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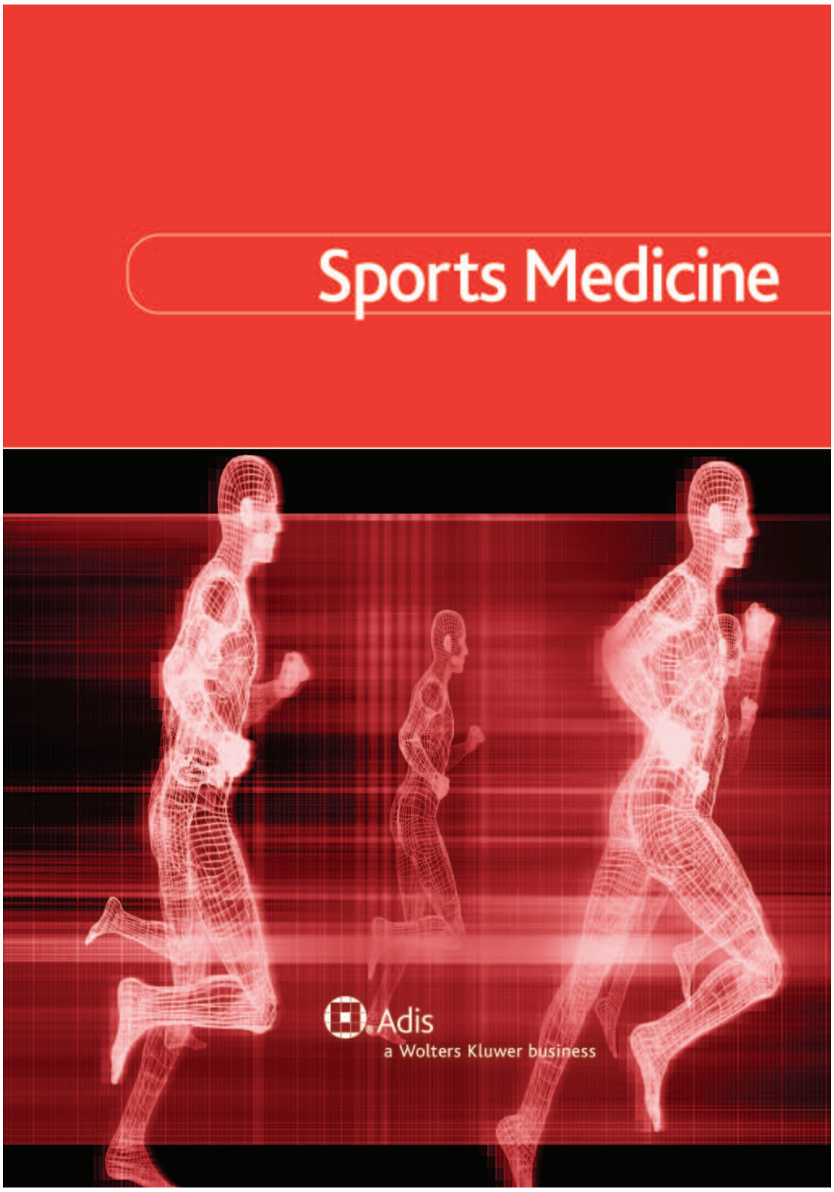

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REVIEW ARTICLE

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Neuro-Musculoskeletal and Performance Adaptations to Lower-Extremity Plyometric Training

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Contents

Abstract

Plyometric training (PLY) is a very popular form of physical conditioning of healthy individuals that has been extensively studied over the last 3 decades. In this article, we critically review the available literature related to lower-body PLY and its effects on human neural and musculoskeletal systems, athletic performance and injury prevention. We also considered studies that combined lower-body PLY with other popular training modalities, as well as studies that applied PLY on non-rigid surfaces. The available evidence suggests that PLY, either alone or in combination with other typical training modalities, elicits numerous positive changes in the neural and musculoskeletal systems, muscle function and athletic performance of healthy individuals. Specifically, the studies have shown that long-term PLY (i.e. 3–5 sessions a week for 5–12 months) represents an effective training method for enhancing bone mass in prepubertal/early pubertal children, young women and premenopausal women. Furthermore, short-term PLY (i.e. 2–3 sessions a week for 6–15 weeks) can change the stiffness of various elastic components of the muscle-tendon complex of plantar flexors in both athletes and non-athletes. Short-term PLY also improves the lower-extremity strength, power and stretch-shortening cycle (SSC) muscle function in healthy individuals. These adaptive changes in neuromuscular function are likely the result of (i) an increased neural drive to the agonist muscles; (ii) changes in the muscle activation strategies (i.e. improved intermuscular coordination); (iii) changes in the mechanical characteristics of the muscle-tendon complex of plantar flexors; (iv) changes in muscle size and/or architecture; and (v) changes in single-fibre mechanics. Our results also show that PLY, either alone or in combination with other training modalities, has the potential to (i) enhance a wide range of athletic performance (i.e. jumping, sprinting, agility and endurance performance) in children and young adults of both sexes; and (ii) to reduce the risk of lower-extremity injuries in female athletes. Finally, available evidence suggests that short-term PLY on non-rigid surfaces (i.e. aquatic- or sand-based PLY) could elicit similar increases in jumping and sprinting performance as traditional PLY, but with substantially less muscle soreness. Although many issues related to PLY remain to be resolved, the results of this review allow us to recommend the use of PLY as a safe and effective training modality for improving lower-extremity muscle function and functional performance of healthy individuals. For performance enhancement and injury prevention in competitive sports, we recommend an implementation of PLY into a well designed, sport-specific physical conditioning programme.

Plyometric training (PLY) is a very popular form of physical conditioning of healthy individuals and certain patient populations (e.g. osteoporotic patients). It involves performing bodyweight jumping-type exercises and throwing medicine balls using the so-called stretch-shortening cycle (SSC) muscle action. The SSC enhances the ability of the neural and musculotendinous systems to produce maximal force in the shortest amount of time, prompting the use of plyometric exercise as a bridge between strength and speed.[1] In this regard, PLY has been extensively used for augmenting dynamic athletic performance, particularly vertical jump ability.[2-4] Indeed, the vast majority of the earliest PLY studies examined the effects of SSC jumping programmes on vertical jump height.[5-12] Several other reviews on this topic have also been published.[2-4,13]

However, the focus and application of PLY has evolved over the last 15 years. Specifically, PLY has been frequently used for improving human neuromuscular function in general,[14-16] as well as for improving performance in both explosive[9,17,18] and endurance athletic events.[19,20] Furthermore, a number of studies have shown that PLY (i) could improve biomechanical technique and neuromuscular control during high-impact activities like cutting and landing;[21-28] and (ii) has the potential for reducing the risk of lower-extremity injuries in team sports.[25,29-31] Finally, experimental evidence suggests that PLY appears to induce not only favourable neuromuscular, but also bone[32,33] and musculo-tendinous adaptation.[34,35]

Our aim in this article is to critically review the available literature related to PLY and its effects on the human neural and musculoskeletal systems, athletic performance and injury prevention. Given that the vast majority of PLY studies focused on lower body, we reviewed only lower-body PLY that involved SSC jumping-type exercise. We also considered studies that combined lower-body PLY with other popular training modalities such as weight training (WT), endurance training, sprint training or electromyostimulation.

1. Search Strategy

Computerized literature searches of articles published between January 1966 and April 2009 were performed with the use of MEDLINE, Scopus and SportDiscus® databases. The following keywords were used in different combinations: ‘plyometric’, ‘pliometric’, ‘stretch-shortening cycle’, ‘drop jump’, ‘jump training’, ‘performance’, ‘muscle strength’, ‘muscle power’, ‘injury prevention’, ‘muscle-tendon’ and ‘bone mass’. All titles were scanned and the abstracts of any potentially relevant articles were retrieved for review. In addition, the reference lists from both original and review articles retrieved were also reviewed. The present literature review includes studies published in peer-reviewed journals that have presented original research data on healthy human subjects. Regarding training studies, we only considered PLY studies (and studies that combined PLY with other training modalities) which lasted ≥4 weeks.

The size of the effect of PLY on each performance variable (i.e. muscle force or torque, muscle power, rate of force/torque development, vertical jump height, horizontal jump distance, sprint running performance, agility performance and endurance performance) is given either by the difference between the mean change in performance of subjects in the plyometric group and the control group (controlled trials), or by the difference between the mean change in performance of subjects in the plyometric group (single-group trials). To be able to compare the effects of PLY on different muscular and performance characteristics, we expressed the size of the effect either relative to the mean value of the control group (controlled trials), or relative to the mean pre-test value of the PLY group (single-group trails) – that is, in percentage values.

2. Plyometric Training (PLY) on Rigid Surfaces

2.1 Musculoskeletal Adaptation to PLY

2.1.1 Bone Adaptation to PLY

It is well established that physical exercise has a positive effect on bone mass. This is particularly evident for dynamic loading[36] of high magnitude, i.e. high strain rate.[37] Since plyometric jump training is associated with high ground reaction forces (up to 7 times bodyweight),[38] this type of exercise could be particularly suitable for increasing bone mass. Our literature search identified 18 studies that examined bone adaptation to PLY in humans (table I); 13 involved children or adolescents, two involved young adults and three involved pre- and/or post-menopausal women. Most studies incorporated PLY into either school- or home-based exercise programmes; only two studies combined PLY with WT. Training interventions in these studies mainly included 50–100 jumps per session, three to five sessions per week and lasted between 5 and 24 months, considerably longer than PLY interventions that are focused on performance enhancement (see sections 2.2 and 2.3).

Twelve of 13 studies performed on children or adolescents reported significant positive effects of PLY on bone mass, with *relative* gains ranging from 1% to 8%. However, bone adaptation to mechanical loading in children is not homogenous but depends on the skeletal site and the maturity status of the participants. Specifically, positive effects of PLY on bone mass appear to be highest in early pubertal children, are somewhat lower in prepubertal children and are the lowest in pubertal children.[33,41,43,44] Furthermore, increases in bone mineral content and density tended to be greater at the femoral neck than at the lumbar spine, trochanter or proximal femur. Importantly, school-based jump training programmes not only increase bone mass in children, but also improve bone structure and strength.[44,49] Finally, recent longitudinal studies showed that PLY in early childhood has a persistent long-term effect over and above the effects of normal growth and development.[52,55]

Table I. Chronological summary of studies examining the effects of plyometric jump training on bone tissue adaptation

Study	No. of subjects; design	Training protocol	Measures	Relative effects[a] (%)
Bassey and Ramsdale[39]	27 pre-menopausal women: 14 underwent a high-impact training programme; RCT	CMJ training programme performed 5 d/wk for 6 mo	Femoral neck BMD	↑ 2.1
			Wards's triangle BMD	↓ 0.3
			Trochanteric BMD	↑ 2.9[b]
			Lumbar spine BMD	↓ 0.3
Bassey et al.[40]	55 pre-menopausal women: 30 underwent a training intervention 123 post-menopausal women: 69 underwent a training intervention; RCTs	CMJ training programme (50 jumps) performed 6 d/wk for 6 mo (pre-menopausal) or 12 mo (post-menopausal)	Pre-menopausal:	
			Femoral neck BMD	↑ 1.6
			Trochanteric BMD	↑ 2.6[b]
			Lumbar spine BMD	↓ 0.8
			Post-menopausal:	
			Femoral neck BMD	↓ 1.1
			Trochanteric BMD	↓ 0.4
			Lumbar spine BMD	↓ 0.1
			Post-menopausal (hormone replacement):	
			Femoral neck BMD	↑ 0.2
			Trochanteric BMD	↓ 0.5
			Lumbar spine BMD	↓ 0.3
Witzke and Snow[33]	53 adolescent girls: 25 underwent a training intervention; non-RCT	Combined PLY and resistance training programme performed 3 ×/wk for 9 mo	Total body BMC	↓ 0.4
			Lumbar spine BMC	↑ 0.9
			Femoral neck BMC	↑ 1.4
			Trochanteric BMC	↓ 0.4
			Femoral mid-schaft BMC	↑ 0.9
Heinonen et al.[41]	58 pre-menarcheal girls: 25 underwent a training intervention 68 post-menarcheal girls: 64 underwent a training intervention; non-RCT	Combined aerobic step and jump training programme (100–200 jumps) performed 2 ×/wk for 9 mo	Pre-menarcheal girls:	
			Lumbar spine BMC	↑ 3.3[b]
			Femoral neck BMC	↑ 4.0[b]
			Post-menarcheal girls:	
			Lumbar spine BMC	↑ 1.1
			Femoral neck BMC	↑ 0.2
Fuchs et al.[42]	89 pre-pubescent children: (51 boys, 38 girls) 55 underwent a training intervention; RCT	Jump training programme (50–100 jumps) performed 3 ×/wk for 7 mo	Femoral neck BMC	↑ 4.9[b]
			Femoral neck BMD	↑ 1.2
			Lumbar spine BMC	↑ 3.4[b]
			Lumbar spine BMD	↑ 2.0[b]
MacKelvie et al.[43]	70 pre-pubertal girls: 44 underwent a training intervention 107 early pubertal girls: 43 underwent a training intervention); RCT	Jump training programme (50–100 jumps) performed 3 ×/wk for 7 mo	Pre-pubertal girls:	
			Total body BMC	↔ 0
			Total body BMD	↔ 0
			Lumbar spine BMC	↑ 0.4
			Lumbar spine BMD	↑ 0.2
			Femoral neck BMC	↔ 0
			Femoral neck BMD	↑ 0.2
			Trochanteric BMC	↓ 0.6
			Trochanteric BMD	↓ 0.2
			Proximal femur BMC	↓ 0.9
			Proximal femur BMD	↓ 0.6
			Early pubertal girls:	
			Total body BMC	↑ 4.3
			Total body BMD	↑ 0.3
			Lumbar spine BMC	↑ 1.8[b]
			Lumbar spine BMD	↑ 1.9
			Femoral neck BMC	↑ 3.8[b]
			Femoral neck BMD	↑ 2.7[b]
			Trochanteric BMC	↑ 0.3
			Trochanteric BMD	↓ 0.2
			Proximal femur BMC	↑ 1.3
			Proximal femur BMD	↑ 0.8

