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Review

The effects of plyometric jump training on lower-limb stiffness in healthy individuals: A meta-analytical comparison

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Abstract

Purpose: To examine the effects of plyometric jump training (PJT) on lower-limb stiffness.

Methods: Systematic searches were conducted in PubMed, Web of Science, and Scopus. Study participants included healthy males and females who undertook a PJT programme isolated from any other training type.

Results: There was a small effect size (ES) of PJT on lower-limb stiffness (ES = 0.33, 95% confidence interval (95%CI): 0.07 to 0.60, $z = 2.47$, $p = 0.01$). Untrained individuals exhibited a larger ES (ES = 0.46, 95%CI: 0.08 to 0.84, $p = 0.02$) than trained individuals (ES = 0.15, 95%CI: −0.23 to 0.53, $p = 0.45$). Interventions lasting a greater number of weeks (>7 weeks) had a larger ES (ES = 0.47, 95%CI: 0.06 to 0.88, $p = 0.03$) than those lasting fewer weeks (ES = 0.22, 95%CI: −0.12 to 0.55, $p = 0.20$). Programmes with ≤2 sessions per week exhibited a larger ES (ES = 0.39, 95%CI: 0.01 to 0.77, $p = 0.04$) than programmes that incorporated >2 sessions per week (ES = 0.20, 95%CI: −0.10 to 0.50, $p = 0.18$). Programmes with <250 jumps per week (ES = 0.50, 95%CI: 0.02 to 0.97, $p = 0.04$) showed a larger effect than programmes with 250−500 jumps per week (ES = 0.36, 95%CI: 0.00 to 0.72, $p = 0.05$). Programmes with >500 jumps per week had negative effects (ES = −0.22, 95%CI: −1.10 to 0.67, $p = 0.63$). Programmes with >7.5 jumps per set showed larger effect sizes (ES = 0.55, 95%CI: 0.02 to 1.08, $p = 0.04$) than those with <7.5 jumps per set (ES = 0.32, 95%CI: 0.01 to 0.62, $p = 0.04$).

Conclusion: PJT enhances lower-body stiffness, which can be optimised with lower volumes (<250 jumps per week) over a relatively long period of time (>7 weeks).

Keywords: Jumps; Stretch shortening cycle; Tendon

1. Introduction

High performance in activities that require a "bouncing" motion, such as running, jumping, and hopping, form a basis for success in both individual and team sports alike. At the tissue level, in movements such as these, the musculotendinous unit (MTU) exhibits spring- or elastic-like behavior whereby the MTU stretches as the lower-limb joints undergo angular flexion before tissue shortening occurs as the joints extend.[1,2] In this way, the stretch-shortening cycle is facilitated by the storage of elastic energy that is used to potentiate further movement beyond the movement that was initially executed.[1]

A key mechanical property governing the aforementioned spring-like behavior of musculotendinous tissue is the term "stiffness."[3] Stiffness is calculated as the ratio of the applied force to the change in displacement of a body.[3] During spring-like movements, the individual stiffness values of various passive tissues (i.e., ligaments, tendons) and active tissues (i.e., muscles) are integrated with neural contributions (e.g., reflexes) to enable the musculoskeletal system to behave like a spring.[4,5] Stiffness can be quantified directly by using methods such as ultrasonography,[6] free oscillation,[7] sinusoidal perturbation,[5] quick release,[8] short-range stiffness experiments,[9] and

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the "alpha" method.[10] In addition, stiffness can also be quantified indirectly by using whole-body kinetics and kinematics,[11–13] although such variables would be more appropriately termed *measures of quasistiffness*.[3]

Lower-limb stiffness can enhance performance in various athletic movements, such as vertical jumping,[14] endurance running,[15] sprint running,[16] and performances requiring a changing of direction.[17] This was demonstrated in a recent study[16] in which stiffness of the entire lower limb was shown to share significant relationships with key indicators of athleticism, such as maximal running velocity ($r = 0.74$), squat jump height ($r = 0.51$), and reactive strength index ($r = 0.44$). In performing these movements, an athlete must repeatedly leverage the stretch-shortening cycle, which exploits the elastic characteristics of the MTU as it absorbs braking forces and generates propulsive forces.[18] This process exploits the aforementioned spring-like behavior of the MTU because the resultant kinetic energy facilitates faster locomotion.[18]

Various types of exercise can be used to target lower-limb stiffness,[19–21] although current conclusions concerning the optimal form of training remain equivocal. For example, Kubo et al.[22] compared the effects of plyometric jumping and isometric resistance training on muscle and joint stiffness in previously untrained adult males. The authors reported that plyometric jump training (PJT), but not isometric training, improved direct measures of active plantarflexor muscle stiffness and indirect measures of joint stiffness during jumping actions. However, it has also been reported that changes in stiffness, but not in the pattern of muscle activation, accounted for the observed gains in jump performance following PJT in male participants 22 years of age.[23] The differing results found in these studies, in addition to the conflicting findings in other investigations that have reported significant improvements[22,24–26] or no change at all,[23,27] show that there is currently no clear consensus in the current body of literature about the effect of PJT on measures of stiffness.

