 2005; Orr et al., 2006). Although minor muscle hypertrophy may occur (Hakkinen et al., 1998), the primary adaptations seem to be related to more effective voluntary activation, especially in the early phase of force production. Typical neural adaptations include increased agonist activation (Hakkinen et al., 1998; Van Cutsem et al., 1998), a possible decrease in antagonist co-activation (Hakkinen et al., 1998), and decreased reciprocal inhibition, especially in the early phase of rapid force production (Geertsen et al., 2008). These neural adaptations seem to be related to improved balance control in older individuals (Izquierdo et al., 1999; Orr et al., 2006).

However, adaptations may be training-mode specific. For example, plyometric training utilizes the stretch shortening cycle (SSC), which is typically associated with more effective use of tendon

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elasticity and stretch reflex activation than concentric only training (Aura and Komi, 1986a; Komi, 2000). Few studies have investigated the effects of plyometric training on neuromuscular function. Chimera et al. (2004), Kyrolainen et al. (2005) both found no changes in lower limb muscle activation after plyometric training, whereas Kubo et al. (2007) showed a significant increment in plantar flexor muscle activity, but only in the concentric phase of drop jumps. In terms of reflex responses, Voigt et al. (1998) showed increased soleus H-reflexes during hopping after plyometric training, which they attributed to more automatic control strategies during jumping with less voluntary activation. Therefore, contrary to pneumatic power training, plyometric training may primarily enhance spinal reflex activity rather than voluntary activation.

In spite of the known benefits of both plyometric and pneumatic power training, it is currently unknown which training mode is more beneficial for balance control, especially in older individuals. The purpose of this study was to examine the effects of plyometric and pneumatic power training on neuromuscular adaptations and dynamic balance control during and after a 12-week training period in males aged 60–70. We hypothesized that pneumatic training would increase neural drive to the muscles, thus improving force production properties. Conversely, plyometric training was expected to enhance spinal reflex activity, leading to more efficient feedback from proprioceptors. Thus, both training regimens were expected to improve dynamic balance control, but via different mechanisms.

2. Methods

2.1. Subjects

A total of 20 male subjects aged 60–70 (9 plyometric; PLY age 63 ± 2 , weight 84 ± 9 kg, height 176 ± 7 cm and 11 pneumatic; PNE age 65 ± 3 , weight 77 ± 8 kg, height 176 ± 6 cm) volunteered and completed this 12-week study. After volunteering, subjects were randomly assigned to the two groups. All subjects were physically active but did not participate in any systematic training programs. Exclusion criteria were high blood pressure (systolic over 160 mmHG), heart and circulatory system diseases and musculoskeletal diseases. Subjects provided written informed consent and were aware of the protocol and possible risks of the study. The study was conducted according to the declaration of Helsinki, and was approved by The University of Jyväskylä Ethics Committee.

2.2. Test protocol

To minimise the effects of learning during training, subjects performed a familiarisation session three days prior to the beginning of the study. Subjects then completed 12 weeks of training, with follow-up measurements performed at pre, 4, 8 and 12 weeks. On each measurement day, after preparations and a 10 min cycling warm-up (80 W), measurements were performed in the following order: (1) dynamic balance control, (2) H-reflex during standing rest, (3) maximal voluntary isometric plantar flexion contractions (MVC), (4) maximal drop jumps, (5) H-reflex during drop jumps and (6) isometric knee extension MVC. H-reflexes were only measured pre- and post-training. The total time of one test session was approximately 2.5 h.

2.3. Training program

Subjects trained 2 times per week during weeks 1–3 and 9–12 of the 12-week training period. In weeks 5–7 they trained 3 times per week, while in weeks 4 and 8 they had only one session which