Continued next page

Table I. Contd

Study	No. of subjects; design	Training protocol	Measures	Relative effects[a] (%)
Petit et al.[44]	70 pre-pubertal girls: 44 underwent a training intervention 107 early pubertal girls: 43 underwent a training intervention; RCT	Jump training programme (50–100 jumps) performed 3×/wk for 7 mo	Pre-pubertal girls:	
			Femoral neck BMD	↓ 0.6
			Femoral neck BA	↓ 1.0
			Intertrochanter BMD	↓ 0.5
			Intertrochanter BA	↓ 0.2
			Femoral shaft BMD	↓ 0.8
			Femoral shaft BA	↓ 1.0
			Early pubertal girls:	
			Femoral neck BMD	↑ 2.7[b]
			Femoral neck BA	↑ 0.6[b]
			Intertrochanter BMD	↑ 1.8[b]
			Intertrochanter BA	↑ 1.2
			Femoral shaft BMD	↑ 0.4
			Femoral shaft BA	↑ 0.3
MacKelvie et al.[45]	121 pre-pubertal boys: 61 underwent a training intervention; RCT	Jump training programme (50–100 jumps) performed 3×/wk for 7 mo	Total body BMC	↑ 1.5[b]
			Lumbar spine BMC	↑ 1.3
			Lumbar spine BMD	↑ 0.7
			Femoral neck BMC	↔ 0
			Femoral neck BMD	↑ 0.2
			Trochanteric BMC	↔ 0
			Trochanteric BMD	↑ 1.3
			Proximal femur BMC	↑ 1.2
			Proximal femur BMD	↑ 1.1[b]
Johannsen et al.[46]	54 children (age: 3–18 y; 31 girls): 28 underwent a training intervention; RCT	Jump training (25 jumps) performed 5×/wk for 12 wk	Total body BMC	↑ 1.1[b]
			Legs BMC	↑ 1.7[b]
			Spine BMC	↔ 0
			Spine BMD	↑ 0.6
			Femoral neck BMC	↑ 1.5
			Femoral neck BMD	↑ 1.2
			Distal tibia BMC	↓ 1.3
			Distal tibia BMD	↓ 1.5
Iuliano-Burns et al.[47]	36 pre-pubertal and early pubertal girls: 18 underwent a training intervention; RCT	Jump training performed 3×/wk for 8.5 mo	Total body BMC	↑ 1.4
			Lumbar spine BMC	↓ 2.5
			Femur BMC	↓ 1.5
			Tibia/fibula BMC	↑ 2.0[b]
MacKelvie et al.[48]	75 girls (age: 9.9 y): 32 underwent a training intervention; RCT	Jump training programme (50–132 jumps) performed 3×/wk for 20 mo	Total body BMC	↑ 2.3
			Lumbar spine BMC	↑ 6.0[b]
			Femoral neck BMC	↑ 3.9[b]
			Trochanteric BMC	↓ 3.1
			Proximal femur BMC	↑ 0.6
MacKelvie et al.[49]	64 pre-pubertal or early pubertal boys: 31 underwent a training intervention; RCT	Jump training programme (50–132 jumps) performed 3×/wk for 20 mo	Total body BMC	↑ 1.7
			Lumbar spine BMC	↑ 2.0
			Femoral neck BMC	↑ 3.9[b]
			Trochanteric BMC	↓ 3.1
			Proximal femur BMC	↑ 4.3
Vainionpää et al.[50]	80 pre-menopausal women: 39 underwent a training intervention; RCT	Jump training combined with walking, running and stamping performed 3×/wk for 12 mo	Lumbar spine BMD	↑ 0.3
			Femoral neck BMD	↑ 1.4[b]
			Trochanter BMD	↑ 0.9
			Intertrochanter BMD	↑ 1.0[b]
			Ward's triangle BMD	↑ 1.7

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Table I. Contd

Study	No. of subjects; design	Training protocol	Measures	Relative effects[a](%)
McKay et al.[51]	124 children (age: 10.1 y): 51 (23 boys and 28 girls) underwent a training intervention; non-RCT	CMJ training (10 jumps) performed 3 ×/wk for 8 mo	Total body BMC	↓ 1.3[b]
			Total body BA	↓ 1.5[b]
			Lumbar spine BMC	↓ 0.8
			Lumbar spine BA	↓ 0.3
			Proximal femur BMD	↑ 2.6[b]
			Proximal femur BA	↑ 1.3
			Intertrochanter BMC	↑ 2.9[b]
			Intertrochanter BA	↑ 2.2
			Trochanter BMC	↑ 1.9
			Trochanter BA	↑ 0.6
			Femoral neck BMC	↓ 0.2
			Femoral neck Area	↓ 0.3
Kato et al.[32]	36 female college students (age: 20.7 y): 18 underwent a training programme; RCT	CMJ training (10 jumps) performed 3 ×/wk for 6 mo	Lumbar spine BMD	↑ 1.7[b]
			Proximal femur BMD	↑ 1.8
			Femoral neck BMD	↑ 3.6[b]
			Ward's triangle BMD	↑ 2.6
			Trochanter BMD	↑ 1.5
Gunter et al.[52]	199 children (94 boys, 105 girls): 101 underwent a training intervention; RCT	Jump training (~100 jumps) performed 3 ×/wk for 7 mo	Total body BMC	↑ 7.3[b]
			Lumbar spine BMC	↑ 7.9[b]
			Femoral neck BMC	↑ 7.7[b]
			Trochanter BMC	↑ 8.4[b]
Weeks et al.[53]	81 adolescents (37 boys, 44 girls): 43 underwent a training intervention; RCT	Jump training (~300 jumps) performed 2 ×/wk for 8 mo	Boys:	
			Total body BMC	↑ 4.2[b]
			Femoral neck BMC	↑ 2.1
			Femoral neck BA	↑ 1.1
			Trochanter BMC	↑ 6.7[b]
			Lumbar spine BMC	↑ 3.6[b]
			Lumbar spine BA	↑ 1.7
			Girls:	
			Total body BMC	↑ 1.9
			Femoral neck BMC	↑ 7.8[b]
			Femoral neck BA	↑ 0.3
			Trochanter BMC	↑ 6.9
			Lumbar spine BMC	↓ 1.9
			Lumbar spine BA	↑ 1.7
Guadalupe-Grau et al.[54]	66 physical education students (43 males, 23 females): 28 underwent a training intervention; RCT	PLY (40–70 jumps) combined with WT performed 3 ×/wk for 9 wk	Men:	
			Total body BMC	↑ 0.3
			Total body BMD	↑ 0.8
			Lumbar spine BMC	↑ 1.9
			Lumbar spine BMD	↑ 0.9
			Lower limbs BMC	↔ 0
			Lower limbs BMD	↔ 0
			Femoral neck BMC	↑ 1.5[b]
			Femoral neck BMD	↓ 2.8
			Ward's triangle BMD	↑ 1.0
			Trochanter BMD	↓ 2.2
			Intertrochanter BMD	↔ 0
			Women:	
			Total body BMC	↑ 1.0
			Total body BMD	↓ 0.9
			Lumbar spine BMC	↑ 0.7
			Lumbar spine BMD	↔ 0
			Lower limbs BMC	↑ 0.6

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Table I. Contd

Study	No. of subjects; design	Training protocol	Measures	Relative effects[a](%)
			Lower limbs BMD	↔ 0
			Femoral neck BMC	↑ 4.2[b]
			Femoral neck BMD	↓ 1.0
			Ward's triangle BMD	↓ 2.3
			Trochanter BMD	↔ 0
			Intertrochanter BMD	↔ 0

a [(Post-training – pre-training) – (post-control – pre-control)]/pre-control.

b Significantly ($p < 0.05$) greater increase in the exercise vs control group.

BA = bone area; **BMC** = bone mineral content; **BMD** = bone mineral density; **CMJ** = countermovement jump; **PLY** = plyometric training; **RCT** = randomized controlled trial; **WT** = weight training; ×/**wk** = sessions times per week; ↑ indicates increase in performance; ↓ indicates decrease in performance; ↔ indicates no change in performance.

Bone adaptation to PLY in adults has been much less studied (table I). The available data suggest that PLY effects on bone mass in women are age specific. More precisely, significant positive gains in bone mass (1–4%) following PLY have been observed in young and pre-menopausal women, but not in post-menopausal women.[32,39,40,50,54,56] Taken together, these results suggest that PLY, performed three to five times a week over 5–24 months, represents an effective training method for enhancing bone mass in prepubertal and early pubertal children, young women and premenopausal women. More studies are needed to test the effectiveness of PLY on bone mass in other populations (e.g. athletes and the elderly).

2.1.2 Muscle-Tendon Complex and Joint Adaptations to PLY

In SSC movements, the elastic behaviour of muscles, ligaments and tendons plays a decisive role.[57-59] In that regard, the importance of stiffness characteristics of the muscle-tendon complex in SSC exercise performance has been particularly stressed in scientific literature. Indeed, many authors have suggested that a stiff muscle-tendon complex is optimal for performance of SSC activities since it allows a rapid and more efficient transmission of muscle force to skeleton and, consequently, higher rates of force development.[60-63] However, a number of cross-sectional studies have proven otherwise by showing that the stiffness of the muscle-tendon complex correlates *negatively* to the augmentation of performance in concentric motion during SSC exercises.[64-68] Furthermore, Stafilidis and Arampatzis[69] recently showed that faster sprinters have significantly lower stiffness of vastus lateralis tendon and aponeurosis compared with slower sprinters. The authors also reported that maximum elongation of vastus lateralis tendon and aponeurosis (i.e. lower stiffness) was significantly correlated ($r = -0.57$) with 100 m sprint performance time. Finally, Wilson et al.[70] have observed that flexibility training increased performance in upper-body SSC exercise with a reduction in the muscle-tendon complex stiffness. The authors suggested that a more compliant muscle-tendon unit can store and release more elastic energy, which in turn could improve SSC performance. A more compliant muscle-tendon unit could also improve SSC performance by allowing the muscle fibres to operate at a more optimal length over the first part of their shortening range. Collectively, these findings suggest that a more compliant muscle-tendon complex could be advantageous for SSC performance and that training could change the elastic behaviour of joint sub-components.

In that regard, our literature review revealed several human studies that examined the effects of short-term (6–15 weeks) PLY on stiffness of various anatomical structures and/or their combinations as follows: joint stiffness,[34] musculo-articular stiffness[71,72] or the stiffness of particular elastic components within the Hill's three-component model – parallel elastic component (i.e. passive muscles),[72,73] serial elastic component[19,35,74] or just passive part of the serial elastic component (i.e. tendons).[34,72,75,76] For example, Kubo et al.[34]

reported an increase of 63.4% in ankle joint stiffness assessed during drop jumps (DJs) with no significant changes in Achilles tendon stiffness following 12 weeks of PLY. Notably, the authors also observed that PLY significantly increased (i) the maximal Achilles tendon elongation and the amount of stored elastic energy; and (ii) the SSC-type jumping performance. No change in Achilles tendon stiffness and a significant increase in the SSC-type jumping performance following 8 weeks of PLY was also observed by Foure et al.[72] In addition, Wu et al.[76] recently reported a significant increase in jump performance and Achilles tendon elastic energy storage and release following 8 weeks of PLY; however, the authors also reported a significant increase in Achilles tendon stiffness following PLY intervention.[76] Similarly, Burgess et al.[75] also reported that 6 weeks of PLY significantly increased the Achilles tendon stiffness by 29% in young adults, together with a significant increase in concentric-only explosive muscular performance.