Where different types of exercise are considered effective in enhancing stiffness, this may, in part, be due to variations in total training volume or dosage, which includes factors such as the number of sessions, repetitions, and sets and the time spent under muscular tension.[28] For example, it has been shown that exercise that induces higher levels of strain is more effective for increasing stiffness,[29] with minimal loading durations, at 90% of maximal voluntary contraction, shown to be around 3 s per repetition. In terms of traditional forms of training for performance enhancement, higher levels of strain are, therefore, more readily achievable with traditional resistance training than with PJT. Nevertheless, as evidenced above, this does not exclude PJT as an effective mechanism for enhancing direct and indirect stiffness, and PJT seems to remain a promising method for enhancing these qualities. To our knowledge, the effects of PJT on direct and indirect measures of lower-limb stiffness have not yet been examined in the form of a comprehensive pooled analysis, which could help to gauge the actual level of effectiveness of PJT in enhancing this particular physical quality. Accordingly, to better understand the effectiveness of PJT on lower-limb stiffness, we undertook a comprehensive meta-analysis.

We aimed to examine the effects of PJT on lower-limb stiffness in healthy individuals. We also aimed to establish the characteristics of the dose-response between PJT variables (e.g., training volume, duration, and frequency) and lower-limb stiffness, with a view to optimising training prescription guidelines for coaches.

2. Methods

This meta-analysis was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement.[30]

2.1. Literature search

With no date restrictions, a systematic search was conducted in the electronic databases PubMed (including MEDLINE), Web of Science, and Scopus. Keywords were collected through experts' opinions, a systematic literature review, and controlled vocabulary (i.e., Medical Subject Headings). Boolean search syntax, using the operators "AND" and "OR" was applied, in various combinations, to the following terms: "ballistic," "complex," "explosive," "force-velocity," "plyometric," "stretch-shortening cycle," "jump," "plyometric exercise," "resistance training," "training," "muscle," "tendon," "musculotendinous," "compliance," "elasticity," "viscoelastic," and "hysteresis." Only original articles written in English were considered. Although we used the default values of the database search engines, manual data checking was also performed to increase the precision of data collection from relevant studies.

2.2. Selection of retrieved articles

After an initial search, accounts were created in the relevant databases. Through these accounts, we received automatically generated E-mails for updates regarding the search terms used. Thus, our search in the 3 databases was ongoing, with updates received on a weekly basis. Studies were eligible for inclusion until the initiation of manuscript preparation in July 2020.

2.3. Inclusion criteria

To determine the eligibility of studies for inclusion in our meta-analysis, we used the PICOS (participants, intervention, comparators, study outcomes, and study design) framework.[30] The PRISMA flow diagram illustrating the number of studies excluded at each stage of the systematic review and meta-analysis is shown in Fig. 1. Inclusion and exclusion criteria are shown in Table 1, and the characteristics of the included studies are displayed in Table 2. For PJT intervention studies that were identified as being potentially relevant, the full text was used to determine whether the study contained a relevant measure of stiffness, as stipulated in Table 1. Lower-limb stiffness can be assessed using either direct measures such ultrasonography[29,31] or indirect measures using kinetics and/or kinematics.[11]

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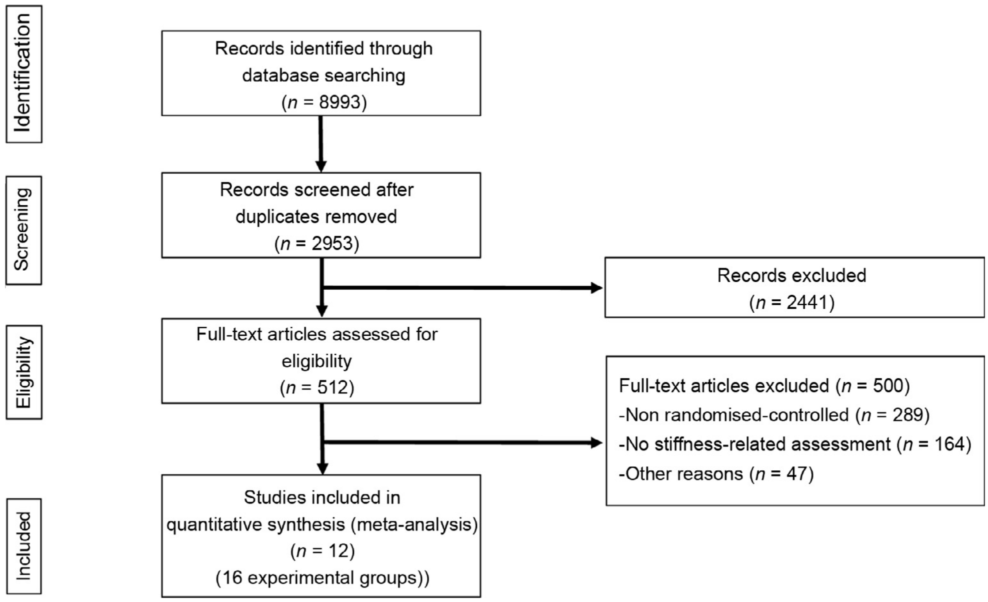

Fig. 1. Flow chart for inclusion and exclusion of studies.

2.4. *Analysis and interpretation of results*

Data were extracted from included articles with a form created in Microsoft Excel. Where required data were not clearly or completely reported, the article's authors were contacted for clarification. Meta-analytical comparisons were carried out in RevMan Version 5.3.[32] Means and SD for measures of stiffness were used to calculate effect sizes. The inverse-variance random-effects model for meta-analyses was used because it allocates a proportionate weight to trials based on the size of their individual standard errors[33] and facilitates analysis whilst accounting for heterogeneity across studies.[34] Effect sizes are represented by the standardised mean

Table 1
Population, intervention, comparison, and outcomes (PICOS) framework for study inclusion and exclusion criteria.

