Effects of Plyometric Jump Training on Electromyographic Activity and Its Relationship to Strength and Jump Performance in Healthy Trained and Untrained Populations: A Systematic Review of Randomized Controlled Trials

Rodrigo Ramirez-Campillo,[1,2] Felipe Garcia-Pinillos,[3,4] Helmi Chaabene,[5,6] Jason Moran,[7] David G. Behm,[8] and Urs Granacher[5]

[1]Human Performance Laboratory, Department of Physical Activity Sciences, Universidad de Los Lagos, Santiagoo, Chile; [2]Exercise Physiology Research Center,. Science Faculty,. Major university,. Santiago, Chile; [3]Department of Physical Education, Sports and Recreation, Universidad de La Frontera, Temuco, Chile; [4]Department of Physical Education and Sport, University of Granada, Granada, Spain [5]Division of Training and Movement Sciences, Research Focus Cognitive Sciences, University of Potsdam, Potsdam, Germany; [6]Department of Sports Science, High Institute of Sports and Physical Education, Kef, University of Jendouba, Jendouba, Tunisia; [7]School of Sport, Rehabilitation and Exercise Sciences, University of Essex, Colchester, United Kingdom; and [8]School of Human Kinetics and Recreation, Memorial University of Newfoundland, St. John's Newfoundland and Labrador, Canada

Abstract

Ramirez-Campillo, R, Garcia-Pinillos, F, Chaabene, H, Moran, J, Behm, DG, and Granacher, U. Effects of plyometric jump training on electromyographic activity and its relationship to strength and jump performance in healthy trained and untrained populations: a systematic review of randomized controlled trials. *J Strength Cond Res* 35(7): 2053–2065, 2021—This systematic review analyzed the effects of plyometric jump training (PJT) on muscle activation assessed with surface electromyography during the performance of strength and jumping tasks in healthy populations across the lifespan. A systematic literature search was conducted in the electronic databases PubMed/MEDLINE, Web of Science, and SCOPUS. Only randomized controlled studies were eligible to be included in this study. Our search identified 17 studies comprising 23 experimental groups and 266 subjects aged 13–73 years, which were eligible for inclusion. The included studies achieved a median Physiotherapy Evidence Database score of 6. No injuries were reported among the included studies. Significant PJT-related improvements were reported in 7 of 10 studies and in 6 of 10 studies for measures of muscle activation during the performance of strength and jumping tasks, respectively. Moreover, a secondary correlational analysis showed significant positive relationships ($r = 0.86$; $p = 0.012$; $r^2 = 0.74$) between changes in muscle activation and changes in jump performance. However, from the total number ($n = 287$) of muscle activation response variables analyzed for strength and jumping tasks, ~80% ($n = 226$) were reported as nonsignificant when compared with a control condition. In conclusion, PJT may improve muscle activation during the performance of strength and jumping tasks. However, conflicting results were observed probably arising from (a) studies that incorporated a large number of outcomes with reduced sensitivity to PJT, (b) methodological limitations associated to muscle activation measurement during strength and jumping tasks, and (c) limitations associated with PJT prescription. Future studies in this field should strive to solve these methodological shortcomings.

Key Words: human physical conditioning, resistance training, plyometric exercises, myoelectrical activity, stretch-shortening cycle, electromyography

Introduction

There is evidence that training with the aim to enhance muscular power is effective in improving performance and health-related outcomes (1,10,35). A specific, easy-to-administer, and, thus, popular type of power training is plyometric jump training (PJT) (27,59). Plyometric jump training is characterized by exercises that leverage the stretch-shortening cycle of the muscle (50,82). Typically, plyometric jump exercises can be conducted with short (<250 ms) or long ground contact times (>250 ms), i.e., fast or slow stretch-shortening cycle durations (26,31,78). There is compelling evidence showing that PJT is an effective tool to improve a wide range of physical capacities (e.g., jumping and sprinting) regardless of age, sex, sports discipline, and training expertise (2,20–22). Increased awareness of the beneficial effects of PJT has led to a greater number of PJT-related studies in recent years. Indeed, Ramirez-Campillo et al. (73) reported a 25-fold increase in PJT-related studies between 2000 and 2017. However, from the available literature, no updated systematic review has focused on the effects of PJT on muscle activation during the

Address correspondence to Rodrigo Ramirez-Campillo, r.ramirez@ulagos.cl.

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performance of strength and jumping tasks. It is noteworthy that a decade ago, a narrative literature review (59) reported mainly positive findings on the effects of PJT on muscle activation. Other than the mix of randomized and nonrandomized controlled studies (RCTs) which this review provided, knowledge about PJT-induced changes in muscle activation were limited at that time (59). Furthermore, considering the pronounced escalation in the number of PJT publications in more recent years (73), an update on this topic is warranted.

In the context of this article, we contextualize the term "muscle activation" as the efferent signals that are transmitted along the final common pathway of the motoneuron and result in excitation–contraction coupling with synchronous contraction of the myofibrils, irrespective of the contraction type (isometric, concentric, and eccentric) that can be assessed through surface electromyography (sEMG) (30,46). Surface electromyography is one of the most established biomechanical testing measures for the assessment of muscle activation (28,55,59,86) facilitating the recording of changes in the action potential of muscles (71). All active motor units underneath the electrode sites contribute to a bipolar signal with symmetric distribution of positive and negative impulses. Lenhardt et al. (56) reported quadratic increases in root-mean-square amplitude of the sEMG signal across force levels from 20, 40, 60, 80, and 100% of maximal voluntary contraction. Most PJT studies used sEMG to elucidate the general (neural vs. muscular) underlying neuromuscular mechanisms responsible for performance improvements (59). Changes in sEMG activity may reflect muscle activation phenomena of relevance for health (e.g., peripheral fatigue) (12), physical fitness, as well as athletic and sport-specific performance (25).

Plyometric jump training programs may induce neural adaptations (59), comprising either central or peripheral neural adaptations (59,73,82). For instance, Foure et al. (33) studied the effects of 14 weeks of PJT on activation of the gastrocnemius and soleus muscles using sEMG analysis in physically active males. The authors observed significant improvements in gastrocnemius and soleus sEMG activity and better jump performance, with no changes in the cross-sectional area of the triceps surae muscle. Similarly, Cormie et al. (16) examined the effects of 10 weeks of PJT with loaded squats on sEMG activity of the vastus medialis/lateralis in resistance-trained males. These authors reported an increase in the rate of sEMG activity in vastus medialis and vastus lateralis during the jump squat exercise, with concomitant improvements in sport-related tasks (e.g., jumping and sprinting), but no changes in body mass, muscle thickness, or leg lean mass (16). However, other studies were unable to show significant muscle activation adaptations after PJT (24,42,44,45,52,60,70,88). Moreover, from the aforementioned studies (16,33), 22 different sEMG-related outcome measures were collected, and ~60% of these measures did not reach the level of statistical significance. Furthermore, it is difficult to ascertain if training-related sEMG changes signify primarily peripheral (muscle action potential: M-wave) or central (e.g., corticospinal excitability) adaptations (28,32,82,85,86). Because neuromuscular electrical stimulation is not often included in PJT studies, it is uncommon to observe sEMG normalized to the M-wave to better delineate central vs. peripheral responses.