Furthermore, several research groups focused on the entire serial elastic component of plantar flexor muscles and observed either a significant increase[19,74] or a decrease[35] in its stiffness following PLY. Interestingly, the two studies that reported conflicting findings regarding PLY effects on the serial elastic component stiffness also reported significant increases in the same SSC jump performance.[19,35] Two studies from the same research group focused on the musculo-articular stiffness of the ankle joint and showed either significant increase,[71] or no change[72] in musculo-articular stiffness of the ankle joint following PLY. Notably, in these two experiments the authors used different techniques for determination of the global musculo-articular stiffness. Finally, Malisoux et al.[73] observed that PLY induced increases in passive stiffness of fast-twitch muscle fibres, and Foure et al.[72] reported a significant increase in the passive stiffness of the gastrocnemii (i.e. predominantly fast-twitch muscle) after 8 weeks of PLY.

Overall, these studies showed that PLY has the potential to change the various elastic components of the muscle-tendon complex. However, the cited studies provided conflicting findings that are difficult to interpret, particularly if we take into account the complexity of the relationships between the elastic properties at different anatomical levels[66,77] and methodological limitations of certain approaches in studying stiffness of biological tissues.[78] The recently reported results by Foure et al.[72] shed some light on this complex issue by showing that 8 weeks of PLY induced a significant relative increase of 33% in the passive stiffness of the gastrocnemii without changes in the Achilles tendon stiffness or global passive musculo-articular stiffness of the ankle joint. As a possible explanation of the results, the authors put forward a hypothesis that the muscle-tendon complex of gastrocnemii (bi-articular muscle) and soleus (mono-articular muscle) may have a different response to PLY. Further studies are needed to test this hypothesis, as well as to focus on the specific effects of PLY on particular elastic components of the muscle-tendon complex, and the overall joint behaviour during SSC movements.

2.2 Neuromuscular Adaptations to PLY

2.2.1 Muscle Fibre Type

Several animal studies have shown that PLY could induce fibre type transition in trained muscles. Specifically, in the soleus muscle of a rat, PLY induces a significant relative increase in type II fibres.[79-82] In humans, only three studies examined the muscle fibre transition as a result of PLY.[83-85] Similar to the results of animal studies, Malisoux et al.[83] also found a significant increase in the proportion of type IIa fibres of the vastus lateralis muscle. In contrast, Kyrolainen et al.[84] and Potteiger et al.[85] did not observe any significant changes in fibre-type composition of the lateral gastrocnemius and vastus lateralis muscles, respectively. When PLY was combined with WT, Perez-Gomez et al.[86] observed a significant increase in percentage of type IIa fibres in vastus lateralis, whereas Hakkinen and co-workers[16,87] found no changes in fibre composition. Combination of PLY with endurance training also had no effect on fibre composition of vastus lateralis muscle.[85] Collectively, the results of a limited number of human studies are inconclusive regarding the effects of PLY on human muscle fibre-type composition. When taking into account the results of animal studies, it is possible that PLY-induced fibre-type transition in leg extensor muscles could be muscle specific. Future studies should test this hypothesis.

2.2.2 Whole Muscle and Single Fibre Contractile Performance

Numerous previous studies examined the effects of various training paradigms such as resistance training, endurance training and sprint training on whole muscle or single fibre contractile performance.[88-91] Surprisingly, however, we found only three studies published in peer-reviewed journals that examined the effects of PLY on human muscle contractile performance.[34,35,73] Grosset et al.[35] recently showed that 10 weeks of PLY increased twitch peak torque and rate of torque development in the gastrocnemius muscle. The authors also observed a slight decrease in contraction time. In another study, Kubo et al.[34] observed that 12 weeks of PLY significantly decreased plantar flexors contraction time, with no changes in twitch peak torque and rate of torque development. These data generally suggest that PLY can increase the contractility of plantar flexor muscles. Malisoux et al.,[73] on the other hand, focused on the contractile properties of single fibres of vastus lateralis muscle and reported that 8 weeks of PLY induced significant increases in peak force and maximal shortening velocity in type I, IIa and hybrid IIa/IIx fibres, while peak power increased significantly in all fibre types. Note that these changes in a single fibre function were accompanied by significant improvements in the whole muscle strength and power. The latter results are particularly important since they suggest that PLY-induced improvements in muscle function and athletic performance could be partly explained by changes in the contractile apparatus of the muscle fibres, at least in knee extensor muscles. Further studies are needed to examine whether PLY induces similar adaptive changes in single fibres of plantar flexors.

2.2.3 Whole Muscle and Single Fibre Hypertrophy

The effects of strength and endurance training on human muscle and/or fibre size are well documented in the literature. Regarding PLY effects on human muscle size, we found one study that focused on the whole muscle[34] and three studies that focused on single muscle fibres.[73,84,85] Kubo et al.[34] used the MRI technique and showed that 12 weeks of PLY induced a significant increase in plantar flexor muscle volume (~5%), and this effect was similar to the effect induced by WT of similar duration. Furthermore, Malisoux et al.[73] reported significant increases in a cross-sectional area of type I (+23%), type IIa (+22%) and type IIa/IIx fibres (+30%) in vastus lateralis muscle following 8 weeks of PLY. Potteiger et al.[85] also reported significant increases in a type I and type II fibre cross-sectional area of the vastus lateralis muscle, but these effects were of smaller magnitude (+6–8%). In contrast, Kyrolainen and co-workers[84] observed no changes in a fibre cross-sectional area of gastrocnemius muscle following 15 weeks of PLY. When PLY was combined with WT, Hakkinen et al.[87] observed no changes in a fibre cross-sectional area of the vastus lateralis muscle in women. However, a similar training protocol did induce a significant increase (~20%) in the mean area of fast-twitch fibres in men.[16] Furthermore, Perez-Gomez et al.[86] reported that combined PLY and WT increased lower-limb lean mass (+4.3%), as determined by dual energy x-ray absorptiometry. Finally, an 8-week combined PLY and endurance training also resulted in a significant fibre hypertrophy (~6–7%) in vastus lateralis muscle.[85] Overall, these data suggest that short-term PLY, alone or in combination with WT, has the potential to induce a moderate hypertrophy of both type I and type II muscle fibres; however, these effects (i) are generally lower compared with those induced by WT; and (ii) appear to be more pronounced in knee extensors than in plantar flexors.

2.2.4 Muscle Geometry

It is well known that a muscle's geometry strongly influences its force and power output and that it can be changed with WT.[92] To our knowledge, only one study examined muscle architectural adaptations to PLY, and it was combined with sprint training.[93] The authors showed that 5 weeks of combined PLY and sprint training intervention decreased fascicle angle and increased fascicle length in knee extensor muscles. Differential muscle architectural adaptations were observed when WT was added to PLY and sprint training; however, both training groups improved athletic performance to a similar extent.[93] Obviously, more studies are needed before any firm conclusions can be drawn regarding PLY effects on muscle geometry.

2.2.5 Neural Adaptation

The neural control, including central and peripheral components, plays a key role in force potentiation during the SCC-type exercises. Of particular importance are muscle activation prior to the ground impact (pre-activation) and reflex facilitation during the late eccentric and early concentric phase.[94] Thus, it is reasonable to assume that PLY-induced changes in human muscle function and performance have a neural origin. Our literature search revealed six PLY studies[28,34,76,84,95,96] and three combined PLY and WT studies[87,97,98] that focused on neural adaptation. Notably, most research groups used only surface electromyography (EMG) during maximal voluntary contractions (MVC) or during vertical jumps to detect changes in muscle activity following an intervention.

Regarding PLY, several studies focused on changes in leg muscle activation during vertical jumping and provided conflicting findings. Chimera et al.[28] reported that adductor muscle pre-activation and adductor and abductor co-activation both increased after PLY during DJ performance. No changes in the EMG activity of quadriceps and hamstrings muscles were observed. Kyrolainen and co-workers[95,96] showed that leg muscle activity patterns during DJ did not change following an intervention; however, in one of these studies the authors did observe a significant increase in the pre-activity of leg extensors during DJ performance.[95] Kubo et al.[34] observed no changes in plantar flexor muscles activity during pre-landing and eccentric phases of vertical jumps following PLY. However, they reported a significant increase in plantar flexor muscles activity during the concentric phase of all studied vertical jumps. Moreover, using the twitch interpolation technique, these authors also assessed the activation level of plantar flexors prior to and after PLY, and reported a significant increase in both MVC (+17.3%) and activation level (+5.6%) of plantar flexor muscles. Wu et al.[76] used another technique – root mean square EMG – that was normalized to the respective M-wave, and showed that soleus (but not gastrocnemius) normalized EMG increased significantly after PLY, without any change in maximal M-wave amplitude. Furthermore, Kyrolainen et al.[84] reported that PLY significantly increased both MVC and muscular activity of plantar flexors, but not of knee extensors. Finally, there is limited evidence from both human[99] and animal[82] experiments that PLY may change the stretch reflex excitability. These findings suggest that neuromuscular adaptation to PLY is not only limited to the motor pathways to the muscle, but also concerns its sensory part. Regarding studies that combined PLY with WT, all of them reported significant training-induced increases in leg extensor muscle activity during either maximal isometric contractions[16,87] or during vertical jump performance.[97,98]

Taken together, the reviewed studies generally suggest that PLY alone can increase MVC and voluntary activation of plantar flexors. This enhanced voluntary activity of plantar flexors could be accounted for by an increase in motor unit recruitment or discharge rate,[76,100] both mediated by changes in descending cortical outflow. Other possible aspects of neural adaptation to PLY include (i) changes in leg muscle activation strategies (or inter-muscular coordination) during vertical jumping, particularly during the preparatory (i.e. pre-landing) jump phase; and (ii) changes in the stretch reflex excitability. When PLY was combined with WT, a greater potential for increasing the EMG activity of leg extensors was observed compared with when PLY was the only training modality. However, one should use considerable caution in interpreting the EMG amplitude following training, as changes in EMG amplitude can be attributed to alterations in central neural drive, muscle factors such as muscle hypertrophy or a variety of technical factors not reflective of physiological changes.[101] Although some of these problems can be overcome by using EMG normalization procedures, single motor unit recording techniques and measurements of evoked reflex responses (Hoffman reflex, F-wave – an electrophysiological variant of the Hoffman reflex),[56] these methods have rarely been used in human PLY studies. Therefore, our current knowledge about PLY-induced changes in neural function is limited.

2.2.6 Muscle Strength and Power

Numerous previous studies have examined the effects of short-term PLY on the strength and power of lower-extremity muscles (table II) and have reported variable results. Specifically, relative changes in maximal strength of lower-extremity muscles induced by PLY ranged from +3.2% to +45.1%; however, most (i.e. 12 of 25) studies reported positive effects and these were mainly ≥10%. For 'explosive' muscle strength or rate of force/torque development, these relative effects were more variable (range –22.3% to +33.0%; table II). Still, most (i.e. 8 of 10) studies did observe a relative increase in 'explosive' muscle strength following a PLY intervention. Finally, PLY produced a relative increase in muscle power in 13 of 16 studies, and these positive effects ranged between +2.4% and +31.3%. Importantly, positive strength and power gains as a result of PLY were observed in both athletes and non-athletes, and in both males and females. A recent meta-analytical review supports this conclusion by showing that PLY significantly improves strength performance and that PLY gains are independent of the fitness level or sex of the subject.[127]

Although numerous studies examined the effects of PLY on muscle strength and power, only four studies actually focused on the possible neuromuscular mechanisms behind these effects. Kyrolainen et al.[84] showed that 15 weeks of PLY improves the strength of plantar flexors but not the rate of force development, and these changes were accompanied by a significant increase in muscle activity without any changes in muscle-fibre distributions and areas. The authors found no change in maximal strength and muscle activation for knee extensor muscles but reported a significant increase in the rate of force development. In contrast, Kubo et al.[34] showed that PLY-induced changes in plantar flexors strength were accompanied by both significant hypertrophy and an increase in the activation level of those muscles. Furthermore, Potteiger et al.[85] showed that PLY increased leg extensors muscle power (+3–5%), and these changes were accompanied by a significant increase in the cross-sectional area of vastus lateralis type I (+4.4%) and type II (+7.8%) muscle fibres. Finally, Malisoux et al.[73] showed that PLY significantly increased leg extensors strength and power by +12–13%, and these changes in performance were accompanied by significant increases in single-fibre diameter, peak force, shortening velocity and power. Collectively, these data, together with the data presented in previous sections (see sections 2.2.1–2.2.5), suggest that increases in muscle strength and power after PLY could have both a neural and muscular origin. Note, however, that some of these changes could be different from the changes induced by other resistance training modalities, namely (i) changes in muscle architecture (i.e. a decrease in fascicle angle and an increase in fascicle length of knee extensors[93]); (ii) changes in the stiffness of various elastic components of the muscle-tendon complex of plantar flexors;[35,66,71,72] and (iii) changes in single fibre mechanics of knee extensors (i.e. enhanced force, velocity and, consequently, power of slow and fast muscle fibres[90]).