Category	Inclusion criteria	Exclusion criteria
Population	Healthy males and females of any age	Individuals who had sustained a recent injury
Intervention	A plyometric jump training programme that conformed to the following definition: "Lower body unilateral and bilateral bounds, jumps, and hops that utilise a pre-stretch or countermovement that incites usage of the stretch-shortening cycle"[31,65]	Interventions that were carried out in conjunction with alternative training methods such as strength or balance training Interventions that were carried out in water or that used additional manipulative techniques such as electrostimulation Interventions <3 weeks
Comparator	Studies must have included an experimental group that undertook plyometric training and a control group to which it could be compared. The control group could not have been engaged in any plyometric training.	Studies that did not have a control group
Outcome	Each study must have included a measure of direct or indirect lower body stiffness, taken both prior to and after the intervention period. Lower-limb stiffness can be assessed using either laboratory measures such ultrasonography to quantify muscle and tendon stiffness directly[29,31] or field-related measures such as vertical hopping stiffness.[11] In our meta-analysis, when the included studies used methods to quantify muscle and/or tendon stiffness, the resultant term *tissue stiffness* is used. In contrast, when included studies used field-based measures, the term *quasistiffness* is used.[3,66] The classification of stiffness, as we judged it, must have conformed to 1 of the following, as described by Latash and Zatsiorsky[3]: Stiffness: the elastic properties of tendons and passive muscles Apparent stiffness: the response of active muscles to stretch forces Quasistiffness: proxies of the above qualities as measured with tests such as rebound hopping	Studies with no measure of stiffness, apparent stiffness or quasistiffness
Study design	Controlled training intervention studies containing 2 independent groups for comparison	The second treatment sequence of a crossover study, cross-sectional studies, or studies that evaluated acute performance variables only (i.e., postactivation potentiation)

Table 2
Study characteristics.

Study	Age (year)[a]	Height (cm)[a]	Weight (kg)[a]	Training status	Weeks	Mean frequency (per week)	Total sessions	Mean weekly jumps	Jump type	Sets	Repetitions	Test	Type of stiffness
Chaouachi et al. (2014)[65]	13.7 ± 0.8	161.5 ± 7.7	45.9 ±9.7	Inactive (physical education only)	8	3	24	292.5	Countermovement jump Line jump (standing distance jump), drop jump + 1 step, front to back cone hops, lateral box jump push off, 1-leg distance jump + 1 step, single-leg cone jumps front to back, single-leg cone jumps side to side, single-leg box push off	1-2	8-15	Leg stiffness (submaximal hopping test)	Direct
Cornu et al. (1997)[5]	22.3 ± 2.4	—	—	Athletes (basketball and volleyball)	7	2	14	1200	Squat jumps, drop jumps, hopping, jumps from high (70 cm) and low (40 cm) platforms, jumps over hedges using 1 or both feet			Mechanical impedance	Indirect
Fouré et al. (2014)[27]	18.8 ±0.9	179.2 ± 6.1	68.5 ± 7.1	Athletes (basketball, volleyball, and handball)	8	2	16	400	Squat jumps, counter-movement jumps, drop jumps from either low (40 cm), medium (60 cm), or high (80 cm) platforms, jumps over hedges using 1 or both feet			Maximal musculo-articular stiffness with dynamometer	Direct
Fouré et al. (2010)[26]	18.8 ± 0.9	177.3 ± 6.2	68.4 ± 6.5	Active (10.5 h per week)	14	2.4	34	485.7	Squat jumps, counter-movement jumps, drop jumps from either low (40 cm), medium (60 cm), or high (80 cm) platforms, jumps over hedges using 1 or both feet			Maximal musculo-articular stiffness with dynamometer (stiffness index)	Direct
García-Pinillos et al. (2014)[xx]	27.2 ± 8.6	172.0 ± 10.0	66.0 ±10.4	Recreationally trained (3−5 weekly running sessions)	10	3.2	32	1000	Bilateral and unilateral—alternating jump rope	1	100-140	Arch stiffness	Indirect
Hirayama et al. (2017)[67]	22.0 ± 3.0	172.0 ±5.8	66.9 ± 10.5	Recreationally active with no plyometric experience	12	3	36	300	Unilateral depth jumps	10	10	Achilles' tendon stiffness (ultrasound)	Direct
Houghton et al. (2013)[68]	21.0 ± 4.0	174.6 ± 3.1	73.7 ±10.3	Athletes (no prior plyometric experience)	8	1.875	15	223.12	Land off box, standing long jump in squat jump position, standing long jump, forward jump over hurdle, vertical countermovement jump, lateral jump over hurdle, reactive jumps, forward jump (50 cm apart), bounding forward hurdles, forward jumps to box, box jumps, bounding forward repeated hurdles, forward jumps, lateral jumps to box, drop jumps, drop jump and jump over hurdle	1-6	2-12	Achilles' tendon stiffness at 90% MVC (dynamometer)	DIrect
Jeffreys et al. (2014)[69] (HPG)	20.3 ± 1.6	182.0 ± 5.0	91.6 ± 10.4	Trained (1−2 years plyometrics)	6	2	12	320	Standing vertical jumps (tuck jumps), multiple two-foot hurdle jumps, repeated 2-foot jumps (horizontal), alternate leg bounds, lateral 2-foot jumps, multiple two-foot hurdle jumps, single-foot hops, drop jumps, lateral one-foot jumps, single-foot drop jumps	4-8	5-10	Leg stiffness (force plate)	Indirect

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Table 2 (Continued)

