Zhang *et al.*
European Journal of Medical Research (2025) 30:90
https://doi.org/10.1186/s40001-025-02347-3

European Journal of Medical Research

REVIEW

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Effects of lower limb strengthening training on lower limb biomechanical characteristics and knee pain in patients with patellofemoral pain: a systematic review and meta-analysis

Zeyang Zhang[1,2], Zeyi Zhang[1,2], Bosong Zheng[1,2], Yuhang Yang[3] and Youping Sun[1,2*]

Abstract

The objective of this study was to conduct a comprehensive comparison of the effects of hip and knee strengthening training in patients with patellofemoral pain (PFP). A meta-analysis was conducted to investigate the effects of these two types of strengthening training on patients' lower limb biomechanics, knee pain and function. The aim was to evaluate the effectiveness of the two training modalities and provide evidence-based recommendations for the rehabilitation of patients with PFP. A total of 12 studies were identified through a search of the Web of Science, EBSCO, and PubMed databases. The selected studies comprised nine randomized controlled trials (RCTs), one comparative controlled trial (CCTs) and two cohort studies (CSs), with a total of 1,066 patients. The quality of the included studies was evaluated via the PEDro scale, and a meta-analysis was conducted via Stata18 software. The results show that both types of strengthening training positively impact pain reduction and improved knee function in PFP patients. Moderate evidence from meta-analyses indicated that hip strengthening training (SMD = −1.740, 95%; CI −2.212 to −1.267, $P < 0.001$) was more effective than knee strengthening training (SMD = −1.302, 95%; CI −1.75 to −0.86, $P < 0.001$) in reducing pain (VAS). Similarly, Strong evidence suggests that hip strengthening training (SMD = 1.205, 95%; CI 0.968 to 1.443, $P < 0.001$) was significantly more effective than knee strengthening training (SMD = 1.023, 95%; CI 0.722 to 1.325, $P < 0.001$) in improving knee function (AKPS). Additionally, moderate evidence suggests that hip strengthening training significantly increased hip abductor strength (SMD = 0.848, 95%; CI 0.508–1.187, $P < 0.001$) and external rotator strength (SMD = 0.780, 95%; CI 0.416–1.145, $P < 0.001$), while strong evidence suggests that knee strengthening training did not significantly enhance knee extensor strength (SMD = 0.212, 95%; CI −0.014 to 0.439, $P = 0.066$). Therefore, clinicians should use hip strengthening as one of the primary training interventions when treating patients with PFP.

Keywords Patellofemoral pain, Hip strengthening training, Knee strengthening training, Lower limb biomechanics

*Correspondence:
Youping Sun
1574937499@qq.com
Full list of author information is available at the end of the article

Introduction

Patellofemoral pain (PFP) is one of the most prevalent overuse injuries of the lower extremities [1]. The symptoms typically manifest as pain in the retro-patellar or peripatellar area of the knee during functional activities such as squatting, jumping, walking up/down stairs and running [2]. Patellofemoral joint pain impairs a patient's ability to engage in sports and work-related activities. Furthermore, recurrent or chronic symptoms may also occur in 70–90% of patients [3]. Early patellofemoral joint pain may also potentially contribute to the development of patellofemoral arthritis at a later date [4], which may have a long-term impact on life and work status.

Defining the symptoms and causative risk factors for patients with PFP is a prerequisite for intervention and treatment. Patients with PFP have been found to have impaired pain regulation, abnormal neuropathic pain processing, and impaired proprioceptive and sensorimotor function [5]. Furthermore, the majority of contemporary studies indicate that altered biomechanics of the lower limb may represent a significant risk factor for PFP [5]. Nevertheless, the precise biomechanical mechanisms through which these risk factors contribute to the development of PFP, and the extent to which the evidence supporting them is reliable, remain to be further substantiated [6]. As the only dynamic stabilizing structure of the patella, the knee extensors play an important role in maintaining normal patellar motion through their strength and the relative balance between medial and lateral muscle strength. Weak hip abduction and external rotation muscles can cause the femur to exhibit incorrect movement patterns, such as excessive internal retraction and internal rotation during activity, which can lead to abnormal patellar movement trajectories and thus increase the risk of patellofemoral joint cartilage abrasion [7–9]. Therefore, the treatment plan for patients with PFP should be bespoke to the individual patient and employ a multimodal intervention approach, with exercise forming the foundation of the treatment. In view of the complex an etiology of PFP and the potential presence of multiple risk factors, therapeutic measures for its risk factors should be approached with caution. The objective of the treatment plan should be to provide symptomatic relief, to improve the abnormal biomechanics of the lower extremity [10, 11], and ultimately to improve the outcomes for patients with PFP.