When PLY is combined with WT, its potential for augmenting human muscle strength and power is further increased (table III). Indeed, all studies that compared PLY with combined PLY and WT reported significantly greater relative changes in muscle strength and power after combined PLY and WT.[10,15,102] This conclusion is further supported by the results of a recent meta-analytical review that showed significantly higher strength gains after combined PLY and WT compared with after PLY alone.[127] The relative increase in maximal strength and power after combined PLY and WT is present in all published studies and it ranges from +5–43%, and from +2–37%, respectively (table III). Limited data exist regarding the effects of combined PLY and WT on the rate of force/torque development (table III).

Table II. Chronological summary of studies examining the effects of plyometric training (PLY) on skeletal muscle function and athletic performance

Study	No. of subjects; sex; fitness level; control group	PLY intervention exercise (wk/sessions)	Relative effects (%) maximal strength (performance variable)	explosive strength	muscle power	jumping performance (jump type)	sprinting performance (distance, m [yd]^a)	agility performance	endurance performance (measure)
Blattner and Noble[5]	26; M; N-A; yes	DJT (8/24)				↑ 8.5 (CMJA)			
Dvir[8]	16; M; N-A; yes	DJT (8/24)			↑ 6.4	↑ 13.0 (CMJA) ↑ 6.9 (CMJA)			
		CMJT (8/24)			↑ 5.7				
Hakkinen and Komi[97]	10; M; N-A; no	COMB (24/72)				↑ 21.2 (SJ) ↑ 17.6 (CMJ) ↑ 25.0 (DJ) ↑ 26.8 (DJ) ↑ 32.4 (DJ)			
Brown et al.[9]	26; M; A; yes	DJT (12/34)				↑ 5.0 (CMJ) ↑ 6.0 (CMJA)			
Hortobagyi et al.[12]	25; M; N-A; yes	COMB (10/20)				↑ 6.1 (CMJA) ↑ 12.1 (CMJA) ↑ 2.9 (HJ) ↑ 1.4 (HJ)			
Bauer et al.[102]	8 NS; N-A; no	COMB (10/30)	↑ 15.1 (F/T) ↑ 5.7 (F/T) ↑ 7.1 (F/T)			↑ 5.5 (CMJA)			
Hakkinen et al.[87]	14; F; N-A; yes	COMB (16/48)	↑ 27.5 (F/T)	↑ 8.2					
Hortobagyi et al.[11]	19; M; N-A; yes	COMB (10/30)	↓ 3.2 (F/T)			↑ 3.9 (HJ) ↑ 2.7 (HJ)	↓ 0.6 (30)		
Wilson et al.[103]	27; M; N-A; yes	DJT (5/10)	↑ 3.3 (F/T)	↑ 2.4					
		DJT (10/20)	↑ 0.2 (F/T)		↑ 1.1	↑ 6.7 (SJ) ↑ 7.8 (CMJ)	↑ 1.1 (30)		
Holcomb et al.[104]	19; M; N-A; yes	CMJ (8/24)			↓ 0.9 ↑ 7.2	↑ 3.3 (SJ) ↑ 6.7 (CMJ)			
		DJT (8/24)			↑ 4.6 ↑ 10.2	↑ 7.3 (SJ) ↑ 9.4 (CMJ)			
		DJT (8/24)			↑ 3.1 ↑ 7.7	↑ 6.4 (SJ) ↑ 6.9 (CMJ)			

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Table II. Contd

Study	No. of subjects; sex; fitness level; control group	PLY intervention exercise (wk/sessions)	Relative effects (%)						
			maximal strength (performance variable)	explosive strength	muscle power	jumping performance (jump type)	sprinting performance (distance, m [yd][a])	agility performance	endurance performance (measure)
Wilson et al.[105]	27; M N-A; yes	DJT (8/16)	↓ 2.4 (1RM)	↓ 6.9		↑ 12.2 (CMJ)			
Hewett et al.[25]	11; F; A; no	COMB (6/18)	↑ 12.2 (F/T) ↑ 24.3 (F/T)		↑ 43.6 ↑ 22.3				
Cornu et al.[71]	19; M; N-A; yes	COMB (7/14)	↑ 14.3 (F/T)						
Wagner and Kocak[106]	40; M; A; yes	COMB (6/12)			↑ 23.2	↑ 2.2 (CMJA)	↑ 1.7 (50)		
	40; M; N-A; yes	COMB (6/12)			↑ 19.8	↑ 2.7 (CMJA)	↑ 1.3 (50)		
Gehri et al.[107]	10; M: 11; F; N-A; yes	DJT (12/24)				↑ 10.8 (SJ) ↑ 10.8 (CMJ) ↑ 10.1 (DJ)			
	9; M: 8; F; N-A; yes	CMJT (12/24)				↑ 10.8 (SJ) ↑ 9.0 (CMJ) ↑ 8.6 (DJ)			
Young et al.[108]	14; M; N-A; yes	DJT (6/18)	↑ 6.1 (F/T)			↓ 1.7 (SJ) ↑ 4.3 (CMJA) ↑ 9.0 (DJ)			
	20; M; N-A; yes	DJT (6/18)	↑ 0.8 (F/T)			↓ 3.7 (SJ) ↑ 1.6 (CMJA) ↑ 7.4 (DJ)			
Potteiger et al.[85]	8; M; N-A; no	COMB (8/24)			↑ 2.9 ↑ 5.8	↑ 4.6 (CMJA)			↑ 13.8 ($\dot{V}O_{2max}$)
Paavolainen et al.[109]	18; M; A; yes	COMB (9/0)	↑ 20.4 (F/T)			↑ 6.0 (HJ)	↑ 5.7 (20)		↓ 5.8 ($\dot{V}O_{2max}$) ↑ 0.8 (LT)
Fatouros et al.[15]	21; M; N-A; yes	COMB (12/36)	↑ 8.2 (1RM) ↑ 11.4 (1RM)		↑ 25.9	↑ 10.3 (CMJA)			
Rimmer and Sleivert[110]	17; M; A; yes	COMB (8/15)					↑ 2.2 (40) ↑ 1.8 (30) ↑ 1.6 (20) ↑ 2.6 (10)		

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Table II. Contd

Study	No. of subjects; sex; fitness level; control group	PLY intervention exercise (wk/sessions)	Relative effects (%)						
			maximal strength (performance variable)	explosive strength	muscle power	jumping performance (jump type)	sprinting performance (distance, m [yd]^a)	agility performance	endurance performance (measure)
Diallo et al.[111]	20; M; A; yes	COMB (10/30)			↑ 16.6	↑ 14.3 (SJ) ↑ 20.0 (CMJ)			
Matavulj et al.[17]	22; M; A; yes	DJT (6/18)	↑ 11.5 (F/T) ↑ 10.7 (F/T) ↑ 2.0 (F/T) ↓ 1.8 (F/T)	↓ 6.6 ↓ 3.0 ↓ 22.7 ↓ 18.2		↑ 15.6 (CMJ) ↑ 13.8 (CMJ)			
Miller et al.[112]	27 NS; N-A; yes	COMB (8/16)	↑ 2.2 (F/T) ↑ 0.9 (F/T) ↑ 7.9 (F/T) ↓ 1.7 (F/T) ↑ 2.8 (F/T) ↑ 2.9 (F/T)		↑ 0.4	↓ 0.2 (CMJA)			
Spurrs et al.[19]	17; M; A; yes	COMB (6/15)	↑ 13.3 (F/T) ↑ 15.4 (F/T)	↑ 31.3 ↑ 21.0		↑ 18.2 (CMJ) ↑ 7.0 (HJ)			↑ 7.8 (RE) ↑ 6.4 (RE) ↑ 5.1 (RE) ↑ 1.2 (ERPT) ↓ 3.1 ($\dot{V}O_{2max}$)
Turner et al.[113]	8; M: 10; F; A; yes	COMB (6/18)				↔ 0.0 (SJ) ↑ 4.8 (CMJ)			↓ 0.4 ($\dot{V}O_{2max}$)
Luebbers et al.[114]	19; M; N-A; no	COMB (4/12)			↓ 1.4 ↑ 3.7	↓ 3.5 (CMJA)			
		COMB (7/21)			↑ 0.3 ↑ 6.3	↓ 0.3 (CMJA)			
Canavan and Vescovi[115]	20; F; N-A; yes	COMB (6/18)			↓ 5.2	↑ 2.9 (CMJ)			
Chimera et al.[28]	16; F; A; yes	COMB (6/12)				↑ 3.7 (DJ)	↓ 0.3 (37 [40 yd])		
Irmischer et al.[26]	28; F; N-A; yes	COMB (9/18)		↑ 15.4		↑ 5.7 (CMJA)			
Robinson et al.[116]	16; F; N-A; no	COMB (8/24)	↑ 25.2 (F/T) ↑ 45.1 (F/T) ↑ 44.5 (F/T) ↑ 24.3 (F/T)			↑ 32.5 (CMJA)	↑ 6.2 (40)		
Kato et al.[32]	36; F; N-A; yes	CMJT (24/60)				↑ 5.6 (CMJ)			

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Table II. Contd

Study	No. of subjects; sex; fitness level; control group	PLY	Relative effects (%)						
		intervention exercise (wk/sessions)	maximal strength (performance variable)	explosive strength	muscle power	jumping performance (jump type)	sprinting performance (distance, m [yd][a])	agility performance	endurance performance (measure)
Kyrolainen et al.[84]	23; M; N-A; yes	COMB (15/30)	↑ 16.0 (F/T) ↑ 4.2 (F/T)	↑ 17.6		↑ 31.8 (DJ)			
Lehance et al.[117]	20; M; N-A; yes	DJT (6/12)			↓ 5.1	↑ 17.8 (CMJ) ↑ 15.8 (CMJA) ↑ 25.4 (DJ)	↑ 1.6 (10)		
Tricoli et al.[118]	15; M; N-A; yes	COMB (8/24)				↑ 3.6 (SJ) ↑ 4.5 (CMJ)	↑ 1.4 (30) ↑ 2.1 (10)	↑ 2.0	
Herrero et al.[119]	19; M; N-A; yes	COMB (4/8)	↓ 0.3 (F/T)			↓ 3.8 (SJ) ↓ 0.3 (CMJ)	↓ 0.3 (20)		
Kotzamanidis[120]	30; M; N-A; yes	COMB (10/20)				↑ 39.3 (SJ)	↑ 3.0 (30) ↑ 3.7 (20) ↑ 2.6 (10)		
Miller et al.[121]	19; M: 9; F; N-A; yes	COMB (6/12)						↑ 5.5 ↑ 3.0	
Malisoux et al.[73]	8; M; N-A; no	COMB (8/24)	↑ 11.2 (1RM)			↑ 7.5 (SJ) ↑ 14.6 (CMJ)		↑ 3.6	
Myer et al.[23]	8; F; A; no	COMB (7/21)	↑ 24.5 (F/T) ↑ 18.0 (F/T)			↑ 5.4 (CMJA)			
Saunders et al.[20]	15; M; A; yes	COMB (9/25)		↑ 14.2		↑ 8.0 (5JT)			↑ 2.4 (RE) ↑ 4.8 (RE) ↓ 2.3 ($\dot{V}O_{2max}$)
Markovic et al.[14]	63; M; N-A; yes	COMB (10/30)	↑ 2.5 (F/T)			↑ 7.1 (SJ) ↑ 6.4 (CMJ) ↑ 2.4 (HJ)	↑ 0.9 (20)	↑ 2.0	
Stemm and Jacobson[122]	17; M; N-A; yes	COMB (6/12)				↑ 7.2 (CMJA)			
Kubo et al.[34]	10; M; N-A; no	COMB (12/48)	↑ 13.3 (F/T)			↑ 28.5 (SLSJ) ↑ 35.3 (SLCMJ) ↑ 42.0 (SLDJ)			
Burgess et al.[75]	≈7; M; N-A; no	DJ (6/≈15)		↑ 19.0 ↑ 12.0		↑ 58.0 (USLCJ)			