Study	Age (year)[a]	Height (cm)[a]	Weight (kg)[a]	Training status	Weeks	Mean frequency (per week)	Total sessions	Mean weekly jumps	Jump type	Sets	Repetitions	Test	Type of stiffness
Jeffreys et al. (2019)[69] (LPG)	20.3 ± 1.6	183.0 ±5.0	91.6 ±10.4	Trained (1−2 years plyometrics)	6	2	12	80	Standing vertical jumps (tuck jumps), multiple two-foot hurdle jumps, repeated 2-foot jumps (horizontal), alternate leg bounds, lateral 2-foot jumps, multiple 2-foot hurdle jumps, single-foot hops, drop jumps, lateral 1-foot jumps, single-foot drop jumps	1-2	5-10	Leg stiffness (force plate)	Indirect
Laurent et al. (2020)[70] (KE)	22.5	180.5 ±5.8	68.7 ± 14.0	Active but untrained	10	2	20	298	Stationary hopping, drop jump on the spot, drop jump with displacement	3-5	10	Achilles' tendon stiffness (ultrasound)	Direct
Laurent et al. (2020)[70] (KF)	22.5	180.9 ±10.5	69.7 ± 10.8	Active but untrained	10	2	20	298	Stationary hopping, drop jump on the spot, drop jump with displacement	3-5	10	Achilles' tendon stiffness (ultrasound)	Direct
Lloyd et al. (2012)[71] (G12)	12.3 ± 0.3	151.8 ± 7.9	44.8 ± 9.4	Inactive (physical education only)	4	2	8	92.5	Squat jump, countermovement jump, pogo hopping, standing long jump, lateral hops, hop scotch, bilateral "power" hops, ankle jumps, "power" skipping, unilateral pogo hops, max rebound hops, drop jumps, hurdle "power" hops, total foot contacts	2-4	4-10	Absolute leg stiffness (submaximal hopping)	Indirect
Lloyd et al. (2012)[71] (G15)	15.3 ± 0.3	174.4 ± 6.6	65.0 ± 8.9	Inactive (physical education only)	4	2	8	92.5	Squat jump, countermovement jump, pogo hopping, standing long jump, lateral hops, hop scotch, bilateral "power" hops, ankle jumps, "power" skipping, unilateral pogo hops, max rebound hops, drop jumps, hurdle "power" hops, total foot contacts	2-4	4-10	Absolute leg stiffness (submaximal hopping)	Indirect
Lloyd et al. (2012)[71] (G9)	9.4 ± 0.5	133.2 ± 8.7	32.6 ± 7.0	Inactive (physical education only)	4	2	8	92.5	Squat jump, countermovement jump, pogo hopping, standing long jump, lateral hops, hop-scotch, bilateral "power" hops, ankle jumps, "power" skipping, unilateral pogo hops, max rebound hops, drop jumps, hurdle "power" hops, total foot contacts	2-4	4-10	Absolute leg stiffness (submaximal hopping)	Indirect
Spurrs et al. (2003)[15]	25.0 ± 4.0	178.0 ± 4.0	72.4 ±5.5	Trained athletes (10 years)	6	2.5	15	131.1	Squat jump, split scissor jump, double-leg bound, alternate leg bound, single-leg forward hop, depth jump, double-leg hurdle jump, single-leg hurdle hop	2-3	6-15	Musculotendinous stiffness (seated calf raise)	Direct

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Table 2 (Continued)

Study	Age (year)[a]	Height (cm)[a]	Weight (kg)[a]	Training status	Weeks	Mean frequency (per week)	Total sessions	Mean weekly jumps	Jump type	Sets	Repetitions	Test	Type of stiffness
Wu et al. (2010)[25]	22.1 ±1.6	174.4 ± 7.6	65.8 ±8.6	Untrained students	8	2	16	180	Squat jump, split squat jump, cycled split squat jump, pike jump, double-leg tuck jump, double-leg zigzag hop, double-leg hop, in-depth jump, box jump	2-3	10	Stiffness (Chemomechanical potentiation)	Direct

[a] The data are presented as mean ± SD.Abbreviations: G9 = age 9 experimental group; G12 = age 12 experimental group; G15 = age 15 experimental group; HPG = high volume plyometric group; KE = Knees extended; KF = Knees flexed; LPG = low volume plyometric group.

difference and are presented alongside 95% confidence intervals (95%CI). The calculated effect sizes (ESs) were interpreted by using the conventions outlined by Hopkins et al.[35] (<0.19 = trivial; 0.20−0.59 = small, 0.60−1.19 = moderate, 1.20−1.99 = large, 2.00−3.99 = very large, ≥4.0 = extremely large). In cases in which there was more than 1 intervention group in a given study, the comparison group was proportionately divided to facilitate comparison across all participants.[36]

To gauge the degree of heterogeneity amongst the included studies, the I^2 statistic was calculated. This represents the proportion of effects that are caused by heterogeneity as opposed to chance.[30] Low, moderate, and high heterogeneity correspond to I^2 values of 25%, 50%, and 75%, respectively; however, these thresholds are considered tentative.[37] A value >75% is rated as being considerably heterogeneous.[33] The χ^2 (chi-square) is assessed if any observed differences in results are compatible with chance alone. A low *p* value or a large χ^2 statistic relative to its degree of freedom provides evidence of heterogeneity of intervention effects beyond those attributable to chance.[33]