Considering the controversy from the aforementioned studies in relation to PJT and changes in sEMG-related muscle activation outcomes, and given the large number of studies on the effects of PJT on physical fitness and performance outcomes, it is time to systematically examine the PJT literature to describe training-induced changes in muscle activation assessed through sEMG and performance changes. Indeed, most previous PJT studies reported performance data such as jump height, sprint time, change-of-direction speed (4,21,76). Although these studies provide interesting information for strength and conditioning specialists and practitioners, they hardly allow us to elucidate the underlying neuromuscular mechanisms responsible for PJT-related performance increases. Accordingly, more studies are needed that use sEMG to further our knowledge on neuromuscular adaptive processes after PJT. Over the past years, a critical number of PJT studies have been published that used sEMG, which enabled us to aggregate findings in the form of a systematic review. Therefore, the aim of this systematic review was to analyze the effects of PJT on muscle activation assessed through sEMG and its relationship to strength and jumping performance in healthy trained and untrained populations across the lifespan.

Methods

Experimental Approach to the Problem

A systematic review was conducted following the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses statement (57).

Search Strategy

A systematic literature search was performed in the electronic databases PubMed/MEDLINE, Web of Science, and SCOPUS, from the inception of indexing until December 14, 2020. Keywords were collected through experts' opinion, literature reviews, and controlled vocabulary (e.g., Medical Subject Headings: MeSH). As an example, in PubMed/MEDLINE database, the following search syntax was used: ((((((((("randomised controlled trial"[Publication Type]) OR "controlled clinical trial"[Publication Type]) OR "randomised"[Title/Abstract]) OR "trial"[Title]) OR "clinical trials as topic"[MeSH Major Topic]) AND "training"[Title/Abstract]) OR "plyometric"[Title/Abstract])) AND "electromyography"[MeSH Terms])). After the initial search, accounts were created in the respective databases. Through these accounts, the lead investigator (R.R.C.) received automatically generated emails for updates regarding the search terms used. These updates were received on a daily basis (if available), and studies were eligible for inclusion until the initiation of article preparation. In selecting studies for inclusion, a review of all relevant article titles was conducted before an examination of article abstracts and then full-published articles. After the formal systematic searches, additional hand-searches were conducted. Gray literature sources, in the form of conference proceedings, were also considered, but only if a full article text was available. Secondary searches were performed by reviewing the reference lists of the included studies and previous reviews and meta-analyses to detect additional studies potentially eligible for inclusion. Two authors (R.R.C. and F.G.P.) conducted the process independently; discrepancies between the 2 reviewers were resolved through discussion and consensus.

Eligibility Criteria

The a priori inclusion criteria for this review were as follows: (a) RCTs that incorporated a PJT program which was defined as "lower-body unilateral or bilateral bounds, jumps, and hops that commonly use a prestretch or countermovement that includes the activation of the stretch-shortening cycle (14,64,73) and, less commonly, concentric-only jump actions" (76). The control group was typically an active or inactive matched group of subjects not involved in PJT. Trials that included PJT combined with another intervention (e.g., resistance training) were included in this systematic review if the study design contained an active control group as well and as long as the PJT intervention covered ≥50% of the combined training regime in the intervention (arbitrary criteria based on authors expertise); and (b) the study included a pre-to-post intervention assessment of muscle activation parameters (i.e., sEMG measure including but not limited to area, mean, and peak) during strength and jumping tasks. No restrictions were imposed for age or sex.

Exclusion Criteria

Articles were excluded if they were cross-sectional, a literature review, or a training-related study that did not focus on the effects of PJT exercises. Also excluded were retrospective studies, prospective studies, studies in which the use of jump exercises was not clearly described, studies for which only the abstract was available, case reports, studies with ambiguous study protocols, nonhuman investigations, special communications, duplicate references, letters to the editor, invited commentaries, errata, overtraining studies, and detraining studies. If the studies included a detraining component, we only considered the data obtained during the training period (i.e., results obtained before the detraining period). Finally, non-English language studies were not explored, as a previous scoping review (73) in the field of PJT observed that 99.6% of published studies are in English language, and the remaining studies may not be feasibly translated.

Data Extraction

From the included studies, data were extracted independently by 2 authors (R.R.C. and F.G.P.), using a template created in Microsoft Excel (Microsoft Corporation, Redmond, WA). Aside from response variables (details in the *Eligibility Criteria* section), extracted data included the following information: the first author's name, year of publication, PJT description, description of the control comparison, and number of subjects per group. We also extracted data regarding the subjects' sex, age (years), body mass (kg), height (m), and previous experience with PJT. If applicable, the type and level (e.g., professional and amateur) of sport practice were also extracted. The extracted data also included the frequency of training (days·wk^{-1}), duration (weeks), intensity level (e.g., maximal), and marker of intensity (e.g., jumping height), jump box height (cm), number of total jumps completed during the intervention (as some studies incorporated volumes based on distance or times [rather than repetitions], according to the reviewers experience in this field, each second or meter was considered equivalent to one jump repetition), types of jump drills performed, combination (if applicable) of PJT with another form of training type, rest time between sets (s), rest time between repetitions (s), rest time between sessions (hours), type of jumping surface (e.g., grass), type of progressive PJT overload (e.g., volume-based and technique-based), training period of the year (e.g., in-season), replace (if applicable) portion of the regular training with PJT, and tapering strategy (if applicable). A complete description of these PJT characteristics has been previously published (76).

Risk of Bias of Individual Studies

The Physiotherapy Evidence Database (PEDro) scale was used to assess the risk of bias and methodological quality of eligible studies included in the review. This scale evaluates internal study validity on a scale from 0 (high risk of bias) to 10 (low risk of bias). As in a similar previous PJT review (81), the quality assessment was interpreted using the following 10-point scale: ≤3 points was considered poor quality, 4–5 points as moderate quality, and 6–10 points as high quality. Two independent reviewers (R.R.C. and F.G.P.) performed this rating. Agreement between reviewers ($k = 0.91$) was verified using a Kappa correlation for risk of bias.

Statistical Analyses

Among the 17 included studies, a correlation analysis was conducted between changes in muscle activation and changes in strength and jumping performance. Analyses were conducted only for those studies showing pretraining to post-training data for both muscle activation and strength, jumping performance, measured simultaneously. Studies that did not report data (aside from *p*-values), or only reported data in graphs, were not included (5,43–45,83,84). In addition, 2 studies (61,87) were discarded as these applied muscle activation measurements during strength and/or jumping tests but did not report strength and/or jump performance data.

In studies that included different phases of the jump (e.g., preparatory, landing, and propulsive), with muscle activation measurements in each phase, the one resembling the "propulsive" phase was chosen because this was expected to be more highly associated with jumping height. When different strength tests were conducted (dynamic and isometric), isometric test were selected because these were more frequently applied in the included studies, thus allowing a set of less heterogeneous (more homogenous) testing protocols. When different muscles were assessed, the most relevant for jumping height or strength performance were selected (e.g., knee extensors over flexors). However, in some studies, although different muscles were assessed, data were reported only for some of them. In these cases, the most representative muscle was selected.

The raw data for the additional analyses can be found in Supplemental Digital Content 1 (see Table 1, http://links.lww.com/JSCR/A263). Data for both muscle activation and strength and jumping performance outcomes were parametric. Therefore, Pearson correlation coefficients were used to compute data between deltas in muscle activity and strength/jumping performance.

Results

Study Selection

Figure 1 provides a graphical schematization of the study selection process.