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Table II. Contd

Study	No. of subjects; sex; fitness level; control group	PLY intervention exercise (wk/sessions)	Relative effects (%) maximal strength (performance variable)	explosive strength	muscle power	jumping performance (jump type)	sprinting performance (distance, m [yd]^{a})	agility performance	endurance performance (measure)
Dodd and Alvar[123]	28; M; A; no	COMB (4/7)				↑ 1.9 (CMJA)	↑ 0.1 (18 [20 yd]) ↓ 1.3 (37 [40 yd]) ↑ 0.3 (55 [60 yd])	↔ 0.0	
de Villarreal et al.[124]	20; M; N-A; yes	DJT (7/7)	↓ 2.9 (F/T) ↑ 1.6 (1RM)			↑ 1.1 (CMJ) ↑ 0.3 (DJ)	↑ 0.8 (20)		
						↓ 1.4 (DJ) ↑ 2.6 (DJ)	↑ 3.2 (20)		
		DJT (7/28)	↑ 14.9 (F/T) ↑ 13.1 (1RM)			↑ 19.3 (CMJ) ↑ 12.8 (DJ)			
	22; M; N-A; yes	DJT (7/14)	↑ 11.5 (F/T)			↑ 16.0 (DJ)			
			↑ 2.4 (1RM)			↑ 20.2 (DJ)	↑ 0.8 (20)		
						↑ 14.4 (CMJ)			
						↑ 8.5 (DJ) ↑ 5.1 (DJ) ↑ 11.1 (DJ)			
Salonikidis and Zafeiridis[18]	32; M; A; yes	COMB (9/27)					↑ 2.1 (12)	↑ 10.2 ↑ 9.6 ↑ 1.5	
Vescovi et al.[125]	18; F; N-A; yes	COMB (6/18)			↑ 3.6 ↑ 3.4	↑ 3.8 (CMJ)			
Grosset et al.[35]	6; M: 3; F; N-A; no	COMB (10/20)	↑ 9.0 (F/T)	↑ 16.3		↑ 10.0 (CMJA) ↑ 6.3 (HJ)			↑ 2.0 (MAV)
Potach et al.[126]	4; M: 12; F; N-A; yes	COMB (4/8)				↑ 8.1 (CMJA)			
Foure et al.[72]	17; M; N-A; yes	COMB (8/16)	↑ 4.3 (F/T)			↑ 17.6 (SJ) ↑ 19.8 (HOP)			
Wu et al.[76]	21; M; N-A; yes	COMB (8/16)				↑ 12.9 (CMJA)			

[a] Studies that state imperial measurements are shown in metric measurement with the conversion to imperial in square brackets.

1RM = one repetition maximum; **5JT** = five-jump test; **A** = athletes; **CMJ** = countermovement jump; **CMJA** = countermovement jump with the arms swing; **CMJT** = countermovement jump training; **COMB** = combination of various jump exercises; **DJ** = drop jump; **DJT** = drop jump training; **ERPT** = endurance running performance time; **F** = females; **F/T** = force/torque; **HJ** = horizontal jump; **HOP** = hopping; **LT** = lactate threshold; **M** = males; **MAV** = maximal aerobic velocity; **N-A** = non-athletes; **NS** = not specified; **RE** = running economy ($\dot{V}O_2$ during submaximal running); **SJ** = squat jump; **SLCMJ** = single-leg countermovement jump; **SLDJ** = single-leg drop jump; **SLSJ** = single-leg squat jump; **USLCJ** = unilateral straight-legged concentric jump; **$\dot{V}O_{2max}$** = maximal oxygen uptake; ↑ indicates increase in performance; ↓ indicates decrease in performance; ↔ indicates no change in performance.

The results of a limited number of studies suggest that muscle hypertrophy[16,86] and increased neural drive to the agonist muscles[16,87,97,98] are the likely mechanisms behind significant increases in muscle strength and power following combined PLY and WT. Finally, note that electromyostimulation represents another training modality that can be successfully combined with PLY in augmenting lower extremity strength and power.[119,136]

2.2.7 Stretch-Shortening Cycle Muscle Function

SSC muscle function has been classified as either slow (ground contact time >0.25 seconds) or fast (ground contact time <0.25 seconds).[144] In both slow and fast SSC, a pre-stretch enhances the maximum force and work output that muscles can produce during the concentric phase. The mechanisms responsible for this enhancement could be (i) the time available for force development; (ii) storage and reutilization of elastic energy; (iii) potentiation of the contractile machinery; (iv) interaction between the series elastic component and the contractile machinery; and (v) the contribution of reflexes.[145-147] It is beyond the scope of this article to discuss these mechanisms in detail (for a review, see van Ingen Schenau et al.[147]). We will only mention that the relative contribution of each mechanism to muscle performance enhancement appears to be different in slow SSC versus fast SSC.

The efficacy of the slow SSC in lower extremities is usually assessed through pre-stretch augmentation during vertical jumping and expressed in either centimetres:[148] (countermovement jump [CMJ], squat jump [SJ]), or in percentages:[64] ([CMJ – SJ]/SJ × 100). The efficacy of the fast SSC, also known as reactive strength,[108] is usually assessed by dividing the DJ height with ground contact time,[108] or by dividing the DJ flight time with ground contact time.[14] A limited number of studies showed that PLY significantly improves fast SSC muscle function.[14,15,108] Regarding the effects of PLY on slow SSC function, the results are conflicting.[14,34,103,107] However, a recent meta-analysis[3] strongly suggested that PLY produces greater effects in CMJ compared with SJ, and the present study confirmed these findings (see section 2.3.1). The observed discrepancies could be the result of different types of plyometric exercises used.[38] Namely, although most PLY studies used DJ as the training exercise, the authors rarely described whether they applied countermovement-type (i.e. slow) or bounce-type (i.e. fast) DJ training.[3] Taken together, these results indicate that PLY could enhance both slow and fast SSC muscle function, but these effects appear to be specific with respect to the type of SSC exercise used in training.

2.3 Athletic Performance Adaptation to PLY

2.3.1 Jumping Performance

Vertical Jumping Performance

PLY has been extensively used for augmenting jumping performance in healthy individuals. Numerous studies (see table II) have shown that short-term PLY improves vertical jump height in both children and young adults, regardless of their previous athletic experience, sex and training status. The results of two recent meta-analyses further support this view by showing significant and practically relevant PLY-induced increases in vertical jump height in athletes and non-athletes of both sexes.[3,13] However, some studies[108,112-114,119,124] reported no change or even slight decreases in vertical jumping performance following PLY. While no effect on jumping performance in some of the studies[119,124] might be related to an insufficient training stimulus (i.e. ≤8 training sessions), the observed decreases in jumping performance following PLY[108,112,114] could be related to factors such as muscle damage and residual fatigue. Indeed, in one of these studies, a significant (+3%) increase in vertical jump height was observed after a short recovery period.[114]

In the reviewed studies, vertical jumping performance was assessed using all four types of standard vertical jumps such as SJ, CMJ, CMJ with the arm swing (CMJA) and DJ. In addition, some studies[20,34,75] used one or more single-leg jumps (table II). Overall, the results of this review suggest that PLY considerably improves vertical jump height. The calculated relative improvements range, on average, from +6.9% (range, −3.5% to +32.5%) for CMJA, over +8.1% (range, −3.7%

Table III. Chronological summary of studies examining the effects of plyometric training (PLY) combined with another form(s) of physical conditioning on skeletal muscle function and athletic performance

Study	PLY combined with exercise training type; control group	No. of subjects; sex; fitness level	PLY intervention; wks; no. of sessions; type of exercise	Relative effects (%)						
				maximal strength	explosive strength	muscle power	jumping performance	sprinting performance (m [yd][a])	agility performance	endurance performance
Polhemus and Burkhardt[128]	WT; no	34 M; A	6; 18; COMB	↑ 14.6 (1RM) ↑ 23.3 (1RM)						
	WT; no	35 M; A	6; 18; COMB	↑ 17.4 (1RM) ↑ 34.5 (1RM)						
Polhemus et al.[129]	WT; yes	27 M; A	6; 18; COMB				↑ 6.9 (CMJA) ↑ 5.1 (HJ)	↑ 4.4 (37 [40 yd])		
	WT; yes	31 F; A	6;18; COMB				↑ 14.6 (CMJA) ↑ 1.8 (HJ)	↑ 5.4 (37 [40 yd])		
Ford et al.[7]	Wrestling, softball; no	12 M; N-A	10; 25; COMB				↑ 7.6 (CMJA)	↑ 3.0 (37 [40 yd])	↑ 3.2 ↓ 0.7	
	WT; no	15 M; N-A	10; 25; COMB				↑ 9.1 (CMJA)	↑ 3.0 (37 [40 yd])		
Clutch et al.[6]	WT; no	16 M; N-A	16; 32; DJT				↑ 6.9 (CMJA)			
	WT, volleyball training; no	16 M; A	16; 32; DJT				↑ 4.7 (CMJA)			
Hakkinen et al.[16]	WT; yes	18 M; N-A	24; 72; COMB	↑ 9.3 (F/T)	↑ 21.6					
Hakkinen and Komi[97]	WT; no	10 M; N-A	24; 72; COMB				↑ 21.2 (SJ) ↑ 17.6 (CMJ) ↑ 25.0 (DJ) ↑ 26.8 (DJ) ↑ 32.4 (DJ)			
Adams et al.[10]	WT, endurance running; no	31 M; A	10; 30; COMB				↑ 1.5 (CMJA)	↑ 1.7 (46 [50 yd])		

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Table III. Contd

Study	PLY combined with exercise training type; control group	No. of subjects; sex; fitness level	PLY intervention; wks; no. of sessions; type of exercise	Relative effects (%)						
				maximal strength	explosive strength	muscle power	jumping performance	sprinting performance (m [yd][a])	agility performance	endurance performance
Blakey and Southard[130]	WT; no	11 M; N-A	8; 16; DJ	↑ 7.2 (1RM)		↑ 13.7				
	WT; no	10 M; N-A	8; 16; DJ	↑ 7.4 (1RM)		↑ 21.8				
	WT; no	10 M; N-A	8; 16; CMJ	↑ 8.1 (1RM)		↑ 11.8				
Bauer et al.[102]	WT; no	6 NS; N-A	10; 30; COMB	↑ 14.3 (F/T) ↑ 10.0 (F/T) ↑ 6.7 (F/T)			↑ 10.0 (CMJA)			
	WT; no	7 NS; N-A	10; 30; COMB	↑ 17.5 (F/T) ↑ 5.0 (F/T) ↑ 18.8 (F/T)			↑ 7.6 (CMJA)			
Paavolainen et al.[131]	WT, sprint training, endurance training; yes	15 M; A	6; NS; COMB	↑ 2.1 (F/T)			↑ 10.9 (SJ) ↑ 8.0 (CMJ)			↑ 1.9 ($\dot{V}O_2$max) ↔ 0.0 (AT)
Kramer et al.[132]	WT; no	12 F; A	9; 27; COMB	↑ 16.0 (1RM)		↑ 5.2 ↑ 6.7 ↑ 5.3 ↑ 17.4	↑ 5.6 (CMJA)			↑ 3.5 (REPT)
Delecluse et al.[133]	Sprint training; yes	32 M; N-A	9; 18; COMB					↑ 2.0 (100)		
Lyttle[134]	WT; yes	22 M; A	8; 16; DJ	↑ 12.7 (1RM)		↑ 6.8	↑ 18.0 (SJ) ↑ 11.4 (CMJ)	↑ 0.2 (40) ↔ 0.0 (20)		
Potteiger et al.[85]	Aerobic training; no	11 M; N-A	8; 24; COMB			↑ 2.6 ↑ 5.1	↑ 5.0 (CMJA)			↑ 16.3 ($\dot{V}O_2$max)
Witzke and Snow[33]	WT; yes	53 F; N-A	≈40; ≈120; COMB	↑ 6.2 (F/T)		↑ 2.0				

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Table III. Contd

Study	PLY combined with exercise training type; control group	No. of subjects; sex; fitness level	PLY intervention; wks; no. of sessions; type of exercise	Relative effects (%)						
				maximal strength	explosive strength	muscle power	jumping performance	sprinting performance (m [yd]^{a})	agility performance	endurance performance
Fatouros et al.[15]	WT; yes	20 M; N-A	12; 36; COMB	↑ 42.2 (1RM) ↑ 26.8 (1RM)		↑ 37.1	↑ 15.0 (CMJA)			
Hunter and Marshall[135]	WT; yes	11 M; N-A	10; 19; COMB				↑ 8.6 (CMJ) ↑ 8.8 (DJ) ↑ 10.0 (DJ) ↑ 5.5 (DJ)			
	WT, flexibility training; yes	14 M; N-A	10; 19; COMB				↑ 14.1 (CMJ) ↑ 8.2 (DJ) ↑ 7.4 (DJ) ↑ 8.7 (DJ)			
Maffiuletti et al.[136]	Electrostimulation; no	20 M; A	4; 12; COMB	↑ 27.3 (F/T) ↑ 24.6 (F/T)			↑ 19.5 (SJ) ↑ 20.8 (SJ) ↑ 12.8 (DJ) ↑ 12.0 (CMJ) ↑ 8.2 (CMJA)			
Tuomi et al.[98]	WT; yes	14 M; A	6; 24; COMB	↑ 16.3 (F/T)			↑ 11.3 (SJ) ↑ 13.2 (CMJ)			
Wilkerson et al.[137]	Flexibility training, strengthening; no	11 F; A	6; NS; NS	↑ 8.1 (F/T) ↑ 7.0 (F/T) ↑ 11.7 (F/T) ↑ 13.7 (F/T)						
Moore et al.[138]	WT; no	2 M, 5 F; A	12; 33; COMB	↑ 169.8 (4RM)			↑ 6.7 (CMJA)	↑ 9.6 (25)		
Herrero et al.[119]	Electrostimulation; yes	20 M; N-A	4; 16; COMB	↑ 13.0 (F/T)			↑ 7.3 (SJ) ↑ 7.6 (CMJ)	↑ 1.7 (20)		