was a control measurement session. PLY trained the legs using a sledge apparatus (University of Jyväskylä, Finland) that enables drop jumps to be performed more safely than standard vertical jumping. This was deemed necessary considering the age of the subjects. The sledge jumping angle was 23.6° from horizontal and the load consisted of sledge weight (33 kg) and each subject's own body mass. The average load in PLY was 459 ± 38 N during the entire 12-week training period. Jumps were performed as continuous countermovement jumps. The lowest knee angle during the jumps was 70 – 90° , which was determined based on a position signal from the sledge apparatus. The PNE group trained using pneumatic leg extension and calf raise devices (HUR, Kokkola, Finland) with a load of 40% of MVC, which was measured and updated every four weeks. For leg extension, absolute loads were 94 ± 13 N, 118 ± 20 N and 148 ± 20 N in weeks 1–4, 5–8 and 9–12, respectively. Corresponding values for calf raises were 147 ± 22 N, 200 ± 27 N and 308 ± 48 N, respectively. Concentric MVCs were measured by increasing the load by 10 N m after each trial until full extension was no longer achieved. Because of the nature of the different training tasks, it was not possible to match the training loads between groups. However, both groups performed the same number of repetitions (6) and sets (5) in each session during the entire period. In addition, trials were always performed with maximal effort as explosively as possible. Despite the differences between training modes, the same main muscle groups (thigh and calf) were trained in both groups. Both groups also performed an identical hypertrophy protocol for the upper body throughout the study period, leading to whole body development of strength properties and thus improved training motivation.

3. Measurements

3.1. Dynamic balance

Dynamic balance was measured using a custom-made dynamic balance measurement system (University of Jyväskylä, Finland; HurLabs Oy, Tampere, Finland), which consists of four pneumatic cylinders placed vertically under a BT4 balance platform (HurLabs Oy, Tampere, Finland). Maximal cylinder displacement amplitude is 12.5 cm, giving 12° freedom of movement in each direction. By releasing air out of the cylinders, it is possible to drop (free fall) each side of the plate independently to produce a perturbation. The device is described in more detail elsewhere (Piirainen et al., 2010). Hur Balance software (HurLabs Oy, Tampere, Finland) was used for data collection. During the measurements, subjects stood on the balance plate for two 30 s sets, during each of which four sudden balance perturbations were induced, one in each direction (medial–lateral, anterior–posterior). Subjects were unaware of the direction and timing of the perturbations. During each perturbation, one side of the plate dropped by 12.5 cm in free fall. A black mark was fixed on the wall ~ 2.8 m from the subject at eye level to stabilize their visual focus during the measurements. For each perturbation direction, the attempt with the least average centre-of-pressure (COP) sway was chosen for further analysis. Average maximal swaying distance in the medial–lateral and anterior–posterior stabilograms were analysed during a one second period after the disturbance while the platform remained in the tilted position.

3.2. Plantar flexion and knee extension MVC

Plantar flexion MVC was measured using a custom-built force dynamometer (University of Jyväskylä, Finland). Subjects sat in the dynamometer with hip, knee, and ankle joint angles at 110° , 180° , and 90° , respectively, and performed five MVCs at 1 min inter-

vals. Knee extension MVC was measured using a knee dynamometer (hip angle 110° and knee angle 120°; Hurlabs Oy, Tampere, Finland) with a force transducer placed just above the ankle joint. Subjects performed three isometric MVCs with 1 min rest between trials. In both cases, subjects were instructed to perform the MVCs as fast as possible. Force and EMG data were collected using an A/D converter (CED Power 1401, CED Ltd., Cambridge, UK) combined with Spike 5.14 software (CED Ltd., Cambridge, UK). Torque values were calculated by multiplying the force with the respective lever arm (plantar flexion: from ankle joint to distal head of the first metatarsal bone; knee extension: from force sensor to knee joint centre). Torque and muscle activity (see below) were analysed between 0 and 200 ms relative to contraction onset.

3.3. Electromyography (EMG)

Bipolar EMG electrodes (Ag–AgCl, 2 cm interelectrode distance) were placed over the vastus lateralis (VL), soleus and medial gastrocnemius (MG) muscles according to the recommendations of SENIAM (Hermens et al., 1999). Before placement, the skin was shaved, abraded with sand paper and cleaned with alcohol. If electrode impedance was higher than 10 k Ω , the preparation was repeated. Data were sampled at 1000 Hz using a Noraxon Telemyo 2400R system (Scottsdale, USA), amplified (gain 1000) and band pass filtered (10–500 Hz). Root mean square (RMS) EMG values were normalised to maximal EMG obtained during a 200 ms window around the point of MVC.