Through database searching, 6,926 records were initially identified from which 30 PJT studies included a muscle activation measure during the performance of a strength and jumping task in healthy individuals aged 13–73 years. From these, 2 reported repeated data (15,16), one used a potentially inappropriate control group (i.e., cross-training effect/interaction between legs trained unilaterally) (51), 6 did not provide sEMG measures related to strength or jumping tasks (9,24,33,42,70,88) and another did not use a control group (38). Two studies, although controlled, did not incorporate a randomization procedure (39,54). One potentially eligible article was published in a discontinued journal, and after contact was established with the

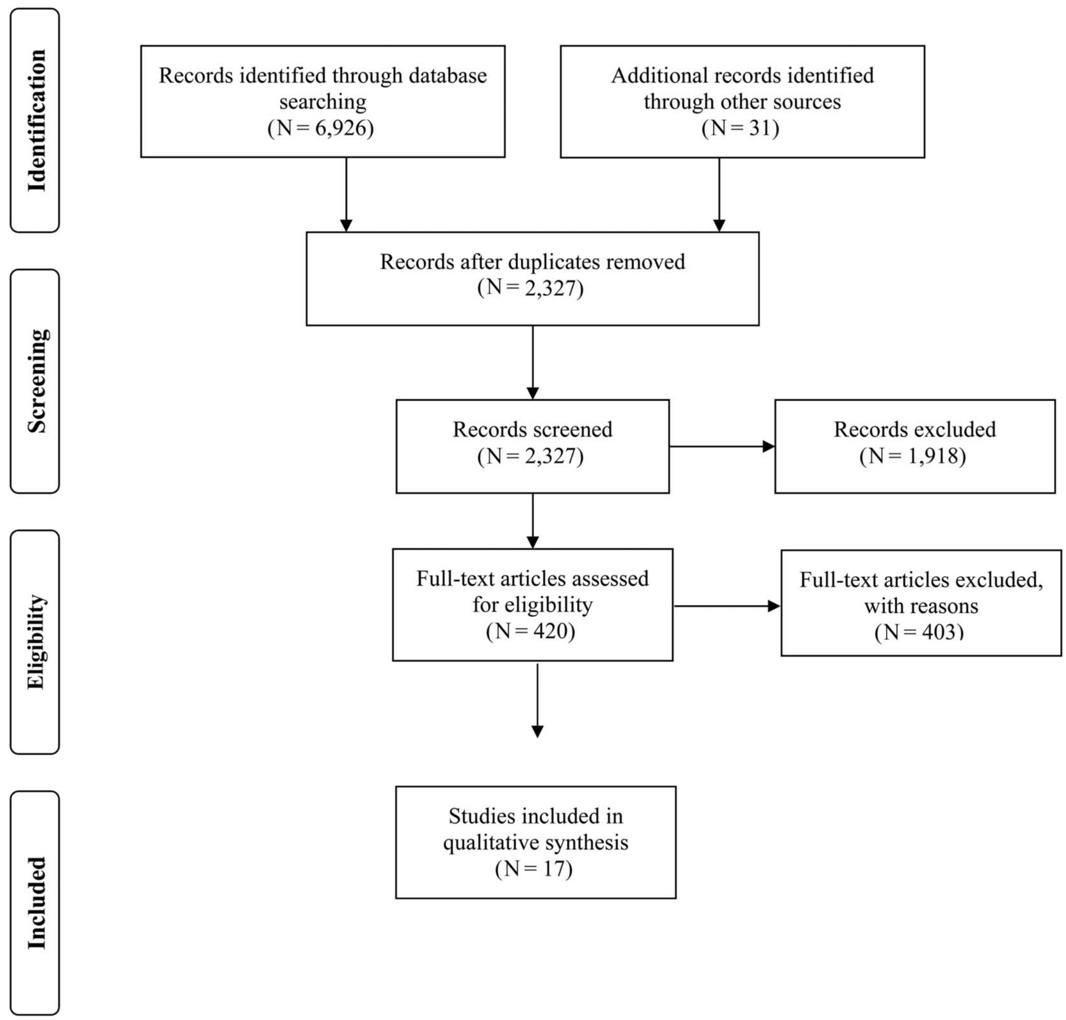

Figure 1. PRISMA flow diagram.

corresponding author, no response was received (53). Finally, 17 studies were eligible for this systematic review (3,5,6,13,16,17,40,43–45,52,60,61,79,83,84,87). They comprised 23 experimental groups and 266 subjects.

Of note, a meta-analysis was considered a priori. However, the included studies displayed high heterogeneity (34) of muscle activation measurement protocols and outcomes (e.g., dynamic vs. isometric muscle actions, gastrocnemius vs. vastus lateralis muscle analyzed, concentric vs. eccentric muscle action, and maximal vs. submaximal effort). More detailed information regarding sEMG measurement protocols is provided in Supplemental Digital Content 2 (see Table 2, http://links.lww.com/JSCR/A264). Therefore, because of the clinical and statistical diversity of the included studies, as well as the potential for a high risk of bias, a meta-analysis was not undertaken. Under such circumstances, a meta-analysis may be compromised and genuine differences in effects may be obscured (23). Decisions concerning what should and should not be combined are inevitably subjective, requiring discussion and clinical judgment (23). The consensus of the group of authors of this article is that the PJT interventions and muscle activation measurement protocols and assessed outcomes were not sufficiently similar to allow a meta-analysis. Relatedly, another shortcoming observed among the included studies in this review was the lack of numerical data reporting. Of note, 10 studies (from a total of 17) reported results in graphical form, which makes the calculation of an accurate effect size difficult.

Study Characteristics

The characteristics of the study subjects and the programming parameters of the PJT interventions are displayed in Table 1.

Methodological Quality Within Studies

The methodological quality of the included studies was moderate-to-high with a median PEDro score of 6, interpreted as high quality (Table 2).

Adverse Effects

Regarding adverse effects, only one study (45) reported one (older) subject (from a total of 10) who developed pain in the Achilles tendon, possibly because pf overuse through training (Achilles tendon tendinitis). Of the remaining 16 studies, none reported any evidence of significant soreness, pain, fatigue, injuries, damage, or any adverse events that resulted in abstinence

Table 1
Characteristics of jump training programs and of included study subjects.*†‡