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Table III. Contd

Study	PLY combined with exercise training type; control group	No. of subjects; sex; fitness level	PLY intervention; wks; no. of sessions; type of exercise	Relative effects (%)						
				maximal strength	explosive strength	muscle power	jumping performance	sprinting performance (m [yd][a])	agility performance	endurance performance
Dodd and Alvar[123]	WT; no	32 M; A	4; 7; COMB				↑ 1.0 (CMJA)	↑ 0.6 (18 [20 yd]) ↑ 0.3 (37 [40 yd]) ↑ 0.3 (55 [60 yd])	↑ 2.3	
Ratamess et al.[139]	WT, sprint training; no	6 F; A	10; 20; COMB	↑ 25.0 (1RM)			↑ 10.8 (CMJA) ↑ 9.7 (HJ)			
	WT, sprint training; no	8 F; A	10; 20; COMB	↑ 24.6 (1RM)			↑ 6.3 (CMJA) ↑ 6.5 (HJ)			
Faigenbaum et al.[140]	WT; no	13 M; N-A	6; 12; COMB				↑ 8.1 (CMJA) ↑ 6.0 (HJ)	↔ 0.0 (9.1)	↑ 3.8	
Salonikidis and Zafeiridis[18]	Tennis-drill exercises; yes	32 M; A	9; 27; COMB					↑ 3.3 (12)	↑ 7.6 ↑ 7.4 ↑ 2.7	
Perez-Gomez et al.[86]	WT; yes	37 M; N-A	6; 18; COMB	↑ 42.9 (1RM) ↑ 22.9 (1RM) ↑ 41.7 (1RM) ↑ 13.7 (1RM)	↑ 0.4 ↓ 10.5	↑ 4.9 ↑ 5.0	↑ 6.7 (SJ) ↑ 8.8 (CMJ)	↑ 2.7 (5) ↑ 1.1 (10) ↑ 0.8 (15) ↑ 0.6 (20) ↓ 0.3 (25) ↔ 0.0 (30)		↓ 1.7 ($\dot{V}O_2$max)
Chappell and Limpisvasti[24]	Core strengthening, balance training; no	30 F; N-A	6; 36; COMB				↑ 8.2 (CMJA)			
Marques et al.[141]	WT; no	10 F; A	12; 24; COMB	↑ 13.0 (4RM)			↑ 3.9 (CMJ) ↑ 9.6 (CMJ) ↑ 10.3 (CMJ) ↑ 12.7 (CMJ)			

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Table III. Contd

Study	PLY combined with exercise training type; control group	No. of subjects; sex; fitness level	PLY intervention; wks; no. of sessions; type of exercise	Relative effects (%) maximal strength	explosive strength	muscle power	jumping performance	sprinting performance (m [yd]^a)	agility performance	endurance performance
Ronnestad et al.[142]	WT; yes	15 M; A	7; 14; COMB	↑ 20.2 (1RM)		↑ 2.3 ↑ 3.3 ↑ 4.3	↑ 12.5 (SJ) ↑ 2.8 (CMJ)	↑ 1.1 (10) ↑ 0.2 (40)		
Mihalik et al.[143]	WT; no	5 M, 10 F; A	4; 8; COMB			↑ 5.1	↑ 5.6 (CMJA)			
	WT; no	6 M, 10 F; A	4; 4; COMB			↑ 8.2	↑ 10.0 (CMJA)			

a Studies that state imperial measurements are shown in metric measurement with the conversion to imperial in square brackets.

1RM = one repetition maximum; **4RM** = four repetition maximum; **A** = athletes; **AT** = anaerobic threshold; **CMJ** = countermovement jump; **CMJA** = countermovement jump with the arms swing; **COMB** = combination of various jump exercises; **DJ** = drop jump; **DJT** = drop jump training; **F** = females; **F/T** = force/torque; **HJ** = horizontal jump; **M** = males; **N-A** = non-athletes; **NS** = not specified; **REPT** = rowing ergometer performance time; **SJ** = squat jump; $\dot{V}O_{2max}$ = maximal oxygen uptake; **WT** = weight training; ↑ indicates increase in performance; ↓ indicates decrease in performance; ↔ indicates no change in performance.

to +39.3%) for SJ and +9.9% (range, –0.3% to +19.3%) for CMJ, to +13.4% (range, –1.4% to +32.4%) for DJ. The estimated relative improvements could also be considered practically relevant since the improvement in vertical jump height of ~7–13% (i.e. ~2–7 cm, depending on the type of a vertical jump) may be of high importance for trained athletes in sports such as volleyball, basketball or high jump.[3]

Our results also suggest that the relative effects of PLY are likely to be higher in fast SSC vertical jump (DJ) than is the case for slow SSC vertical jumps (CMJ and CMJA) and concentric-only vertical jump (SJ). These findings are largely in accordance with the previous suggestion by Wilson et al.[103] that PLY is more effective in improving vertical jumping performance in fast SSC jumps as it enhances the ability of participants to use neural, chemo-mechanical and elastic benefits of the SSC. Also, as discussed in previous section (see section 2.2.7), PLY has been found to significantly improve fast SSC muscle function while the results on the effects of PLY on slow SSC function have been conflicting, which could partly explain the greatest improvements in vertical jumping performance observed for DJ. The present study also confirmed the findings of a recent meta-analysis,[3] which strongly suggested that PLY produces greater effects in CMJ compared with SJ. Note that we remain cautious toward the relative improvements in vertical jump performance that exceed +30%, as reported in four studies (one for SJ,[120] one for CMJA[116] and two for DJ;[84,97] table II). Since these studies were heterogeneous with respect to subject characteristics and programme design, the observed unrealistically large gains in jump height following PLY intervention are difficult to explain.

In the majority of athletic conditioning programmes PLY is combined with other training modalities, most commonly with some form of WT. The combination of PLY and WT (see table III) seems to have a greater potential in enhancing vertical jumping performance compared with PLY as the only training modality. For example, following combined PLY and WT, CMJA improved on average by +7.8%, whereas the average improvement when PLY was the only training modality was +6.9%. Given that both PLY and WT improve vertical jump performance (although with different adaptive changes in the neural and musculoskeletal systems[34,98]), it is likely that their combination elicits greater overall training adaptation in the athlete's body. This view is supported by recent results of Kubo et al.[34] The authors showed that PLY improved concentric and SSC jump performance mainly through changes in mechanical properties of the muscle-tendon complex, while WT-induced changes in concentric-only jump performance were mainly the result of an increased muscle hypertrophy and neural activation of plantar flexors.

The effects of PLY combined with electromyostimulation[133] have also been examined[119,136] and are worthy of discussion. Herrero et al.[119] observed that, while PLY effects indicated a slight relative decrease in both SJ (–3.8%) and CMJ (–0.3%) performance, the combined PLY and electromyostimulation resulted in a relative improvement in both SJ (+7.3%) and CMJ (+7.6%) performance, suggesting that PLY and electromyostimulation together may be used to enhance vertical jumping ability. The relative improvements in vertical jumping performance in another study that evaluated the effects of combined PLY and electromyostimulation[136] were of even greater magnitude (range +8.2–20.8%; table III). Unfortunately, the authors[136] did not address the effectiveness of the protocol compared with PLY or electromyostimulation alone.

Horizontal Jumping Performance

The effects of PLY on horizontal jumping performance have been investigated in six studies,[11,12,14,19,35,109] and horizontal jump performance was assessed using long jump,[11] standing long jump[12,14] and five bounding jumps.[11,12,19,35,109] On average, the relative improvement in horizontal jump performance was +4.1% (range +1.4–7.0%), and was observable in both athletes[19,109] and non-athletes.[14] This finding suggests smaller effects following PLY compared with the effects on vertical jumping performance. Of course, due to the relatively low number of studies, the results need to be interpreted with caution.

It is generally assumed that transfer of PLY effects to athletic performance likely depends on the specificity of plyometric exercises performed. Therefore, athletes who require power for moving in the horizontal plane (e.g. sprinters, long jumpers) mainly engage in bounding plyometric exercises, as opposed to high jumpers, basketball or volleyball players who require power to be exerted in a vertical direction and who perform mainly vertical jump exercises. This corresponds to the well known principle of training specificity.[149] The findings of Hortobagy et al.,[12] however, could not support the above-mentioned assumption, as the two experimental groups that performed two distinctly different PLY routines did not yield specific gains in performance. The authors state that these unexpected findings may be explained by the high degree of generality among the jumping tests performed, as the vertical and horizontal jumping tests were highly correlated. Obviously, the issue of specificity of plyometric exercises in improving the horizontal jumping performance needs to be clarified in future studies.

Two studies[129,140] investigated the PLY-induced effects on horizontal jump performance when PLY was combined with WT. The calculated relative improvement in standing long jump in 12- to 15-year-old boys following 6 weeks of combined PLY and WT[140] was +6.0%, possibly indicating that a combination of PLY and WT may be beneficial for enhancing horizontal jumping performance. Furthermore, in support of this assumption are almost identical findings (i.e. +5.1%) in a study by Polhemus et al.[129] Additional well designed studies evaluating the effects of PLY on horizontal jumping performance are needed before the magnitude of effect can be established more accurately.

Collectively, the reviewed studies in this section strongly suggest that PLY alone, or in combination with WT, improves jumping performance in both athletes and non-athletes.

2.3.2 Sprinting Performance

Sprint running, in varying degrees, is essential for successful performance in many sports. It represents a multidimensional movement skill that requires an explosive concentric and SSC force production of a number of lower-limb muscles. It is, therefore, expected that sprint performance could benefit from PLY. Our review of studies suggests improvements in sprint performance following PLY over distances from 10 to 55 m (60 yards),[14,18,105,106,109,110,116-118,120,123,124] although slight decreases in sprint performance following PLY have also been observed[11,28,119,123] (table II).

The benefits of PLY for sprint performance are expected to be the greatest at the velocity of muscle action that most closely approximates the velocity of muscle action employed in training.[110] Therefore, it has been suggested[110,133] that the greatest effects of PLY on sprinting performance occur in the acceleration phase, since the velocity of muscle action in bounding plyometric exercises most closely approximates the velocities of muscle action in the acceleration phase of the sprint. The results of this review (table II) partly support the above-mentioned theory as the greatest relative effects of PLY were observed for a 10 m sprint performance (average improvement +2.2%; range +1.6–2.6%), reducing to the improvement of +2.1% for 12 m sprint performance, further reducing to the average improvement of +1.5% (range –0.3% to +5.7%) for a 20 and 18 m (20 yards) sprint performance, and finally reducing to the average improvement of +1.3% (range –0.6% to +3.0%) for 30 m sprint performance. However, the average improvement for 40 and 37 m (40 yards) sprint performance was +1.7% (range –1.3% to +6.2%) and for 50 m sprint performance was +1.5% (range +1.3–1.7%).

An important question in everyday training practice as well as among scientists is the following: if PLY is an effective method of speed improvement, can it improve speed more so than the conventional speed training? In that regard, Rimmer and Sleivert[110] compared the effects of sprint-specific PLY against traditional sprint training on 10 and 40 m sprint performance times. Following 8 weeks of PLY, the PLY group significantly improved 10 m (+2.6%) and 40 m (+2.2%) sprint performance times, but these improvements were not significantly different from those observed in the sprint group. A study by Markovic et al.[14] could not support these findings as the authors found sprint training to be superior to PLY in improving the 20 m sprint performance time. It should be noted that PLY exercises used in this study were not sprint specific; possibly making the power transfer from PLY to sprint performance more difficult. Given the findings of the two described studies,[14,110] as yet, no evidence of superiority of PLY for speed improvement compared with traditional sprint training has been presented. Further work is also required to determine the exact mechanisms behind speed improvement as a result of PLY.