3.4. Drop jumps

Maximal drop jumps were performed on a sledge ergometer with a built-in force plate positioned perpendicular to the jumping direction. Jumping height was measured using an electronic odometer, which was also used to assess the transition point (lowest point) between the braking and push-off phases. Take-off velocity was calculated from the odometer signal. The system is described in more detail elsewhere (Aura and Komi, 1986b; Kyrolainen et al., 1990). Optimal dropping height was assessed by increasing the dropping height by 10 cm after each jump until the rebound jump height no longer increased. Subjects performed 5–10 jumps in total depending on the optimal dropping height. Knee angle during landing was visually controlled to be between 70° and 90° (full extension 180°), and verified by checking the odometer signal. Average forces during the braking and push-off phases were analysed. Three different time windows were used to analyse EMG during drop jumps: pre-activity (–100 ms–0 ms relative to ground contact), braking phase and push-off phase. The braking phase was determined from the beginning of force production to the lowest sledge position, and the push-off phase from the lowest sledge position to take-off.

3.5. H-reflex during standing rest and drop jumps

Subjects stood relaxed with earmuffs on during the H-reflex measurements. H-reflex and M-wave responses were measured from the soleus muscle by stimulating the tibial nerve in the popliteal fossa. An anode (5 × 8 cm) was placed superior to the patella. A cathode (1.5 × 1.5 cm) was placed over the optimal stimulation point and electrodes were fixed in place using elastic tape. The most appropriate stimulation point was located based on the strength of the EMG signal (highest M-wave peak-to-peak response). An increasing intensity interval (mA) was then chosen so that the H-reflex excitability curve could be measured with at least 30 measurement points up to the maximal M-wave. Rectangular pulses with a duration of 0.2 ms were given at 10 s intervals (Digitimer model DS7A, Digitimer Ltd, Welwyn Garden City,

England). From the standing rest measurement, Hmax/Mmax-ratios were analysed. In addition, background RMS EMG activity was analysed during a 200 ms window before electrical stimulation, and normalised to maximal EMG activity during a 200 ms window around the point of MVC.

H-reflexes were also measured in the sledge ergometer during maximal drop jumps (Avela et al., 2006; Piirainen et al., 2012). The stimulus was given 20 ms after ground contact in order to avoid collision of the stretch reflex response with M-wave and H-reflex responses, and to ensure that H-reflex excitability would be highest (Dyhr-Poulsen et al., 1991). Stimulus intensity was adjusted to elicit an M-wave corresponding to 20 ± 5% of the maximal M-wave amplitude during the subsequent jumps. This was checked after each jump, and five successful trials were later averaged.

3.6. Statistical methods

Mean values and standard deviations (±SD) were calculated. Correlations were measured using Pearson's rank correlation coefficient because results were normally distributed. Two-way repeated measures ANOVA was used to assess the effects of measurement interval (pre, 4, 8 and 12 weeks) and training mode (PNE, PLY). Mauchly's test of sphericity was used to test the assumption of sphericity. Where this assumption was violated, Geisser-Greenhouse adjustments were used. Where significant main effects were observed, pair-wise comparisons were used to identify the location of differences between measurement intervals and training modes. For variables that were only examined pre and post training, dependent samples (within groups) and independent samples (between groups) *t*-tests were used. Results were considered statistically significant for *p*-values below 0.05. Data were analysed using SPSS software version 16.0 (SPSS Inc., Chicago, IL, USA).