	n	G	A	BM	H	SPT	Sport	Fitness	Freq	Wk	I	BH	TJ	Type	Comb	RBS	RBR	RBTS	Surf	PO	TP	R	Ta
Arabatzi et al. (3)	9 (half-squat RT) 10 (multiexercise RT)	M	20.3	85.2	184.8	No	NR	Moderate	3	8	NR	NA	2,376	Comb	RT	NR	NR	NR	NR	Comb	NA	NA	No
Behrens et al. (6)	14	Comb	24.4	77.7	180.5	No	NA	Normal	3	6	Max	NR	1,002	Comb	No	180	10	NR	NR	V	NA	NR	No
Behrens et al. (5)	13	Comb	24	77	183	No	Volleyball	Normal–moderate	2	8	Max	40	972	Comb	No	90	4	NR	NR	V	NR	No	No
Chimera et al. (13)	9	F	20	59.2	164.5	No	Team sports	Moderate–high	2	6	Max	45	3,940 rep +1,680 s	Comb	No	30–120	NR	NR	NR	Comb	OS	A	No
Cormie et al. (16)	8 (trained) 8 (untrained)	M	23.4	79.1 79.9	179.3	NR	NR	NR	3	10	Individualized	NA	1,090	Loaded jump squats	No	180	NR	≥24	NR	Power-based	NR	Yes No	No
Correa et al. (17)	14	F	67	NR	158	No	NA	NR	2	6	Max	10–30	630 s	Lateral box jump	RT	NR	NA	NR	NR	V	NA	NR	No
Hammami et al. (40)	14 (RT) 14 (no RT)	M	16.1 15.7	59 58.9	177 175	NR NR	Soccer	Moderate	2	8	NR Max	NA 50–70	1,440 722	Comb Comb	RT + sprints No	NR	NR 5	48 to 120	NR Tartan track	No Comb	IS IS	Yes Yes	Yes No
Hirayama et al. (43)	11	M	22	66.9	172	No	Active	Normal	3	12	Max	Optimal	3,600	Comb	No	30	NA	NR	Force plate	No	NA	NR	No
Hoffman et al. (44)	15 (SSC- load) 16 (concentric-load)	M	19.8	100 101.2	181.7 185.8	No	American football	Moderate–high	2	5	70% 1RM squat	NA	160	Loaded jump squat	No	180	NR	≥48	Jump apparatus	No	OS	No	No
Hoffren-Mikkola et al. (45)	10	M	73.1	76.8	170.5	No	NA	Older (active)	3	11	75–90% peak vertical GRF	NA	1,980 s	Hops	No	60–300	NA	48–72	NR	V	NA	NR	No
Kyrolainen et al. (52)	13	M	24	77.9	178	No	NA	Moderate	2	15	Max	20–70	2,400–5,400	Comb	No	NR	NR	NR	NR	V	NA	A	No
McKinlay et al. (60)	13	M	12.6	47.2	157.8	No	Soccer	Moderate	3	8	Max	NR	3,438	Comb	No	60–180	NR	NR	NR	Comb	NR	Yes	No
Mirzaei et al. (61)	9 (DJ) 9 (CMJ)	M	20.5 20.6	70.6 69.5	180.6 176.5	NR	NR	NR	2	6	Max (RSI) Max (height)	45 NA	1,200	DJ CMJ	No	120	8	72	Sand	No	NR	NR	No
Silva Correa et al. (79)	16	F	67	NR	158.1	No	NA	NR	2	6	Max	10, 20, 30	630 s	Comb	RT	120	NA	48	NR	Comb	NA	NA	No
Taube et al. (83)	11 (combined drop box heights) 11 (30-cm drop box height)	Comb	24 25	68 69	177 179	No	Team sports	Normal–moderate	3	4	Max (RSI)	30–75 30	396	BDJ	No	600	10	NR	NR	V	NR	A	No
Toumi et al. (84)	8	M	20	78	180	NR	Handball	Moderate–high	4	6	NR	35	720	Comb	No	180	3	≥24	NR	No	PS	No	No
Wu et al. (87)	11	M	22.1	65.8	174.4	NR	NA	Low	2	8	Comb	45	1,440	Comb	No	30–120	NR	NR	NR	Comb	NA	NA	No

*G = gender; A = age of subject (years); BM = body mass (kg); H = height of subjects (cm); SPT = systematic plyometric jump training experience before the intervention; Freq = frequency of training ($d\cdot wk^{-1}$); Wk = weeks of training; I = intensity of training; BH = box height for plyometric drop jumps (cm); TJ = total number of jumps; Type = type of jump drill; Comb = combined; RBS = rest between sets and/or exercises (seconds); RBR = rest between repetitions (seconds); RBTS = rest between training sessions (hours); Surf = surface type; PO = progressive overload, in the form of either volume, intensity, type of jump drill, or a combination of these; TP = training period of the season; R = replacement of habitual training drills with plyometric jump training drills; Ta = taper; RT = resistance training; M = male; NR = nonreported; NA = not applicable (in the case of RBR, this means that all jumps were performed continuously in a given set); V = volume; N = number of subjects; Max = maximal; OS = off-season; IS = in-season; Optimal = regarding the RSI; SSC = stretch-shortening cycle; GRF = ground reaction force; DJ = depth jump; CMJ = countermovement jump (cm); RSI = reactive strength index (ms/ms); F = female.

†For max (i.e., maximal), this involved either maximal effort to achieve maximal height, distance, reactive strength index, velocity, or another marker of intensity.

‡When "comb" is indicated, this involved a combination of 2 or more of the following jumping drills: vertical, horizontal, bilateral, unilateral, repeated, nonrepeated, lateral, cyclic, sport-specific, slow stretch-shortening cycle, and fast stretch-shortening cycle.

Table 2
Physiotherapy Evidence Database (PEDro) scale ratings.

	N° 1*	N° 2	N° 3	N° 4	N° 5	N° 6	N° 7	N° 8	N° 9	N° 10	N° 11	Total (from a possible maximal of 10)
Arabatzi et al. (3)	1	1	0	1	0	0	0	1	1	1	1	6
Behrens et al. (6)	1	1	0	1	0	0	0	1	1	1	1	6
Behrens et al. (5)	1	1	0	1	0	0	0	1	0	1	1	5
Chimera et al. (13)	1	1	0	1	0	0	0	1	0	1	1	5
Cormie et al. (16)	1	1	0	1	0	0	0	1	1	1	1	6
Correa et al. (17)	1	1	0	1	0	0	0	1	1	1	1	6
Hammami et al. (40)	1	1	0	1	0	0	0	1	1	1	1	6
Hirayama et al. (43)	1	1	0	1	0	0	0	0	1	1	1	5
Hoffman et al. (44)	1	1	0	1	0	0	0	1	1	1	1	6
Hoffren-Mikkola et al. (45)	1	1	1	1	0	0	0	1	1	1	1	7
Kyrolainen et al. (52)	1	1	0	1	0	0	0	1	1	0	1	5
McKinlay et al. (60)	1	1	0	1	0	0	0	1	1	1	1	6
Mirzaei et al. (61)	1	1	0	1	0	0	0	1	1	1	1	6
Silva Correa et al. (79)	1	1	0	1	0	0	1	1	1	1	1	7
Taube et al. (83)	1	1	0	1	0	0	0	1	1	1	1	6
Toumi et al. (84)	1	1	0	1	0	0	0	1	1	1	1	6
Wu et al. (87)	1	1	0	1	0	0	0	1	1	1	1	6

*PEDro scale items. A detailed explanation for each PEDro scale item can be accessed at https://www.pedro.org.au/english/downloads/pedro-scale.

from the PJT programs. In one study (13), a potential reduction of injury risk was noted after PJT.

Main Results

Table 3 displays the results for the items considered for data extraction from the eligible articles. The complete list of muscle activation and physical fitness data, as well as the magnitude and significance level of changes between pre-to post-PJT, is available as Supplemental Digital Content 1 (see Table 1, http://links.lww.com/JSCR/A263).

Significant muscle activation–related improvements were reported among most (13 from 17) included studies after a PJT intervention. Specifically, improvements were reported in 7 of 10 studies for measures of muscle activation during the performance of strength tasks and in 6 of 10 studies for jumping tasks. Moreover, in a secondary analyses including 4 studies with 7 experimental groups (3,13,16,40) that examined muscle activation parameters (i.e., sEMG) during jumping, statistically significant and high correlations ($r = 0.86$; $p = 0.012$; $r^2 = 0.74$) were noted between changes in sEMG and changes in jump performance. Conversely, such a relationship was not observed among 5 studies (6,17,52,60,79) that examined muscle activation parameters during strength tasks ($r = -0.28$; $p = 0.654$; $r^2 = 0.08$). A more detailed explanation regarding the different types of strength tests that were applied in the included studies can be found in Table 3. Moreover, from the total number ($n = 287$) of muscle activation response variables analyzed across the included studies, ~80% ($n = 226$) were reported as nonsignificant when compared with a control condition Supplemental Digital Content 1 (see Table 1, http://links.lww.com/JSCR/A263). Particularly, nonsignificant improvements were reported in ~70% (47 of 66) and ~80% (179 of 221) of the muscle activation response variables assessed during the performance of strength and jumping tasks, respectively.