PLY has most commonly been combined with WT to evaluate the effects on sprinting performance[7,10,86,123,129,134,138,140,142] (table III), and also with sport-specific training[7,18] and electromyostimulation.[119] When combined with WT over 6–12 weeks,[7,86,142] sprinting performance improved in the range of +0.2–3.0%, with one study[140] reporting no change in performance. Note that the relative improvements in one study[138] seem unrealistically large (+9.6%) compared with other related studies. Note also that the use of the Meridian Elyte athletic shoe during PLY could induce some additional positive effects on sprint performance of athletes, particularly on their sprint endurance ability.[139,150] Overall, the results presented in this section suggest that PLY alone, as well as its combination with WT, have the potential for improving sprinting performance in both athletes and non-athletes.

2.3.3 Agility Performance

Agility has been defined as a rapid whole-body movement with change of velocity or direction in response to a stimulus.[151] This definition recognizes both the cognitive (decision-making process) and physical (change of direction speed) components of agility. In this review, we will use the term 'agility' to denote only its physical component.

Most agility tasks require a rapid switch from eccentric to concentric muscle action in the leg extensor muscles (i.e. the SSC muscle function). Thus, it has been suggested[152] that PLY can decrease ground reaction test times through the increase in muscular force output and movement efficiency, therefore positively affecting agility performance. The literature search revealed six studies that examined PLY effects upon agility performance.[14,18,73,118,121,123] Moreover, a combination of PLY and WT,[7,123,140] and PLY and sport-specific training[7,18] upon agility performance has also been examined. Agility assessment has been performed using the following various agility tests: T-agility test,[121,123] Illinois agility run,[121] pro agility shuttle run,[140] 20 yard shuttle run,[7,14] square agility test,[118] 30 m shuttle run[73] and 4 m side steps.[18] The reviewed studies[14,18,73,118,121,123] indicate consistent findings in that PLY yielded improvements in agility performance, and the range of relative improvement was +1.5–10.2%. Only one study[123] reported no change in agility performance following PLY. When PLY was combined with WT[7,123,140] and sport-specific training,[7,18] similar relative improvements (i.e. +2.7–7.6%) were observed. Again, one study[7] reported a minimal relative decrease in agility performance (–0.7%).

Agility tasks are relatively complex, certainly more so than jumping or sprinting. Tricoli et al.[118] found that a 6-week PLY, consisting of plyometric exercises executed in the vertical direction, improved agility performance by +2.0% but the magnitude of improvement was no different from the group that underwent Olympic weightlifting training. The authors speculate that the complexity of agility tasks makes power transfer from plyometric exercises to the tasks requiring agility difficult. In that regard, Young et al.[153] suggested that agility tasks could be more influenced by motor control factors than by muscle strength or power capacity. Miller et al.[121] assessed the effects of a 6-week PLY intervention on agility performance. An additional force-plate test was used to measure ground contact time while hopping. The participants improved their performance times in two agility tests (+5.5% and +3.0%) and the authors concluded that PLY improved performance in agility tests because of either better motor recruitment or neural adaptations. Ground contact times measured by a force plate were also reduced. Overall, although further research examining PLY effects on agility performance is needed, the current findings seem promising for the athletes requiring agility to perform their sport.

2.3.4 Endurance Performance

Endurance athletes (e.g. distance runners, cyclists, cross-country skiers, triathletes) have traditionally focused their training on improving cardiovascular and muscular endurance, as these factors are assumed to be the primary determinants of competitive success in endurance events. In distance runners for example, the primary factors known to affect performance include maximum oxygen uptake ($\dot{V}O_{2max}$), lactate threshold and running economy.[154] However, in a homogenous group of elite distance runners, similar levels of $\dot{V}O_{2max}$, lactate threshold and even running economy might be observed, suggesting that other factors (i.e. factors related to the anaerobic work capacity) might contribute to competitive performance at the elite level. In that regard, Noakes[155] suggested that muscle power factors may have a role in limiting endurance performance and may be better performance predictors that $\dot{V}O_{2max}$ when comparing elite aerobic athletes.

Literature searching indicated four studies[19,20,109,113] that investigated the effects of PLY on endurance performance variables in moderately to highly trained distance runners, while two studies were also conducted using cross-country skiers[131] and rowers[132] as participants. In studies[19,20,109,113] examining the PLY effects in distance runners, the findings seem to be consistent in that the parameter that benefits the most in terms of endurance performance improvement is running economy (i.e. the oxygen cost of sub-maximal running), which, consequently, might lead to an improvement in distance running performance time. The findings of improved running economy following PLY are certainly beneficial to distance runners since even small improvements in running economy become very important over long distances. However, a true indicator of improved endurance performance is race performance time, and in that regard two studies[19,109] included pre- and post-race time data. In a study by Paavolainen et al.,[109] participants improved their running economy which, along with an increased muscle power, resulted in +3.1% relative improvement in a 5 km running performance time. Meanwhile, the $\dot{V}O_{2max}$ decreased by –5.8%.

A study conducted by Spurrs et al.[19] yielded the following similar findings: improved running economy following PLY in a group of distance runners; improved musculotendinous stiffness and jumping performance variables; improved race performance time (+1.2%); and a decrease in $\dot{V}O_{2max}$ (–3.1%).

The exact mechanism by which the improvement in running economy following PLY occurs remains unclear; however, it has been theorized that this improvement is a result of improvements in neuromuscular characteristics including motor unit recruitment and reduced ground contact time. Further supporting this assumption is the fact that cardiovascular endurance variables (i.e. $\dot{V}O_{2max}$ and lactate threshold) showed no change or even slightly decreased[19,20,113] following PLY in distance runners, while indicators of muscle strength and power,[19,20,109] as well as indicators of anaerobic work capacity,[109] improved. It appears likely that the improvements in anaerobic power and neuromuscular characteristics following PLY in distance runners transfer to the improvement in running economy, since $\dot{V}O_{2max}$ and lactate threshold values appear not to be affected or are even slightly reduced.

The introduction of PLY in moderately to highly trained endurance athletes[19,20,109,113] did not improve $\dot{V}O_{2max}$ and/or lactate threshold, suggesting that PLY appears to produce an insufficient aerobic stimulus in moderately to highly trained endurance athletes to improve $\dot{V}O_{2max}$ and/or lactate threshold beyond values achieved by aerobic training alone. Contrary to the findings in endurance trained individuals, an 8-week PLY was found to produce improvements in $\dot{V}O_{2max}$ in physically active men by +13.8%.[85] Obviously, untrained and 'physically active' individuals allow greater room for improvement compared with the endurance-trained population. On the other hand, including PLY in the training programme of endurance athletes seems to be justified for reasons other than $\dot{V}O_{2max}$ and/or lactate threshold improvement. Future studies aiming to assess the PLY effects on endurance performance should strive to include pre- and post-PLY data on endurance race performance time, as this parameter serves as a definitive yardstick by which endurance performance of an athlete can be evaluated. While $\dot{V}O_{2max}$, lactate threshold, running economy and neuromuscular characteristics are valuable measurements, their meaning is largely limited without an insight into the magnitude of improved race performance.

Collectively, the reviewed studies clearly show that PLY, either alone or in combination with other training modalities, has a strong potential to enhance a wide range of athletic performance in children and young adults, regardless of their sex, previous athletic experience and training status. The mechanisms behind these improvements are still not fully understood; however, they appear to be muscle specific and may include:

- an increased neural drive to the agonist muscles;
- changes in the muscle activation strategies (i.e. improved intermuscular coordination);
- changes in the mechanical characteristics of the muscle-tendon complex of plantar flexors;
- changes in muscle size and/or architecture;
- changes in single-fibre mechanics.

3. PLY on Non-Rigid Surfaces

PLY is commonly performed on firm surfaces such as grass, athletic tracks and wood. An increased risk of muscle soreness and damage caused by the forces generated during ground impact and intense plyometric contraction, as suggested in a number of studies,[16,156-161] might be reduced when PLY is performed on a non-rigid surface. In this section, we review studies that investigated the application of aquatic- and sand-based PLY in healthy individuals. The retrieved studies only focused on PLY effects on muscle strength/power or athletic performance.[112,116,122,162,163] Therefore, our discussion is limited to adaptive changes in these neuromuscular and performance qualities.

3.1 Neuromuscular and Performance Adaptations to Aquatic- and Sand-Based PLY

Our literature review found four studies that applied aquatic-based PLY. Martel et al.[163]

reported a relative improvement in CMJA performance by +7.5% following 6-weeks of PLY conducted in 1.2 m of deep water. In addition, the authors observed a relative increase in knee extensor strength at high velocities (+9.6–26.5%), but also a relative decrease in knee flexor strength and knee extensor strength at low velocities (from −9% to −3.4%). Stemm and Jacobson[122] compared the effects of land-based and aquatic-based (knee-level water) PLY on vertical jump performance with identical PLY exercises performed by both groups. The aquatic-based group improved CMJA performance by +5.0% and the magnitude of improvement was similar to that achieved by the land-based PLY group. Furthermore, Robinson et al.[116] reported large relative increases in vertical jump performance (+33.5%), sprint performance (+6.7%) and concentric and eccentric knee extensor/flexor muscle strength (+25–52%) in an aquatic-based group, and the magnitude of improvements was not significantly different from the land-based group. As expected, the reported muscle soreness was significantly higher in the land-based group. Finally, Miller et al.[112] reported a small relative increase in vertical jump performance (+1.6%) and muscle power (+4.3%), with no relative changes in knee extensor/flexor muscle strength following 8 weeks of aquatic PLY.

The usefulness of sand-based PLY has also been investigated. Impellizzeri et al.[162] recently compared the effects of 4 weeks of PLY performed on sand versus grass on vertical jump and sprint performance in soccer players. PLY on both surfaces yielded similar relative improvements in sprint performance (+2.5–4.3%) with PLY on sand inducing less muscle soreness than PLY on grass during the whole 4-week training period. Relative increases in SJ (+10.2%) and CMJ (+6.5%) were also observed following sand-based PLY; however, the results suggest that grass surface was superior in enhancing CMJ performance while sand surface tended to induce greater improvements in SJ.

Collectively, current knowledge justifies the use of aquatic- and sand-based PLY for rapid movement performance enhancement. Of particular practical importance for coaches and athletes is the fact that aquatic- and sand-based PLY induces significantly lower muscle soreness compared with land-based PLY. However, regarding the effects of PLY performed on non-rigid surfaces on muscle strength and power, the current results are inconclusive. Further studies should perhaps focus on determining (i) the optimal water level to elicit a training effect with measurement of impact forces; and (ii) the mechanisms behind performance changes following aquatic- and sand-based PLY.

4. PLY in Prevention of Lower-Extremity Injuries

Aside from its benefits in enhancing both the muscle function and athletic performance, PLY combined with other neuromuscular training modalities (e.g. strength training, balance training, stretching and agility training) also represents an effective training paradigm for reducing the risk of lower-extremity injuries in team sports.[25,29-31] This is particularly evident for non-contact anterior cruciate ligment (ACL)[51] injuries in female athletes participating in sports that involve a substantial amount of jumping, landing, and pivot turns, such as soccer, basketball, netball and team handball.[30,164-167]

In that regard, our literature search revealed the following two groups of studies related to the use of PLY for the prevention of lower-extremity injuries: (i) studies focusing on the reduction of lower-extremity injury rates in sports; and (ii) studies focusing on modifying lower-extremity injury risk factors, particularly those related to non-contact ACL injury. Given that several recent reviews have been published on this topic,[164-166] we will only briefly summarize the results of these two groups of studies.

In total, we found 20 published neuromuscular interventions that included PLY, targeted toward lower-extremity injury prevention in athletes and/or targeted toward modifying risk factors for lower-extremity (mainly ACL) injuries in athletes. Studies that included only technical aspects of jumping (e.g. landing technique) in their interventions were not included in this review. The details of the studies are given in tables IV and V. In eight of ten studies from the first group, the applied multi-component training programme reduced the lower-extremity injury rates in female athletes (table IV). This was particularly evident for non-contact ACL injury rates. The two studies that did not observe a reduction in lower-extremity injury rates had some specificities and/or limitations compared with the remaining eight studies. More precisely, Pfeiffer et al.[170] conducted the preventive intervention post-training, contrary to the remaining nine studies, while Steffen et al.[172] had very low compliance with the applied intervention programme.