4. Results

4.1. Dynamic balance

Both groups showed similar anterior–posterior (Fig. 1A) and medial–lateral (Fig. 1B) COP displacement at the beginning of the training period. After 4 weeks of training, both training groups improved anterior–posterior balance control (PLY *p* < 0.001, PNE *p* < 0.001), which remained at the same level for the rest of the training period. In the medial–lateral direction, PLY showed no significant improvements during the entire training period, whereas in PNE, medial–lateral balance control improved after 8 weeks of training (*p* < 0.01) with no changes thereafter. No significant differences were observed in COP displacement between groups at any time point. Relative changes in anterior and posterior balance displacement correlated negatively with knee extension rapid torque production after 12 weeks of training in both groups (PLY *r* = –0.775, *p* < 0.05; PNE *r* = –0.734, *p* < 0.05). In addition, both groups showed negative correlations between VL MVC EMG activity (0–200 ms) and anterior–posterior balance displacement after 8 weeks (PNE; *r* = –0.688, *p* < 0.05) or 12 weeks of training (PLY; *r* = –0.868, *p* < 0.01).

4.2. Plantar flexion and knee extension MVC

Relative to pre values, PNE showed significantly higher plantar flexion torque (43 ± 11 to 52 ± 17 N m, *p* < 0.01) and soleus muscle EMG activity (65 ± 32% to 80 ± 36%, *p* < 0.01) during the first 200 ms of MVC after 12 weeks of training. Conversely, PLY showed

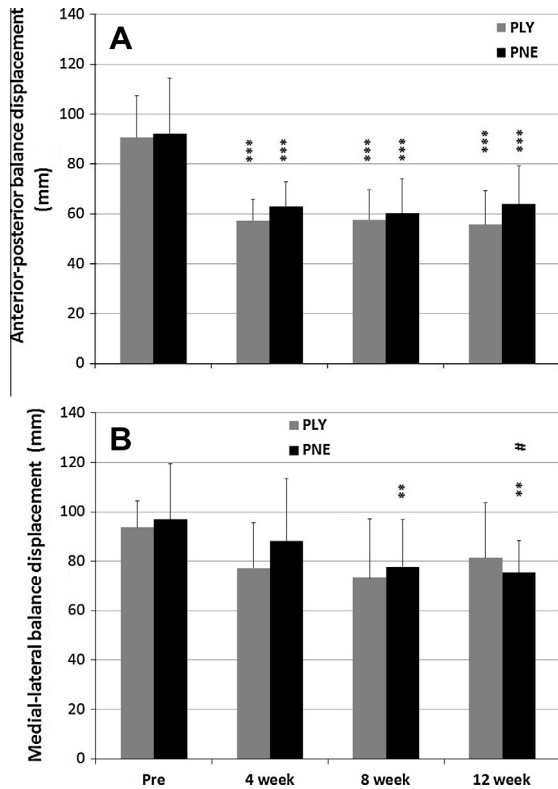


Fig. 1. Anterior–posterior (A) and medial–lateral (B) COP displacement before, during and after 12 weeks of pneumatic (PNE) or plyometric (PLY) training (** $p < 0.01$ *** $p < 0.001$ compared to pre-level, # between weeks 4 and 12).

no significant change in torque (36 ± 17 to 43 ± 11 N m) or EMG of soleus and MG muscles.

At pre, rapid knee extension torque production (Fig. 2A) was similar in both training groups. PNE showed an increase in torque after 4 weeks ($p < 0.01$), a further increase after 8 weeks ($p < 0.001$) and no change between 8 and 12 weeks, although torque remained higher ($p < 0.01$) than the pre level. PNE also showed a significant increment (Fig. 2B) in VL muscle EMG ($p < 0.01$) after 4 weeks of training compared to the pre level, which did not change thereafter. Conversely, PLY only showed significantly higher rapid torque development after 12 weeks of training ($p < 0.01$) and a significant increment in VL EMG after 8 weeks ($p < 0.05$) of training. In addition, significant ($p < 0.05$) differences between groups were observed in VL EMG activity after 4, 8 and 12 weeks of training.

4.3. Drop jump performance

Before training, take-off velocity during drop jumps was similar in both groups. PNE showed increased velocity ($p < 0.001$) and increased dropping height ($p < 0.05$) after 4 weeks of training, while PLY showed improved velocity ($p < 0.01$) and dropping height ($p < 0.01$) only after 8 weeks of training. Also after 8 weeks, PLY showed a trend towards higher optimal dropping height ($p = 0.051$). In PLY, braking phase force production significantly increased after 8 weeks of training ($p < 0.05$) whereas no changes were observed during the entire training period in PNE. Dropping heights, take-off velocities, contact times and forces are presented in Table 1.