2.5. Assessment of risk of bias

The Physiotherapy Evidence Database scale was used to assess the risk of bias and methodological quality of the included studies. This scale evaluates internal study validity on a scale from 0 (high risk of bias) to 10 (low risk of bias). Two reviewers (HC and YN) independently rated each study. Any ratings that yielded different results between the 2 reviewers were further adjudicated by a third reviewer (UG), a course of action that did not have to be followed. The agreed rating was used in the risk of bias scale. A median score of ≥6 represents the threshold for studies with a low risk of bias.[38]

2.6. Analysis of moderator variables

To assess the potential effects of moderator variables, subgroup analyses were performed. We selected, a priori, moderators likely to influence the main effect of PJT on stiffness. For this, a subgroup division between direct and indirect measures of stiffness was made. Indirect stiffness is that which can be quantified using whole-body kinetics and kinematics[11−13] and can be alternatively termed *quasistiffness* because it does not necessarily evaluate the mechanistic elements of this physical quality. Conversely, direct stiffness, which is representative of localised passive stiffness in anatomical structures such as the Achilles tendon,[39] is that which is quantified with methods such as ultrasonography,[6] free oscillation,[7] sinusoidal perturbation,[5] quick release,[8] short-range stiffness experiments,[9] and the "alpha" method.[10] Other subgroups included the number of weeks in the applied programme, the total number of training sessions, and the weekly frequency of those sessions. These variables were chosen based on the accepted influence of the FITT (frequency, intensity, time, and type) principle on adaptations to exercise.[40] The median number of sets and repetitions per exercise were chosen on the basis of their use in previous PJT meta-analyses.[41] A cumulative total of mean weekly jumps was also used as a moderator. The training status of the study participants was considered due to the presence of an upper threshold of adaptation to exercise after a particular level is achieved.[42] For this moderator, study participants were divided into "trained" and "untrained" subgroups, with athletes, active individuals, and those with >1 year of training experience considered for the former group and inactive and recreationally trained individuals allocated to the latter. For these classifications, we depended on the study authors' own assessment of the level of activity undertaken by participants in their study. We did not, however, consider children engaged in physical education only as "active." For all other variables, a median, or "natural split," was used to divide subgroups, whereby clear divisions in the data were identified and used as a delineator. For example, the most logical division of mean weekly jump total resulted in the formation of subgroups of <250 jumps, 250−500 jumps, and >500 jumps per week. This constitutes a more intuitive division, where indiscriminate use of the median split would be inappropriate.

3. Results

3.1. Study selection

The PRISMA flow diagram illustrating the number of studies excluded at each stage of the systematic review and meta-analysis is shown in Fig. 1. Together, the studies were considered to be at low risk of bias (median quality score = 6.0). These data are presented in Table 3. In total, 12 studies, with 16 experimental groups, met the inclusion criteria and were included in the systematic review. A total of 7 of these groups incorporated measures of indirect stiffness, and 9 of them incorporated measures of direct stiffness.

3.2. Primary analyses

For the main effect analysis of the effect of PJT on lower-limb stiffness, there was a small effect size (ES = 0.33, 95%CI: 0.07−0.60, $z = 2.47$, $p = 0.01$). Between-study heterogeneity was moderate ($I^2 = 38\%$, $p = 0.06$). These results are displayed in Fig. 2.

3.3. Effect of moderator variables

The results of the moderator analysis are displayed in Table 4. Differences between subgroups demonstrated low heterogeneity and were nonsignificant. For training status, "untrained" individuals exhibited a small effect (ES = 0.46 95%CI: 0.08 to 0.84, $p = 0.02$), whereas no effects were observed for "trained" participants (ES = 0.15, 95%CI: −0.23 to 0.53, $p = 0.45$). For test type, those tests for direct measures of stiffness showed a small effect (ES = 0.48, 95%CI: −0.03 to 0.98, $p = 0.06$) that exceeded the borderline trivial to small effect for indirect measures of stiffness (ES = 0.21, 95%CI: −0.03 to 0.45), $p = 0.09$). For programme duration, those interventions lasting a greater number of weeks (>7 weeks) displayed a larger (ES = 0.47, 95%CI: 0.06 to 0.88), $p = 0.03$) than those lasting a lower number of weeks (ES = 0.22, 95%CI: −0.12 to 0.55, $p = 0.20$). A contradictory trend was seen for total sessions per programme, with programmes having ≤16 sessions showing a larger (ES = 0.37, 95%CI: −0.04 to 0.77, $p = 0.08$), though still small, effect compared to its opposite subgroup (ES = 0.24, 95%CI: −0.05 to 0.53), $p = 0.11$). Similarly, programmes with ≤2 sessions per week exhibited a larger effect size (ES = 0.39, 95%CI: 0.01 to 0.77, $p = 0.04$) than programmes that incorporated >2 sessions per week (ES = 0.20, 95%CI: −0.10 to 0.50, $p = 0.18$). This trend is also apparent in the subgroups for number of jumps per week, with <250 jumps (ES = 0.50, 95%CI: 0.02 to 0.97, $p = 0.04$) showing a larger effect than 250−500 jumps (ES = 0.36, 95%CI: 0.00 to 0.72, $p = 0.05$), which was, in turn, larger than the negative effect size for >500 jumps per week (ES = −0.22, 95%CI: −1.10 to 0.67, $p = 0.63$). Interventions

Table 3
Physiotherapy Evidence Database (PEDro) scale ratings.