Discussion

The aim of this systematic review was to analyze the effects of PJT on muscle activation assessed through sEMG during the performance of strength and jumping tasks in healthy trained and untrained populations aged 13–73 years. Seventeen randomized controlled trials were eligible for this systematic review. The included studies comprised 23 experimental groups and 266 subjects involved in PJT interventions. There was substantial variability in the type of outcome measures used across the studies in this review, including divergent measurement protocols (e.g., dynamic vs. isometric muscle actions, gastrocnemius vs. vastus lateralis muscles, concentric vs. eccentric phase of movement, and maximal vs. submaximal effort). In addition, there was substantial variability in the characteristics of the PJT programs (e.g., total volume of 160 vs. 5,620 jumps) and among the recruited subjects (e.g., age 13 vs. 73 years, trained vs. untrained).

Most published PJT studies reported positive effects on physical fitness, functional performance, and injury prevention (59,76). The beneficial effects of PJT are usually attributed to increased neural drive to the agonist muscles (i.e., intramuscular coordination) and/or improved intermuscular coordination (e.g., agonist, synergistic, and antagonist interaction) (59,73). Indeed, such muscle activation adaptations may allow an increase in muscle performance (29). Moreover, in this systematic review, significant PJT-related improvements were reported for measures of muscle activation during the performance of strength and jumping tasks in 13 of the 17 included studies. More specifically, improvements were reported in 7 of 10 studies for measures of muscle activation during the performance of strength tasks and in 6 of 10 studies for jumping tasks. Moreover, a secondary correlational analysis showed significant positive relationships between changes in muscle activation and changes in jump performance. However, such a relationship was not observed between changes in muscle activation and changes in strength parameters. Moreover, from the total number ($n = 287$) of muscle activation response variables analyzed for strength and jumping tasks, ~80% ($n = 226$) were reported as nonsignificant when compared with a control condition.

In the next sections, we discuss the significant (and nonsignificant) effects of PJT interventions on muscle activation during the performance of strength and jumping tasks reported in the included studies. In addition, a discussion of the potential influence of subjects and PJT programs characteristics on these findings follows. Also follows a discussion regarding some

Table 3
Summary of results from eligible studies.*

Studies examining muscle activation parameters (EMG) during jumping tasks	
Arabatzi et al. (3)	Reduced/increased RF EMG and reduced/increased gastrocnemius EMG in the eccentric phase of the CMJ was noted, whereas in the concentric phase, a reduction was noted in the gastrocnemius EMG.
Chimera et al. (13)	From 40 EMG-related outcomes derived from 6 different muscles (i.e., VM, VL, medial hamstrings, lateral hamstrings, hip abductors, and hip adductors), only 4 showed a significant change during a drop jump.
Cormie et al. (16)	An increase in the rate of EMG rise in the VM and VL during a jump squat was noted. Adaptations were similar in trained (stronger) and untrained (weaker) subjects.
Hammami et al. (40)	An increase was observed in VM and RF EMG during the SJ and CMJ.
Hirayama et al. (43)	The EMG of the triceps surae increased in the 1st and 2nd phase of a DJ test, with a decrease in the 3rd phase and no change in the 4th phase, whereas the tibialis anterior EMG decreased in the 1st, 2nd, and 4th phase, without changes in the 3rd phase. Note: 1st and 2nd phase denote breaking phases and 3rd and 4th phases denote propulsive phases (determined with force plate).
Hoffman et al. (44)	No changes were noted among the analyzed EMG-related outcomes during a squat jump.
Hoffren-Mikkola et al. (45)	No changes were noted among the analyzed EMG-related outcomes, including the soleus, gastrocnemius medialis, gastrocnemius lateralis, and tibialis anterior muscles of the right leg during a 2-legged hoping 10-second test.
Kyrolainen et al. (52)	No changes were noted among the analyzed EMG-related outcomes for the VL, VM, gastrocnemius, soleus, and tibialis anterior muscles, from a 50-cm drop jump.
Taube et al. (83)	From 114 muscle activation outcomes, 15 showed significant change, including greater soleus muscle activity in the early duration of DJ ground contact (20–70 ms), and RF and soleus muscles activity in the later phases of ground contact (70–120 and 120–170 ms).
Toumi et al. (84)	The EMG of the VL + VM muscles increased during the transition phase, and transition + concentric phase of the CMJ, in line with an increased EMG ratio between VL + VM/BF muscles during the transition phase of the CMJ.
Studies examining muscle activation parameters (EMG) during strength tasks	
Behrens et al. (6)	An increase in voluntary EMG activation during isometric, concentric, and eccentric MVC was noted. Normalized muscle activity of the quadriceps during isometric and eccentric MVC was improved.
Behrens et al. (5)	Changes were noted in muscle activation during an isometric maximum voluntary torque test at 80° of knee flexion.
Cormie et al. (16)	No changes in VM, VL, or BF muscle activation were noted during an isometric squat.
Correa et al. (17)	Maximal muscle activation of VL and VM were increased during an isometric maximal leg press test. Muscle onset latency was reduced in the RF.
Kyrolainen et al. (52)	No changes were noted among the analyzed EMG-related outcomes for the VL, VM, gastrocnemius, soleus, and tibialis anterior muscles, from a bilateral isometric MVC test for knee extensors and plantar flexors.
McKinlay et al. (60)	No changes were noted among the analyzed EMG-related outcomes during a MVC knee extension test (isometric and dynamic).
Mirzaei et al. (61)	An EMG increase of the VL and RF was observed in an isometric MVC knee extension test.
Silva Correa et al. (79)	An EMG increase of the VL and VM was observed in an isometric MVC test. The rate of rise of the EMG of the RF and VM at 25 and 50% of body mass were reduced (i.e., better muscle economy).
Toumi et al. (84)	No changes observed in VM + VL muscle activation during the leg press test.
Wu et al. (87)	An EMG increase was observed in the soleus (not gastrocnemius) muscle during an isometric plantarflexion test.

*EMG = electromyography; RF = rectus femoris; VM = vastus medialis; VL = vastus lateralis; SJ = squat jump; CMJ = countermovement jump; DJ = drop jump; BF = biceps femoris; MVC = maximal voluntary contraction.

methodological issues among the included studies (e.g., validity of methods, difficult to measure sEMG during dynamic exercise, lack of long-term sEMG-related gold standards, and focus on muscle activation outcomes instead of mechanical-anatomical) that may be related to these novel findings.

Sex of Subjects

From the 17 studies included, 11 recruited male subjects, 3 combined male and female subjects, and 3 recruited females.

Males. Arabatzi et al. (3) reported that PJT combined with half squats reduced rectus femoris sEMG activity and increased gastrocnemius sEMG activity during the eccentric phase of the countermovement jump (CMJ). The same authors reported (3) that combined PJT with a multimodal resistance training program (including Olympic lifts) increased rectus femoris sEMG activity and reduced gastrocnemius sEMG activity during the eccentric phase of a CMJ. Both trained groups experienced reduced activity of the gastrocnemius in the concentric phase of the CMJ. In handball players (84), 6 weeks of PJT induced increased sEMG activity of the vastus lateralis and vastus medialis muscles during different phases (e.g., transition concentric) of the CMJ, in line with an increased sEMG ratio between the vastus lateralis and vastus medialis/biceps femoris muscles during the transition phase of the CMJ. In active male subjects, Hirayama et al. (43) reported an increase in sEMG activity of the triceps surae during the first and second phases of a drop jump test (braking phases), with a decrease during the third phase (propulsive phase), whereas tibialis anterior sEMG activity decreased during the first, second, and fourth phases after 12 weeks of PJT. Similarly, in older male subjects (45), no significant changes were noted in gastrocnemius medialis sEMG activity in the braking-over push-off phase ratio in a 10-second hopping test at 50, 75, and 100% of maximal intensity after 11 weeks of PJT.