In terms of drop jump EMG activity, after 12 weeks of training, PLY showed significantly increased soleus muscle activity (Fig. 3A) in all phases of the drop jump relative to pre ($p < 0.05$ in all cases), which was not observed in PNE. Conversely, PNE showed signifi-

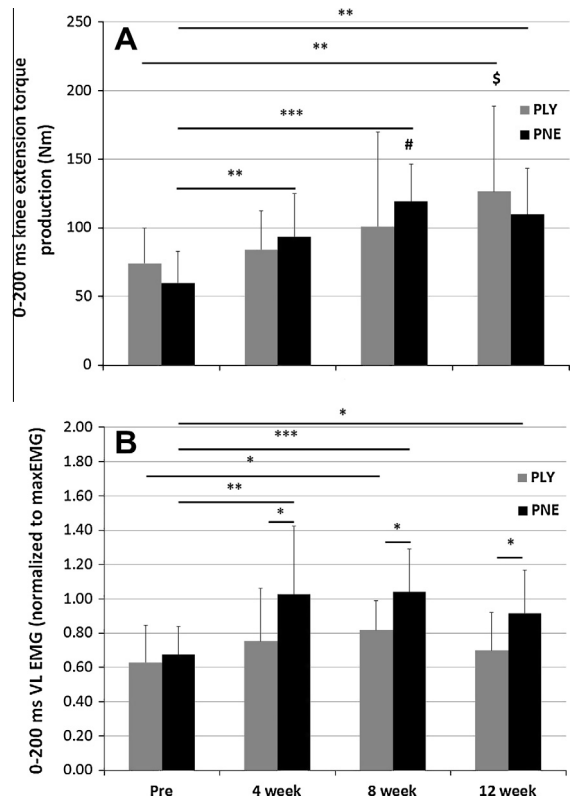


Fig. 2. Explosive isometric knee extension torque production (A) and vastus lateralis EMG (B) activity (0–200 ms) before, during and after 12 weeks of pneumatic (PNE) or plyometric (PLY) training (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; # $p < 0.05$ between weeks 4 and 8, \$ $p < 0.05$ between weeks 4 and 12).

cantly increased VL (Fig. 3B) muscle activity in all phases of the drop jump (pre-activity $p < 0.001$, braking phase $p < 0.05$ and push-off phase $p < 0.05$) after 12 weeks of training, which was not observed in PLY. In addition, PNE showed significantly higher VL braking phase EMG activity ($p < 0.001$) compared to PLY after 12 weeks of training.

4.4. H-reflex during standing rest and drop jumps

Pre Hmax/Mmax-ratio during standing was statistically similar between PLY (0.27 ± 0.09) and PNE (0.41 ± 0.21). After 12 weeks of training, the ratio was unchanged in PLY (0.28 ± 0.12) but decreased significantly in PNE (0.30 ± 0.15 , $p < 0.05$). During drop jumps, the 20% target M-wave level was similar in both groups during all measurements (PLY pre $19.2 \pm 4.8\%$, post $18.8 \pm 4.0\%$; PNE pre $18.8 \pm 2.4\%$, post $18.7 \pm 3.9\%$) making them directly comparable. PLY showed a lower H/M-ratio (0.58 ± 0.38) than PNE (1.01 ± 0.57) before training, although this difference was not statistically significant. After 12 weeks of training, the H/M ratio was unchanged relative to pre in both PLY (0.58 ± 0.28) and PNE (0.70 ± 0.57).

5. Discussion

The purpose of this study was to investigate the effects of plyometric and pneumatic explosive strength training on neuromuscular adaptations and dynamic balance control during and after a 12 week training period. Although the total loading may have been different between the training modes, they both led to specific neuromuscular adaptations, thus following the principle of training specificity. In PLY, training led to increased optimal jumping

Table 1
Drop jump parameters before, during and after the 12 week training period.