	Item 1[a]	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8	Item 9	Item 10	Item 11	Total (from a possible maximal of 10)
Chaouachi et al.(2014)[65]	1	1	0	1	0	0	0	1	1	1	1	6
Cornu et al. (1997)[5]	1	0	0	0	0	0	0	1	1	1	1	4
Fouré et al. (2009)[27]	1	1	0	1	0	0	0	1	1	1	1	6
Fouré et al. (2010)[26]	1	1	0	1	0	0	0	1	1	1	1	6
García-Pinillos et al. (2020)[66]	1	1	0	1	0	0	0	1	1	1	1	6
Hirayama et al. (2017)[67]	1	1	0	1	0	0	0	0	1	1	1	5
Houghton et al. (2013)[68]	1	0	0	0	0	0	0	1	0	1	1	3
Jeffreys et al. (2019)[69]	1	1	0	1	0	0	0	1	1	1	1	6
Laurent et al. (2020)[70]	1	1	0	1	0	0	0	1	1	1	1	6
Lloyd et al. (2012)[71]	1	0	0	0	0	0	0	1	1	1	1	4
Spurrs et al. (2003)[15]	1	1	0	1	0	0	0	1	1	1	1	6
Wu et al. (2010)[25]	1	1	0	1	0	0	0	1	1	1	1	6

Notes: Here is a brief explanation: Item 1, eligibility criteria were specified; Item 2, subjects were randomly allocated to groups; Item 3, allocation was concealed; Item 4, the groups were similar at baseline; Item 5, there was blinding of all subjects; Item 6, there was blinding of all therapists; Item 7, there was blinding of all assessors; Item 8, measures of at least 1 key outcome were obtained from more than 85% of the subjects initially allocated to groups; Item 9, all subjects for whom outcome measures were available received the treatment or control condition as allocated, or data for at least 1 key outcome was analysed by "intention to treat"; Item 10, the results of between-group statistical comparisons were reported for at least 1 key outcome; Item 11, the study provided both point measures and measures of variability for at least 1 key outcome.

[a] A detailed explanation of each PEDro scale item can be accessed at https://www.pedro.org.au/english/downloads/pedro-scale (Access for this review: March 11, 2020.)

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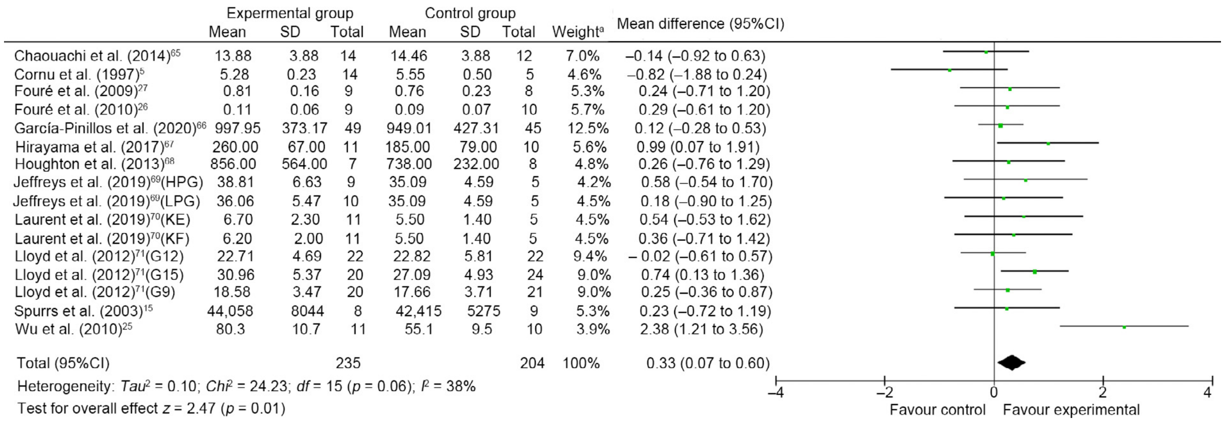

Fig. 2. Forest plot of main effect of plyometric training on lower-limb stiffness.[a] The sum of the percentages is not 100% due to the rounding. 95%CI = 95% confidence interval; G12 = age 12 experimental group; G15 = age 15 experimental group; G9 = age 9 experimental group; HPG = high volume plyometric group; KE = knees extended; KF= knees flexed; LPG = low-volume plyometric group.

with >7.5 jumps per set showed a larger effect size (ES = 0.55, 95%CI: 0.02 to 1.08), $p = 0.04$) than interventions with <7.5 jumps per set (ES = 0.32, 95%CI: 0.01 to 0.62), $p = 0.04$). Interventions with ≥3 sets or <3 sets displayed similar effect sizes (ES = 0.41, 95%CI: 0.13 to 0.69), p = 0.04 *vs.* ES = 0.45, 95%CI: −0.23 to 1.14), $p = 0.2$, respectively).

4. Discussion

This meta-analysis examined the effects of PJT on lower-limb stiffness in healthy males and females. The main results indicate that PJT can induce small but statistically significant increases in lower-limb stiffness. Of potentially greater interest to practitioners are the results of the subgroup analysis, which demonstrated a nonuniform pattern of adaptation across populations. Of potentially greater interest to practitioners are the results of the subgroup analysis, which demonstrated a nonuniform pattern of adaptation across populations: untrained individuals, the programming of a greater number of jumps per set, and an upper weekly limit of 250 jumps were some of the key factors to influence effect magnitude positively.

Table 4
Moderator analyses for the effect of plyometric training on tendon stiffness.