With the investigation of non–stretch-shortening cycle activities such as the squat jumps, Cormie et al. (16) noted an increase in the rate of sEMG activity rise in the vastus medialis and lateralis during a squat jump, with similar results in trained (stronger) and untrained (weaker) subjects after 10 weeks of PJT. In male soccer players, combined PJT with resistance training significantly increased vastus medialis and rectus femoris sEMG activity during the squat and CMJ. These training-induced changes were not found in a similar cohort that completed single-mode PJT alone (40). In male American football players (44), 5 weeks of either concentric-only or stretch-shortening cycle jumps induced no significant changes in maximal or mean sEMG amplitude of the vastus lateralis during a squat jump at 70% of the 1 repetition maximum.

When examining strength variables, among physically active males, 6 weeks of either CMJ-based or drop jump–based PJT (on sand) induced an increase in the sEMG activity of the vastus lateralis muscle during an isometric maximal voluntary strength knee extension test, in conjunction with an increase in the sEMG activity of the rectus femoris muscle (61). In male subjects with low initial fitness level, sEMG activity increased in the soleus muscle, during an isometric contraction of the plantar flexors, with no changes in the gastrocnemius muscle, after 8 weeks of training (87). Among male soccer players, no significant changes were observed in any sEMG-related outcome obtained from the vastus lateralis muscle, either during a maximal isometric or dynamic knee extension test (60). Furthermore, in young physically active males, no changes were noted among the analyzed sEMG-related outcomes after 15 weeks of PJT (52), including the gastrocnemius, soleus, vastus lateralis, vastus medialis, and tibialis anterior muscles, during either maximal isometric contractions or a dynamic drop jump test. Overall, among males, the evidence is mixed, with no clear pattern of muscle or exercise type emerging.

Females. Among team sport athletes, most (90%) of the sEMG-related outcomes showed no significant changes after 6 weeks of PJT (13), including vastus medialis, vastus lateralis, medial hamstrings, lateral hamstrings, hip abductor, and hip adductor muscles, during the preparatory and reactive phases of a drop jump test. Correa et al. (17), after 6 weeks of PJT, reported varied results with increased sEMG activity in the vastus lateralis and medialis muscles, but not in the rectus femoris muscle, during a maximal isometric leg press. In another study, 6 weeks of combined PJT with resistance training (79) resulted in sEMG increases of the vastus lateralis and vastus medialis muscles during the performance of an isometric maximal voluntary contraction. The same study (79) revealed a diminished slope in the sEMG signal of rectus femoris and vastus medialis muscles during a sit-to-stand test. The authors interpreted this change as improved muscle economy.

Males and Females Combined. Behrens et al. (6) reported an increase in sEMG activity during isometric, concentric, and eccentric maximal voluntary contractions. From the same research group (5), an increase was noted during an isometric maximum voluntary test at 80° of knee flexion, including maximal muscle activation and muscle activity at 50–100 ms. Taube et al. (83) showed that from 114 muscle activation outcomes, only 15 showed significant changes among PJT subjects.

Overall, in the studies conducted with either male or female subjects, although most of them reported significant effects of PJT on muscle activation during strength and jumping tasks, the mean percentage of muscle activation outcome measures that did not reach significance was ~70% for male and ~58% for female subjects. Therefore, regardless of sex, it is striking that most of the muscle activation outcomes analyzed in the studies included in this review demonstrated no significant changes. It is possible that certain limitations related to assessment techniques (e.g., sensitivity of the equipment used to measure sEMG, use of portable vs. nonportable equipment, adequate selection of muscles type of action, lack of multiple surface electromyograms, and dynamic vs. isometric actions), among others (28,32,49,55,59,77,85,86), may help to explain the high prevalence of muscle activation outcomes not responsive to PJT. Furthermore, the sEMG-force relationship is best described as curvilinear with a plateau starting at the near maximal force range (8,68), which diminished its sensitivity to change with maximal or near maximal contractions.

Age of Subjects

Recent studies have pointed out the relevance of subjects' age, which can directly affect coaches' programming decisions for PJT (58,62,64,66,72). In the current review, the age of the subjects ranged between 13 and 73 years, with a mean age of ~28 years. Of note, just 2 studies included youth subjects (40,60), 3 studies included older subjects (17,45,79), and the remaining studies included subjects between 20 and 25 years of age. Among youth subjects, McKinlay et al. (60) showed no significant changes in any muscle activation outcome measure after 8 weeks of PJT. In the other study conducted with youth subjects, most (~66%) of the sEMG-related outcomes were not significantly changed after 8 weeks of PJT (40). Moreover, an study (40) that examined the effects of combined PJT with resistance training in young (~16 years) showed significant sEMG increases in vastus medialis and rectus femoris activities during the performance of the squat and CMJ which was not the case for subjects who followed a single-mode PJT program (40). Similar results were found for older subjects aged ~73 years (45). Single-mode PJT did not result in significant sEMG changes after 11 weeks of training. Again, combined PJT and resistance training produced significant sEMG increases in vastus lateralis, vastus medialis, and rectus femoris activities in older subjects aged ~67 years (17,79).

Among young adults, 2 studies found no significant adaptations in muscle activation outcomes after PJT (44,52), whereas in the remaining 10 interventions undertaken in young adults, significant effects of PJT were observed on muscle activation during strength and jumping tasks. However, the percentage of the total muscle activation outcomes analyzed that achieve a significant change was ~36%. It is probable that the selection of a large number of outcome measures nonsensitive to PJT may at least partially explain this relatively low percentage of muscle activation outcomes reaching a significant PJT effect.

Of practical relevance, the combination of PJT with RT may increase the likelihood of finding significant changes in muscle activation assessed through sEMG in both, young and old individuals. However, care has to be taken because of the limited number of studies available for young and older subjects.

Accordingly, it is difficult to draw definite conclusions on the effects of PJT on muscle activation assessed through sEMG in these populations.

Sports Practice

Among the studies that involved trained populations, 2 failed to report any significant muscle activation adaptations (44,60), with the remaining 5 studies reporting significant muscle activation adaptations, although only in ~20% of the analyzed outcomes. Among those studies that did not report a sport-related background for the subjects, 2 reported no significant adaptations (45,52), with the remaining 8 studies reporting significant muscle activation adaptations, although only in ~51% of the analyzed outcomes. Summarizing, muscle activation adaptations seem more readily achievable in subjects with no previous participation in sports (i.e., lower fitness and reduced previous experience with PJT). It seems reasonable to assume that among athletes, a ceiling effect may be attained after years of intensive training, with further improvements to muscle activation function requiring a relatively long period of time to achieve, particularly in the lower limbs (36). Relatedly, the studies that recruited athletes applied PJT interventions that lasted no more than 8 weeks, and it is plausible that a longer training intervention could induce adaptations (81). Indeed, training duration seems to be a common issue in the PJT literature; as a recent review reported that although PJT duration ranged from 2 to 96 weeks, most studies applied ≤7 weeks of training, with a mean of ~8 weeks (73). The identification of PJT dose-response relations, which elicit optimal training effects in athletes, still need to be examined particularly in the long term.