Group	Parameter	Pre	4 Week	8 Week	Post
Plyometric	Optimal drop height (cm)	83 ± 14	89 ± 11	104 ± 14 ^{*,##}	103 ± 14 ^{*,#}
	Take-off velocity (m/s)	2.11 ± 0.17	2.21 ± 0.18	2.23 ± 0.16 ^{**}	2.19 ± 0.17
	Contact time (s)	0.67 ± 0.11	0.69 ± 0.11	0.67 ± 0.07	0.64 ± 0.05
	Force _{ECC} /BW (N/kg)	13.9 ± 2.1	14.2 ± 2.1	16.0 ± 1.6 [†]	15.4 ± 2.5
	Force _{CON} /BW (N/kg)	13.6 ± 1.9	13.7 ± 1.8	13.3 ± 1.3	13.9 ± 1.3
Pneumatic	Optimal drop height (cm)	87 ± 14	94 ± 14 [†]	93 ± 14	98 ± 14 ^{**}
	Take-off velocity (m/s)	2.05 ± 0.16	2.12 ± 0.16 [†]	2.13 ± 0.19	2.12 ± 0.16 [†]
	Contact time (s)	0.64 ± 0.09	0.61 ± 0.07	0.62 ± 0.09	0.63 ± 0.11
	Force _{ECC} /BW (N/kg)	15.0 ± 1.8	15.5 ± 2.0	15.8 ± 2.9	16.1 ± 2.4
	Force _{CON} /BW (N/kg)	13.8 ± 1.5	14.3 ± 1.3	14.2 ± 1.3	14.1 ± 1.7

[†] $p < 0.05$ compared to PRE level.

^{**} $p < 0.01$ compared to PRE level.

[#] Between weeks 4 and 12.

^{##} Between week 4 and 8.

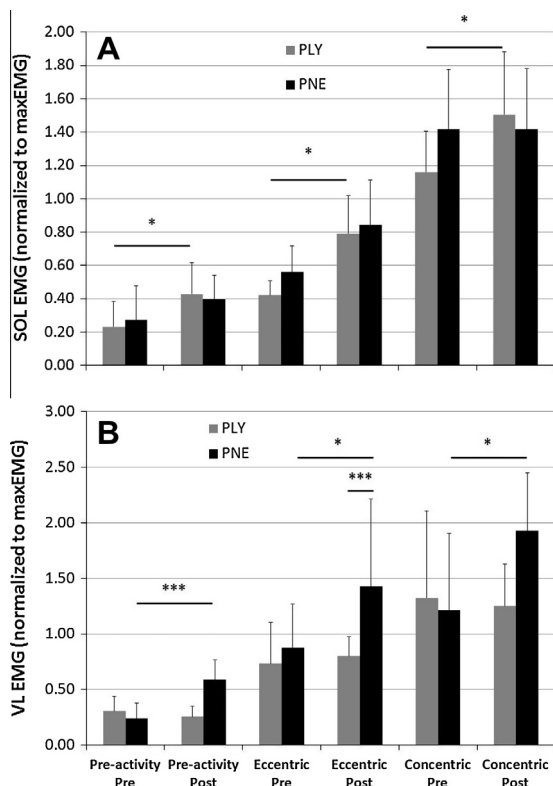


Fig. 3. Plyometric (PLY) and pneumatic (PNE) group soleus (SOL; A) and vastus lateralis (VL; B) EMG activity during maximal drop jumps before and after 12 weeks of training ($^*p < 0.05$, $^{***}p < 0.001$).

height and soleus muscle activity during drop jumps. No muscle activity increments were observed in triceps surae muscles during the early phase of maximal isometric contractions, suggesting that other mechanisms such as increased utilisation of elastic energy and/or increased reflex activity may be responsible for enhanced performance during jumping. In PNE, increases were observed in vastus lateralis muscle activity and knee extension torque during both isometric conditions and drop jumps, suggesting that increased neural drive was primarily responsible for enhanced performance in this group. Despite the between-group differences in neuromuscular adaptations, both groups showed similar improvements in dynamic balance control after just 4 weeks of training. In both groups, COP displacement was also negatively correlated with rapid knee extension torque after training, highlighting the importance of this variable for dynamic balance training in older individuals.