Outcome or subgroup	Studies	ES (95%CI)
Training status	16	0.33 (0.07 to 0.60)
Trained	7	0.15 (−0.23 to 0.53)
Untrained	9	0.46 (0.08 to 0.84)*
Stiffness type	16	0.33 (0.07 to 0.60)
Indirect stiffness	7	0.21 (−0.03 to 0.45)
Direct stiffness	9	0.48 (−0.03 to 0.98)
Mean weekly jumps	16	0.33 (0.07 to 0.60)
>500 jumps	2	−0.22 (−1.10 to 0.67)
250−500 jumps	7	0.36 (0.00 to 0.72)
<250 jumps	7	0.50 (0.02 to 0.97)*
Programme duration (weeks)	16	0.33 (0.07 to 0.60)
>7 weeks	9	0.47 (0.06 to 0.88)*
≤7 weeks	7	0.22 (−0.12 to 0.55)
Total sessions	16	0.33 (0.07 to 0.60)
>16 sessions	6	0.24 (−0.05 to 0.53)
≤16 sessions	10	0.37 (−0.04 to 0.77)
Weekly training frequency	16	0.33 (0.07 to 0.60)
>2 sessions per week	5	0.20 (−0.10 to 0.50)
≤2 sessions per week	11	0.39 (0.01 to 0.77)*
Median number of sets per session	13	0.40 (0.12 to 0.69)
≥3 sets per session	8	0.41 (0.13 to 0.69)*
<3 sets per session	5	0.45 (−0.23 to 1.14)
Median number of jumps per set	13	0.40 (0.12 to 0.69)
>7.5 jumps per set	7	0.55 (0.02 to 1.08)*
<7.5 jumps per set	6	0.32 (0.01 to 0.62)*

*Represents a statistically significant effect within moderator subgroups.
Abbreviation: ES = effect size.

4.1. Main effect

Mechanical loading of the MTU results in increases in tendon stiffness due to enhanced collagen synthesis.[43,44] Such loading can enhance both the size and the mechanical characteristics of the tendon,[44] but the nature of these changes is dependent on the type of loading that is habitually applied.[45] Indeed, this may be why conclusions in the literature related to the effectiveness of PJT for the enhancement of tendon stiffness have been equivocal. Two reviews,[45,46] whilst acknowledging the propensity of PJT to enhance tendon stiffness, reported similar results, with these inconsistencies' possibly being explained by differentials in adaptive potential across various anatomical structures in the body or by differentials in active and passive components of the musculotendinous complex.[22] Hypertrophic gains of up to 35% in tendon tissue are possible in adults.[45] However, it seems that such changes, and subsequent increases in tendon stiffness, are more likely to occur due to traditional resistance training rather than PJT.[23] This could be because the comparatively smaller amount of time spent under an applied force (or tension) during PJT[47] may not be sufficient to induce a hypertrophic response[48,49] and, by extension, an increase in tendon stiffness. Thus, resistance training and, in particular, its eccentric variant may be a more appropriate stimulus for achieving stiffness-related adaptations.[50]

Although PJT can be readily utilised to enhance tendon stiffness, it may not necessarily represent the optimal method with which to drive such adaptation, through hypertrophic pathways at least. This is supported not only by the existing

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literature but also by the small magnitude of the main effect in our meta-analysis, which suggests that a potentially low level of change in stiffness occurs due to PJT, particularly in the short term. To understand this small effect size, the multidimensional nature of sports performance must be considered. For example, the attainment of muscular strength is underpinned by various interdependent pathways of adaptation relating to neurological and morphological changes.[51] There is a differential in the time it takes for muscle and tendon tissue to adapt to training, with PJT seeming to preferentially stimulate adaptations in muscle tissue as opposed to tendons.[45] Also, increases in muscle strength seem to be more sensitive to neuromuscular training stimuli in that they have been found to precede increases in tendon stiffness by up to 2 months.[21,52] The average duration of the studies included in our meta-analysis was just 7.5 weeks, indicating that even if tendon stiffness were assumed to be highly achievable through PJT, the time course of the included studies may not have been of sufficient duration to allow this phenomenon to be observed. This is supported by our finding that programmes lasting >7 weeks produced a 2-fold greater magnitude of effect compared to programmes lasting ≤7 weeks. Accordingly, until longer-term interventions that examine the effects of PJT on tendon stiffness are undertaken, definitive conclusions concerning their true effect will be difficult to make. Indeed, this variance in duration could be the reason that discrepancies exist in the results from studies on the potential to enhance stiffness through PJT. Long-term interventions would also be in line with the principles of athletic development programmes for youth participants (which accounted for nearly 30% of the study groups in our meta-analysis) and would better facilitate the assessment of potential imbalances in the development of muscle and tendon adaptations, thus reducing injury risk.[45,53,54]

4.2. *Effect of moderators*

With respect to the impact of moderators on the main effect, a notable result relates to the higher effect size observed in untrained, compared to trained, participants. This could indicate a pattern of adaptation that is characterised by a rapid onset of small changes in stiffness, with the potential for continued adaptation quickly reduced as an individual attains a larger body of training experience. This could potentially reduce the chances of further development in the longer term because the bulk of adaptive responses are seen in the early stages of training. In order to continue stiffness-related adaptations in more advanced athletes,[29] coaches may want to place a greater emphasis on traditional strain-inducing resistance training than on PJT, underpinning the importance of a multidimensional programme to achieve highly specific aims. This is an important consideration for coaches because advanced athletes, in particular, are accustomed to a "biological ceiling" in their development, beyond which further adaptations to training are reduced or negated.[42] Furthermore, coaches should be aware of the potential for mismatches in the time course of muscle and tendon adaptations, which can result in problematic outcomes for an individual. For example, an increase in muscle strength that occurs independent of any change in tendon stiffness can lead to higher tendon strain during maximal performance, culminating in an increase of the mechanical demand exerted on the tendons by acting musculature.[55] Thus, multidimensional programmes that concurrently develop the strength and stiffness of all tissues should be an integral component of athletic development.