Total Number of Plyometric Jump Training Sessions

Although a meta-analysis was not included in the current review (please refer to the results section for further details), as in previous PJT reviews and meta-analyses (63,65,67), when the studies were divided using the median split technique, some of the included studies in this review applied <16 sessions (13,17,44,61,79,83), with one study (44) reporting no significant changes in sEMG-related outcomes, and the remaining 5 studies reporting significant effects of PJT on muscle activation during strength and jumping tasks, although only in ~48% of the muscle activation outcomes analyzed. Among the 11 studies that applied ≥16 sessions (3,5,6,16,40,43,45,52,60,84,87), no significant changes were noted in 3 studies (45,52,60), with significant effects observed among the remaining 8 studies, although only in ~33% of the muscle activation outcomes analyzed. Moreover, among those studies that applied ≥8 weeks of PJT, no significant changes were noted in 3 studies (45,52,60), with significant muscle activation changes noted in the remaining 6 studies (3,5,16,40,43,87), although in only 38% of the analyzed variables. Among studies with PJT interventions of <8 weeks (6,13,17,44,61,79,83,84), one study (44) reported no significant changes in sEMG-related outcomes, with the remaining 5 studies reporting significant effects of PJT on muscle activation during strength and jumping tasks, although only in ~40% of the muscle activation outcomes analyzed. Therefore, from the 17 studies analyzed in this review, involving total durations between 4 –15 weeks and 10–36 total sessions, the total number of weeks or sessions showed no clear relationship with the effects of PJT on muscle activation during strength and jumping tasks. It remains to be elucidated how longer-term PJT interventions might affect muscle activation.

Muscle Activation Adaptations and Physical Fitness

Only a few of the included studies reported correlation analyses between pre-post changes (deltas) in muscle activation and adaptations in strength and jumping tasks performance. For example, Kyrolainen et al. (52) observed training-induced increases in muscle activity of the plantar flexors after 15 weeks of PJT. The examined changes in sEMG activity correlated well with the observed improvements in maximal isometric voluntary contraction ($r = 0.59–0.77$). However, Wu et al. (87) found no significant correlations between the training-related changes in muscle activation outcomes (i.e., planter flexors muscles sEMG activity) and jumping height. Moreover, in the study of McKinlay et al. (60), the authors reported no significant correlations between the changes in peak rate of torque development and deltas in the rate of muscle activation. Contrasting findings were also noted in a secondary analysis included in our review, with significant and high correlations ($r = 0.86$; $p = 0.012$; $r^2 = 0.74$) noted between changes in sEMG and changes in jump performance, although such a relationship was not observed among studies that examined muscle activation parameters during strength tasks ($r = -0.28$; $p = 0.654$; $r^2 = 0.08$). Accordingly, more research is needed in this area to examine the correlates between muscle activation changes after PJT and changes in strength and jumping performance.

Studies With No Response in Muscle Activation Outcome Measures. Among the studies that demonstrated no significant changes in muscle activation outcomes (44,45,52,60), improvements in physical fitness were noted, including 1 repetition maximum strength, squat and power clean, maximal isometric force-torque, rate of force development, greater vertical jump height, moment and power, as well as for reactive strength index during a 10-s hopping test at different intensities.

Studies With Low Responsiveness of Muscle Activation Outcome Measures. The use of drop jumps as a dependent variable is quite common in the literature. For example, Taube et al. (83) showed that although ~87% of the muscle activation outcomes analyzed did not show a significant change, subjects who combined different drop jump heights during PJT showed greater sEMG activity in the rectus femoris and soleus muscles in the later phases of drop jump ground contact (70–120 and 120–170 ms), whereas a PJT intervention using only 30-cm drop jumps induced muscle activation outcomes changes exclusively in the soleus muscle in the early duration of drop jump ground contact (20–70 ms). Such differences in muscle activation adaptations between groups (83) were in line with different adaptations in a drop jump test, with a group that used varied drop heights improving performance in drop jump height, contrasting with the results of a single drop height group, which improved (reduced) drop jump ground contact times. With both groups achieving similar gains in reactive strength index, the differing adaptations to varied jump protocols suggest that jumps of varying characteristics must be used to elicit the most comprehensive response to PJT. Of note, in the study of Taube et al. (83), although both groups of subjects used drop jumps, from the 57 sEMG-related outcomes measures assessed in each trained group, ~87% of such outcomes demonstrated no significant change, suggesting that drop jumps, despite inducing some specific muscle activation adaptations, may not be capable of further enhancements. Such observation may help to reinforce the notion that jumps of varying characteristics are needed for greater adaptations to PJT.

Studies that focused on CMJ, such as that by Toumi et al. (84), demonstrated that only ~21% of the analyzed muscle activation outcomes significantly changed after PJT, despite CMJ significantly improving by around 13%. In addition, Wu et al. (87) found significant increases in vertical jump height and soleus sEMG although the increases in muscle activation levels were not correlated to the augmented performance. Behrens et al. (6) reported that after 6 weeks of PJT, although only ~20% of muscle activation outcomes responded to the intervention, all the analyzed physical fitness outcomes showed improvements (i.e., CMJ, isometric, concentric, and eccentric torque). Another study from the same research group (5) also showed improvements in only ~17% of the muscle activation outcomes analyzed, although significant improvements were noted in all dynamic maximal-intensity outcomes undertaken (i.e., CMJ and squat jump height), in addition to isometric maximum voluntary torque, rate of force development, and impulse at 80° of knee flexion. Chimera et al. (13) showed that 90% of the muscle activation outcomes analyzed did not attain a significant change, in line with no changes in vertical jump or sprinting abilities.

In a study by Correa et al. (17), the maximal dynamic strength of the knee extensors was increased in addition to improvements in reaction time, rate of force development, vertical jumping, and functional performance (30-s sit-to-stand test). This occurred alongside increases in the maximal muscle activation of the vastus lateralis and medialis muscles (but not from the rectus femoris) and reduced muscle onset latency in the rectus femoris (but not from the vastus lateralis or medialis). Arabatzi et al. (3) demonstrated that subjects who used PJT combined with half squats or a multimodal resistance training improved squat jump height (~14%), with no significant sEMG changes in rectus femoris or gastrocnemius during the performance of the squat jump.

In a study that analyzed the effects of PJT in trained (stronger) and untrained (weaker) individuals (16), although only ~17% of the muscle activation outcomes analyzed achieved a significant change, most physical fitness outcomes were improved including 5–40-m sprint speed, vertical jump height, and indexes of vertical jump performance (power, force, velocity, acceleration, and impulse). Hammami et al. (40) examined the effects of single-mode PJT versus combined PJT with resistance training and observed that single-mode PJT improved linear sprint, change-of-direction speed, and jump performance, without concomitant sEMG changes. The combination of PJT with resistance training improved performance measures (linear sprint, change-of-direction speed, jump performance, and 1 repetition maximum) and sEMG activity of vastus medialis and rectus femoris muscles (40).