The results of the second group of studies (table V) show that the observed reduction of lower-extremity injuries in female athletes following interventions that incorporate PLY is likely to be the result of a modification of biomechanical and neuromuscular injury risk factors, particularly those related to non-contact ACL injury. Specifically, the reviewed interventions generally (i) reduced vertical ground reaction forces;[25-27] (ii) decreased valgus measures;[21,22,24,176] and (iii) increased effective knee and hip muscle preparatory and reactive activation during landing in female athletes.[27,28] Moreover, Zebis et al.[177] recently reported that neuromuscular training markedly increased pre-landing and landing EMG activity of medial hamstring muscles during a side-cutting manoeuvre, thereby decreasing the risk of dynamic valgus. These results generally highlight the importance of enhancing hip and knee muscle pre-activation while performing high-risk manoeuvres such as landings and pivot turns, and PLY appears to be a particularly effective training modality for inducing these changes in the neuromuscular control.[27,28] Finally, the reviewed interventions altered quadriceps dominance in female athletes by increasing hamstring strength and hamstring/quadriceps strength ratio.[23,25,137] Importantly, although mainly focused on injury prevention and/or alteration of injury risk factors, the reviewed interventions also have the potential for enhancing athletic performance.[23,25-27]

Taken together, these results support the conclusions of recent narrative and meta-analytical reviews[164-166] that PLY represents one of the most important elements of effective injury-prevention programmes and, therefore, should be an integral part of the year-round physical conditioning programmes of female athletes in team sports. However, given that all the reviewed studies have been conducted in young female athletes, it remains unknown whether these conclusions and recommendations are also valid for male athletes; hence, there is a clear need for similar studies in male athletes. Moreover, due to the large variation in the total duration of interventions among the reviewed studies (from 6 weeks to 8 months), future research should also determine the optimal duration of injury-prevention interventions.

5. Practical Application of PLY

In this section we briefly discuss issues related to the practical applicability of PLY. Let us first focus on subject characteristics. In this regard, it should be observed that the reviewed studies were performed on both athletes (mainly national and regional level) and non-athletes with varying levels of physical fitness and skill. Nevertheless, the results of recent meta-analyses clearly show that the strength and jump performance benefits from PLY were similar in both athletes and non-athletes,[3,127] regardless of their age,[3,127] level of physical activity and previous athletic experience.[3,13,127] Some discrepancies, however, were observed in the results of these meta-analyses regarding the sex effects on improvements in vertical jump height, and these can probably be attributed to different statistical procedures applied and different methodology used to define the groups with mixed samples.[3,13]

Regarding the programme design, the optimal exercise selection and the optimal combination of acute programme variables in PLY are still unknown. Most PLY studies that focused on performance enhancement used several PLY exercises for a period of 6–15 weeks for 2–3 sessions a week. A recent meta-analytical review showed that the optimal PLY strategy for maximizing gains in strength is to (i) combine PLY and WT; (ii) use a training intervention duration of <10 weeks (with >15 sessions); and (iii) use high-intensity exercises with >40 jumps per session.[127] Another meta-analysis showed that the optimal

Table IV. Summary of neuromuscular training programmes involving plyometric training (PLY) aimed to reduce lower-extremity injury rates in athletes

Study	No. of subjects; design	Training protocol	Results
Hewett et al.[168]	366 F soccer, basketball and volleyball players underwent training and were compared with the control of 434 M and 463 F; prospective cohort	6-wk training programme (PLY, stretching, strengthening) 3 d/wk	Significant reduction of ACL injury risk in the trained F athletes ($p \le 0.05$). The rate of ACL injuries was decreased 72% in the trained group compared with the untrained group
Heidt et al.[169]	300 high school F soccer players: 42 underwent a training programme; prospective cohort	7-wk pre-season conditioning programme (PLY, cardiovascular, strengthening, stretching, agilities)	Significantly fewer injuries in the trained group compared with the control group ($p < 0.01$). No differences in the occurrence of ACL injuries between the groups
Myklebust et al.[30]	900 F team handball players studied over a 3-y period; prospective cohort	15-min training programme (PLY, flexibility, balance and agility exercises) performed 3 d/wk for 5–7 wk, and then 1 ×/wk during the season	In elite team division, there was a significant reduction ($p = 0.01$) in the risk of ACL injury during the second intervention season among those who completed the programme compared with those who did not
Petersen et al.[31]	134 F team handball players underwent training and were compared with the control of 142 F players; prospective controlled	Training programme (PLY, balance) performed 3 d/wk for 5–7 wk and then 1 ×/wk during the season	A non-significant ($p > 0.05$) reduction in the number of ACL injuries in the training group compared with the control group, although ACL injury risk was 80% lower in the training group
Mandelbaum et al.[29]	5703 young F soccer players: 1885 underwent a training programme; prospective controlled cohort	20-min training programme (education, stretching, strengthening, PLY, specific agilities) performed 2–3 ×/wk	88% and 74% ACL injury reduction in the first and second season, respectively
Pfeiffer et al.[170]	1439 F soccer, basketball, and volleyball players: 577 underwent a training programme; prospective controlled design	20-min training programme (deceleration, agilities, PLY, body awareness) performed 2 ×/wk for 9 wk	Rate of non-contact ACL injuries per 1000 exposures was 0.167 in the treatment group and 0.078 in the control group. Odds ratio 2.05 ($p > 0.05$)
Gilchrist et al.[171]	1435 F soccer players: 583 underwent a training programme; prospective RCT	15-min training programme (stretching, strengthening, PLY, agilities, education) performed 3 ×/wk for 12 wk	Overall 41% reduction in ACL injuries and 70% reduction of non-contact ACL injuries
Steffen et al.[172]	2092 F soccer players: 1091 underwent a training programme; prospective cluster RCT	15-min training programme (balance, PLY, eccentric hamstrings exercises, landing technique) performed over 8 mo; 15 consecutive sessions then 1 ×/wk	No differences in overall injury rates or any specific injury between the intervention and control group
Soligard et al.[173]	1982 F soccer players: 1055 in the treatment group; cluster RCT	~20-min training programme (running, strengthening, PLY, balance) performed during each training session for 8 mo	A significant lower risk of injuries overall of overuse injuries and severe injuries in the intervention group
Pasanen et al.[174]	457 F floorball players: 256 in the treatment group; cluster RCT	20–30 min training programme (running, balance, PLY, stretching, strengthening) performed over 6 mo; 2–3 ×/wk for 10 wk and 1 ×/wk for 16 wk	The training group reduced the risk of non-contact leg injuries by 66%

ACL = anterior cruciate ligament; **F** = females; **M** = males; **RCT** = randomized controlled trial; ×/**wk** = sessions times per week.

PLY strategy for maximizing gains in vertical jump height is to (i) combine various PLY exercises; (ii) use a training intervention duration of >10 weeks (with >20 sessions); and (iii) use high-intensity exercises with >50 jumps per session.[13] While these data could be used as general guidelines, we have to acknowledge that PLY is rarely used in sports as a single training modality but, rather, is incorporated into a multi-component physical conditioning programme. This rationale is further supported by data presented in a previous section (see section 4) on injury prevention

Table V. Summary of neuromuscular training programmes involving plyometric training (PLY) aimed to modify risk factors for lower-extremity injuries in athletes

Study	Targeted risk factor	No. of subjects; design	Training protocol	Results
Hewett et al.[25]	Excessive vertical ground reaction force during landing; quadriceps muscle dominance	11 F high school volleyball players in the treatment group; pre-/post-test control group	120-min training programme (PLY, strengthening, stretching) performed 3 ×/wk for 6 wk	A significant decrease (22%; $p<0.01$) in peak landing force from a volleyball block jump and in knee adduction and abduction moments (50%; $p<0.01$); increased hamstrings/quadriceps ratio
Chimera et al.[28]	Knee and hip muscle activation strategies	20 F soccer and field hockey players (9 in the treatment group)/pre-/post-test control group	20–30 min PLY performed 2 ×/wk for 6 wk	A significant increase ($p<0.05$) in hip adductor muscle pre-activation and adductor to abductor co-activation
Wilkerson et al.[137]	Quadriceps muscle dominance	19 F basketball players (11 in the treatment group)/pre-/post-test control group	PLY for 6 wk	Increased hamstrings strength and hamstrings/quadriceps ratio at a speed of 60°/sec
Irmischer et al.[26]	Excessive vertical ground reaction force during landing	28 physically active F (14 in the treatment group); RCT	20 min PLY performed 2 ×/wk for 9 wk	Significant reductions in peak landing forces and rates of force development
Lephart et al.[27]	Excessive vertical ground reaction force during landing; poor jump-landing posture and poor muscle activation strategies	27 F soccer and basketball players (14 in the PLY and strength group); uncontrolled randomized pre-/post-test	30-min training protocol (PLY, strengthening, balance, stretch) performed 3 ×/wk for 8 wk	Increased initial and peak knee and hip flexion, and time to peak knee flexion during the task. Increased peak pre-active EMG of the gluteus medius and integrated EMG for the gluteus medius during the pre-active and reactive time periods
Myer et al.[21]	Poor jump-landing posture	53 F basketball, soccer, and volleyball players (41 in the treatment group); controlled single-group pre-/post-test	90-min training programme (PLY, strengthening, balance, speed) performed 3 ×/wk for 6 wk	Increased knee flexion-extension range of motion during the landing phase of a vertical jump; decreased knee valgus (28%) and varus (38%) torques
Myer et al.[22]	Poor jump-landing posture	18 high school F athletes (9 in PLY group); uncontrolled randomized pre-/post-test	Eighteen 90-min PLY sessions during a 7-wk period	Reduced initial contact and maximum hip adduction angle, reduced maximum ankle eversion angle, increased initial contact and maximum knee flexion during the drop vertical jump. Decreased initial contact and maximum knee abduction angle during the medial drop landing
Myer et al.[23]	Decreased vertical ground reaction forces during landing; increased hamstrings strength	19 high school F athletes (8 in PLY group); uncontrolled randomized pre-/post-test	90-min PLY performed 3 ×/wk for 7 wk	Increased hamstrings strength and hamstrings/quadriceps ratio; improved centre of pressure measures during hop landings in the medial/lateral axis; no change in vertical ground reaction force
Pollard et al.[175]	Poor jump-landing posture	18 F soccer players; longitudinal single-group pre-/post-test	20-min in-season injury prevention programme (stretching, strengthening, PLY, agilities) before each soccer practice	Significantly less hip internal rotation and greater hip abduction at landing; no changes in knee valgus or knee angles

Continued next page

Table V. Contd

Study	Targeted risk factor	No. of subjects; design	Training protocol	Results
Myer et al.[176]	Excessive knee abduction moment at landing (knee valgus)	27 F soccer and basketball players (12 in the 'high-risk' and 6 in the 'low-risk' treatment groups); prospective controlled trial	90-min training programme (PLY, strengthening, balance, speed) performed 3 ×/wk for 7 wk	A significant decrease in knee abduction moments by 13% in the 'high-risk' group; no change in the 'low-risk' or control groups
Chappell and Limpisvasti[24]	Extended knee and hip during landing; knee valgus	30 F soccer and basketball players; single-group pre-/post-test	15-min intervention (core strength, balance, PLY, agilities) performed 6 ×/wk for 6 wk	Stop jump (stance phase): dynamic knee valgus moment decreased; drop jump (stance phase): increased knee flexion

EMG = electromyographic activity; **F** = females; **RCT** = randomized controlled trial; ×/**wk** = sessions times per week.

in sport. Finally, we have to point out that enhancing bone mass in children and pre-menopausal women requires a considerably higher PLY volume (i.e. between 5 and 24 months, 3–5 sessions/week and 50–100 jumps/session), while the exercise intensity should be low to moderate.

6. Conclusions and Recommendations

The available evidence suggests that PLY, either alone or in combination with other typical training modalities such as WT, elicits numerous positive changes in neural and musculoskeletal systems, muscle function and athletic performance of healthy individuals. Specifically, the reviewed studies have shown that long-term (6–24 months) PLY represents an effective training method for enhancing bone mass in pre-pubertal/early pubertal children, young women and pre-menopausal women. Furthermore, short-term (6–15 weeks) PLY can change the stiffness of various elastic components of the muscle-tendon complex of plantar flexors in both athletes and non-athletes; however, due to conflicting results in the literature, it is difficult to arrive at a definitive conclusion on this issue. Regarding neuromuscular adaptation to short-term PLY, the results generally show positive increases in lower-extremity strength, power and SSC muscle function in healthy individuals. These adaptive changes in neuromuscular function are likely to be the result of (i) an increased neural drive to the agonist muscles; (ii) changes in the muscle activation strategies (i.e. improved intermuscular coordination); (iii) changes in the mechanical characteristics of the muscle-tendon complex of plantar flexors; (iv) changes in muscle size and/or architecture; and (v) changes in single-fibre mechanics. Our results also show that PLY, either alone or in combination with other training modalities, has the potential to (i) enhance a wide range of athletic performance (i.e. jumping, sprinting, agility, and endurance performance) in children and young adults of both sexes; and (ii) reduce the risk of lower-extremity injuries in female athletes. Finally, available evidence suggest that short-term PLY on non-rigid surfaces (i.e. aquatic-based or sand-based PLY) could elicit similar increases in jumping and sprinting performance as traditional PLY, but with substantially less muscle soreness. Although many issues related to PLY remain to be resolved, the results of the present review allow us to recommend the use of PLY as a safe and effective training modality for improving lower-extremity muscle function and functional performance of healthy individuals. For performance enhancement and injury prevention in sports, we recommend an implementation of PLY into a well designed, sport-specific physical conditioning programme.

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