Another notable moderator finding relates to the apparently inverse dose-response of PJT for the enhancement of stiffness. Mean weekly jumps in our meta-analysis were divided into low (<250 jumps), medium (250-500 jumps), and high (>500 jumps) load classifications. It is interesting to note that the higher the dose, the lower the observed effect. This inverse trend seems to imply that lower volumes of PJT may be more beneficial than higher volumes for the achievement of enhanced stiffness. Indeed, previous research lends support to this finding, with lower volumes of PJT found to be almost as effective *and* more efficient than higher volumes when jumping performance was measured.[56,57] A recent investigation[69] Q4 also revealed the effect of low and high volumes of PJT on the reactive strength index in collegiate rugby players. Across various measures of the reactive strength index,[58] larger effects were reported from different jump drop heights following low-volume PJT (480 foot contacts) than following high-volume PJT (1920 foot contacts).[69] Although the results of these cited studies do not relate directly to a measure of tendon stiffness, they do lend weight to the notion of an upper limit to the effectiveness of larger volumes of PJT. As has been previously demonstrated, higher volumes of PJT are not universally optimal.[59,60] This could be further elucidated with additional research implemented over a longer period of time than the research cited in our meta-analysis.

The finding that lower volumes of PJT (<250 jumps) may be more beneficial for enhancing stiffness than higher volumes is further supported by our results, which indicated that programmes with ≤16 sessions were marginally more effective than programmes with >16 sessions. Furthermore, programmes with <3 sets of PJT were as effective as those with >3 sets, whilst lower training frequencies (≤2 sessions per week) were preferable to higher training frequencies (i.e., >2 sessions per week). These results imply that, alongside lower jump volumes within individual sessions, having fewer training sessions across a longer time frame may help to optimise adaptations for tendon stiffness, with higher doses seemingly not required to initiate adaptation in the short term. Coaches could, therefore, maximise tendon-stiffness adaptations by programming a lower frequency of PJT alongside low within-session training volumes but over a higher number of training weeks. Such a programming structure would enable coaches to target stiffness specifically without compromising, through fatigue, the other training goals that must be achieved in a physical-preparation programme. A prudent training strategy, therefore, would include jumps that are appropriate specifically for enhancing stiffness as a physical quality, including jumps that require resistance to knee and hip flexion and short ground contact times,[61] such as ankle hops, skipping, hurdle hops, and depth jumps. Because in many cases these jumps are of low intensity,[62] they can regularly be incorporated into

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warm-up activities that conform to the low load of semiregular PJT, thus underpinning progression in this area. Coaches are encouraged to avoid having athletes engage in high volumes of PJT to achieve greater stiffness because this seems unnecessary and could be detrimental to an athlete's conditioning.[60]

4.3. Limitations

Because there are some limitations to our study, our results should be interpreted with caution. Female participants were Q5 part of only 2 studies[66,70] in our meta-analysis; thus, the results of our review may not be fully applicable to that population. Also, because stiffness was measured and represented in the included studies in a number of different ways, it is not possible to conclude that the positive increases we report can be attributed to changes in muscle activity, mechanical properties of the MTU, or a combination of both. It has been shown that changes in muscle morphology and architecture can occur in as few as 3 weeks in response to resistance training, whilst rapid adaptations of tendon morphological or mechanical properties seem unlikely.[45] Additionally, in our moderator analyses, the dichotomisation of continuous data with the median split could have resulted in residual confounding and reduced statistical power.[63,64] Finally, the moderator analyses were calculated independently and not interdependently. Such univariate analysis must be interpreted with caution because the programming parameters were calculated as single factors, irrespective of between-parameter interactions.

5. Conclusions

Based on the pooled data presented in our meta-analysis, PJT can be used as an effective method that coaches can use to enhance direct and indirect stiffness in healthy males and females. However, based on the wider body of evidence, PJT may not be the best way to enhance stiffness and may be better utilised as a complementary method for enhancing it, alongside potentially more effective methods, such as traditional resistance training or eccentric resistance training. The time course of adaptation is also an important factor to consider; programmes lasting longer than 7 weeks are more effective. This could be directly related to the relative responsiveness of tendinous tissue compared to muscle tissue; the latter seems to adapt faster to neuromuscular training stimuli. Balancing the training volume is key because weekly loads >500 jumps may be deleterious to enhancing stiffness, and the need to prescribe sustained volumes that are optimal but not excessive is apparent. Thus, the prescription of <250 jumps per week seems optimal for the enhancement of stiffness. Complicating these recommendations is the training status of the individual. Therefore, coaches are encouraged to remain mindful that small gains in stiffness that can be attained through PJT are likely to be subject to diminishing returns over time. This necessitates the prescription of multidimensional physical-preparation programmes that enhance stiffness via alternative pathways of adaptation.

Authors' contributions

JM collected the data, analysed the data, and wrote the manuscript; BL analysed the data and wrote the manuscript; RRC collected the data and wrote the manuscript; UG analysed the data and wrote the manuscript; NG analysed the data and wrote the manuscript; and HC conceived the study, analysed the data, and wrote the manuscript. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Competing interests

The authors declare that they have no competing interests.

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