Studies With High Responsiveness of Muscle Activation Outcome Measures. From the studies included in this review, only 3 (43,61,79) reported significant changes for most (14 of 18) of the analyzed muscle activation outcomes. Hirayama et al. (43) reported that the sEMG activity of the triceps surae and tibialis anterior showed significant changes in different (e.g., braking and propulsive) phases of a drop jump, in line with increases in drop jump impulse and reduced contact time. Furthermore, another study observed an increase in sEMG activity of the vastus lateralis and rectus femoris during an isometric maximal voluntary contraction of the knee extensors, in line with improved CMJ (61). Another PJT intervention (79) showed an increase in the sEMG activity of the vastus lateralis and medialis in an isometric maximal voluntary contraction test, in addition to sEMG changes indicative of better muscle economy (i.e., reduced rate of rise of the sEMG signal in the rectus femoris and vastus medialis at 25–50% of body mass), in line with improvements in isometric force and the 30-second sit-to-stand test. Examination of these 3 studies does not reveal any particularly unique characteristics in comparison with nonresponsive studies. Thus, it is difficult to pinpoint training program characteristics that would provide a greater certainty for positive muscle activation adaptations.

In summary, it is commonly assumed that PJT-induced changes in human muscle function and performance have a neural origin (59). However, taking the evidence derived from the included studies together it is clear that muscle activation adaptations are not consistently related to improved strength and jumping tasks. It is possible that other adaptations, such as mechanical (e.g., musculotendinous stiffness) (87), motor skill (e.g., joint angle and intermuscular coordination) (3), anatomical (e.g., muscle fiber pennation angle) (59), or hypertrophy-related (37), may help to explain the improvements in physical fitness after PJT when muscle activation outcomes displayed no significant changes. Alternatively, certain limitations related to assessment techniques, such as the sensitivity of the equipment used to measure sEMG, inadequate selection of muscles type or action, lack of multiple surface electromyograms, and among others (28,49,55,59,77,85,86), may also help to explain the commonly observed high proportion of sEMG-related measures nonresponsive to PJT. In addition, nonoptimal PJT prescription might be a potential reason for the high prevalence of nonresponsive muscle activation outcomes. Relatedly, a recent scoping review (73) pointed toward the need to improve the quality of PJT intervention studies, with insufficient reporting of training prescription among ~55% of overall PJT studies. From the included studies in this review, none considered all of the key PJT prescription variables (e.g., intensity, progressive overload, and recovery between jumping efforts), thus, making nonoptimal PJT prescription a potential reason for the high prevalence of nonresponsive muscle activation outcomes.

Shortcomings in the Literature and Future Recommendations

Among the selected studies, many response variables were assessed. This issue seems common in the PJT literature. In a previous review (73), it was reported that from 242 studies, 3,982 dependent variables were measured, yielding ~17 response variables per study. Relatedly, 287 sEMG muscle activation response variables were analyzed across the 17 included studies, yielding ~17 sEMG muscle activation response variables per study. Therefore, although significant changes were noted in outcomes across most (n = 13; total = 17) of the included studies, only ~20% of the total number of muscle activation response variables analyzed across the included studies turned out to be significant when compared with a control condition. Future studies are encouraged to measure sEMG muscle activation variables that are known (or predicted) to be important (41) (e.g., primary outcome reporting). Moreover, specific PJT-related neural adaptive processes should be targeted in future original work to elucidate whether central and/or peripheral sites within the nervous system are responsible for performance improvements. Several recent recommendations have been provided to avoid related shortcomings (11).

Furthermore, only 2 (from 17) of the included studies (6,13) provided a description of muscle activation–related changes reported as effect sizes. This issue also seems common in the PJT literature; as in a previous review (73), it was reported that from the total number of response variables included in PJT studies, changes reported as effect sizes were available for only 34% of the total amount. Although p values can predict the frequency of occurrence, they do not describe the magnitude of the effect (effect sizes). The integration of effect sizes represents a key aspect to improve the quality of future PJT studies (19). Reporting the equation used to calculate the effect size may also be of value, as is the provision of baseline and follow-up data in numerical, not just graphical format. This enables researchers and meta-analysts to calculate study effect sizes by themselves. Relatedly, another shortcoming observed among the included studies in this review was the lack of reporting numerical data, with 10 studies (from 17) reporting results in graphical form alone. Although this issue seems common in the PJT literature, where ~15% of the total outcomes measures are reported in graphical form (73), this number was 4-fold greater in this review, with ~60% of all included studies reporting results in graphical format instead of numerical data.

The screening of the 17 included studies revealed that hardly any adverse responses were reported related to PJT, which is an encouraging result. Although current evidence points toward the safety of PJT exercise in general, practitioners should take a cautious approach to PJT programming. In addition, the reader must consider the lack of uniformity in the way training programs were prescribed and tested (i.e., potential sources of heterogeneity) in studies. For instance, the role of exercise intensity was not considered and varies substantially based on points of contact (single-leg vs. double-leg drills), speed of motion, height or length of drill, and body mass (69). Practitioners are advised to take general guidelines to design PJT programs according to the available scientific evidence and make them appropriate to the individual they are working with (47,48,74,75).

In conclusion, several PJT-related sEMG muscle activation improvements were noted in most of the included studies (13 of 17). Particularly, significant PJT-related improvements were reported in 7 of 10 studies and in 6 of 10 studies for measures of sEMG muscle activation during the performance of strength and jumping tasks, respectively. Moreover, a secondary correlational analysis showed significant positive relationships between changes in sEMG muscle activation and changes in jump performance. However, from the total number of sEMG muscle activation response variables analyzed across the included studies, only ~20% turned out to be statistically significant when compared with a control condition. This observation seems to be due to methodological aspects related to sEMG assessment such as the large heterogeneity of applied sEMG methods, poor sensitivity, and/or the selection of muscle activation outcome measures that are not responsive to PJT. In addition, although PJT may have the potential to induce significant improvements in muscle activation during strength and jumping tasks, none of the included studies in this review conclusively reported PJT programming variables such as exercise intensity, progressive overload, and recovery time between jump efforts. This may have reduced the effects of PJT on sEMG muscle activation outcomes. Future studies may standardize key muscle activation outcomes to facilitate more robust comparisons between studies and populations. Moreover, the included studies were fairly heterogeneous in regards of the applied sEMG methods. Accordingly, future PJT studies are advised to follow sEMG recommendations to improve signal quality and lower study heterogeneity. In addition, future studies may include increased statistical cut-offs solutions (e.g., moving to $p < 0.001$ or beyond, rather than $p < 0.05$) (7,18,80) to reduce the number of false positive findings. Finally, more research is needed to elucidate the underlying muscle activation mechanisms (e.g., peripheral and central) responsible for PJT-related performance improvements, considering key potential moderators of the effects of PJT.

Practical Applications

Muscle activation adaptations have long been considered to be of primary importance in relation to the observed physical fitness improvements after PJT. In this systematic review, a critical appraisal of the literature was conducted regarding the potential of PJT to improve muscle activation assessed through sEMG during strength and jumping tasks in healthy individuals aged 13–73 years. In 13 of the 17 included studies, significant PJT-related improvements were reported for measures of muscle activation during the performance of strength and jumping tasks. More specifically, for strength tasks, 7 of 10 studies reported significant increases for measures of muscle activation and 6 of 10 studies for jumping tasks. A statistically significant and high correlation was noted between changes in sEMG muscle activation and jump performance. However, from the total number of sEMG muscle activation response variables analyzed across the included studies, only ~20% reached the level of statistical significance when compared with a control condition. Conflicting results probably arise from (a) studies that incorporated a large number of outcome measures with reduced sensitivity to PJT, (b) methodological limitations associated with muscle activation measurement during strength and jumping tasks, and/or (c) limitations associated with PJT prescription. Accordingly, other adaptations, such as mechanical (e.g., musculotendinous stiffness), motor skill (e.g., joint angle), and anatomical (e.g., muscle fiber pennation angle), may help to explain PJT-related improvements in strength and jumping performance in cases where muscle activation did not change significantly after training.2

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