Voigt et al. (1998) showed with young subjects that 4 weeks of hopping training increased H-reflex size when preferred contact time was used. They suggested that this was caused by a decrease in pre-synaptic inhibition and that the hopping movement became more automated with less voluntary demand. In our study, H-reflex size during drop jumps did not change significantly during 12 weeks of training. In fact, in PLY, where the training task was similar to that employed by Voigt et al. (1998), pre-activity increased during drop jumps after training, indicating an increase in voluntary command from the central nervous system. However, subjects in the present study performed maximal drop jumps, which was not the case in the study of Voigt et al. (1998). Thus, the mechanisms attributed to the results of Voigt et al. (1998) may not apply to those from the present study.

Leukel et al. (2008) found that H-reflexes decrease with increasing dropping height in young individuals and suggested that this was caused by a prevention strategy to protect the tendomuscular system from excessive loads and thus possible injury. In the present study, PLY showed significantly increased dropping height after 12 weeks of training, but no changes in H-reflex responses. This lack of decrease in H-reflex amplitude due to training may be due to decreased pre-synaptic inhibition or increased reflex activity from ascending pathways. The latter possibility is supported by the higher EMG activity observed during the braking phase in PLY. Thus, the improvements in balance control observed in PLY after just 4 weeks of training may be due to some combination of increased voluntary drive and spinal level adaptations, which differs from the adaptations observed in younger individuals (Voigt et al., 1998). It should be noted that drop jump training is often performed in the vertical direction, whereas for safety reasons, in the current study a 23° sledge angle was used. As this decreases acceleration during drop jumping, it may have influenced neural adaptations. Unsurprisingly on the basis of training specificity, post-training differences in jumping strategies were evident between groups. For example, PLY exhibited higher soleus muscle activation in all phases of the jump, as well as higher braking force, potentially indicating that training increased muscle stiffness, leading to more efficient utilisation of elastic energy. Conversely, PNE showed an increase in VL muscle activity during drop jumps, but no change in braking force or optimal drop jump height due to training.

It is well documented that short (3–5 weeks) strength training periods lead to increased neural drive to the muscles (Hakkinen et al., 1992; Moritani and de Vries, 1979), which is the main reason for increased force in the early phases of training. In this study, PNE showed significantly increased VL muscle activity and knee extensor torque during rapid MVC after just 4 weeks of training. Conversely, PLY did not show significantly higher EMG activities at any point of the study period, and increases in torque were only evident after

12 weeks. Therefore, unlike the observed responses to plyometric training, it can be suggested that neuromuscular improvements due to pneumatic training are mainly attributable to enhancement of voluntary neural drive. It could be argued that as pneumatic training involved single-joint, concentric movements and plyometric training involved a multi-joint SSC task, comparisons of MVC responses between groups are somewhat biased because of training/task specificity. However, the combined load in PNE was lower than in PLY during the first 8 weeks of the training period but similar at the end, which could suggest that the small MVC improvements in PLY were not caused by insufficient loading. Nonetheless, this suggestion should be interpreted with caution because of the unmatched training loads and task specificity. As discussed above, it is noteworthy that during drop jumping, the PLY group exhibited possible evidence of adaptations in reflex pathways that were not evident in PNE. In fact, the post-training decrease in Hmax/Mmax-ratio during standing in PNE might even imply a down-regulation of peripheral pathways in this group. This supports the suggestion that improvements in neuromuscular performance observed in PNE were primarily due to increased voluntary drive.

In conclusion, pneumatic and plyometric explosive training seemed to cause different neuromuscular adaptations that were highly dependent upon training mode and testing conditions. The main adaptation to pneumatic training seems to be increased neural drive whereas plyometric training may also cause enhancement of reflex loop activity along with improved utilisation of elastic energy. Despite the different adaptations between training modes, neither was clearly superior from a balance perspective, as both training types led to improved balance control in response to sudden perturbations. As improvements in balance control were correlated with rapid knee extension torque, the results highlight the need to target rapid force production in training studies aiming to improve dynamic balance in older individuals.

Conflict of interest

The authors declare no conflict of interest.

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