The recommendations on treatment options for PFP jointly recommended by 41 experts in patellofemoral pain [12] support the use of hip-focused strengthening training and knee-focused strengthening training as the primary choice of exercise therapy. However, the therapeutic effects of hip-focused strengthening training versus knee-focused strengthening training in improving pain, function and strength have not been clearly established [12]. The available evidence indicates that hip strengthening training may be more efficacious than knee strengthening training in reducing pain and improving overall strength [13, 14]. Nevertheless, the findings of Hott et al. [15] indicated no statistically significant difference between the two interventions. The inconsistency in the findings of the studies may be attributed to the variations in their design, sample size, participant characteristics, and the outcome measures employed. It is therefore necessary to conduct a comprehensive and objective evaluation of existing research in order to clarify the respective roles of hip and knee strengthening training in the treatment of PFP. Although there have been studies that have attempted to compare the effects of the two training modalities through meta-analysis[16], the number of included studies was limited and the conclusions were not inconclusive enough. It is therefore necessary to conduct further detailed and specific analyses in order to address the differences in study design, sample sizes, study populations and measurement metrics of individual clinical trials, with a view to drawing definitive conclusions.

The objective of this meta-analysis was to assess the impact of hip strengthening training and knee strengthening training on the lower limb biomechanics of patients with PFP and to compare the efficacy of the two types of training on pain relief and functional improvement in patients with PFP. Additionally, the analysis attempts to elucidate the potential mechanisms of action of the two types of strengthening training, thereby providing insights into the optimal direction of rehabilitation for PFP patients. The hypotheses of this study are as follows: hip strengthening training is better than knee strengthening training in relieving pain and improving function; both types of training significantly improve the poor biomechanical characteristics of the lower limbs of PFP patients.

Methods

Prior to the start of this review, the study inclusion criteria were in strict accordance with the PRISMA statement. The program of this systematic review has been prospectively registered in the PROSPERO database under registration number CRD42024603239.

Inclusion and exclusion criteria

Inclusion criteria

(1) Study type and intervention protocol: This study included controlled trials and cohort studies of hip strengthening training and knee strengthening training for evaluation. The intervention was either

hip strengthening training or knee strengthening training. The comparator was the control group, which was either the no-intervention group or the standard care group.

(2) Study population: The patients were described as having patellofemoral pain (PFP) or patellofemoral pain syndrome (PFPS)included in the study presented pain around or behind the patella, which is aggravated by at least one activity that loads the patellofemoral joint during weight bearing on a flexed knee (e.g., squatting, stair ambulation, jogging/running, hopping/jumping) [17].

(3) Outcome indicators: The level of knee pain was quantified on a visual analogue scale (VAS), while knee function was assessed using the anterior knee pain scale (AKPS). Additionally, the maximal isometric strength of the hip abductors, hip external rotators, and knee extensors was incorporated into the evaluation.

Exclusion criteria

Requirements for exclusion: case reports and non-English-language studies, as well as animal and cadaveric studies.

Search strategy

Searches

Two researchers (BZ and ZZ) were responsible for the data, with one of them (ZZ) additionally undertaking the role of independent data validation and overseeing all other necessary operations.

Repository

Searches were conducted via the Web of Science, PubMed and EBSCO databases from inception to February 2024 to screen reference lists for inclusion in publications, and citation tracking was completed via Google Scholar.

Search strategy

Patellofemoral pain syndrome was used as the subject term. Pain syndrome, patellofemoral, anterior knee pain syndrome, patellofemoral syndrome, patellofemoral pain, pain, patellofemoral, and patellofemoral pain were used as free words. Hip exercise, proximal training, gluteal strengthening, knee training, and quadriceps training were used in combination with free words. Taking the PubMed database as an example, the specific search strategy is shown in Additional file 1.

Review process

A search was conducted on the above English databases to obtain relevant literature, which was then imported into the literature management software EndNote X9 (Thomson Reuters, California, USA) for screening. Two researchers subsequently conducted independent literature screenings on the basis of the preestablished inclusion and exclusion criteria. The title and abstract of the literature were initially screened, and only those that met the inclusion criteria were then subjected to a more detailed examination of the full text. This process allowed for a more rigorous assessment of the suitability of the studies for inclusion. Once the rescreening process was complete, the literature deemed eligible by each researcher was compared. Any discrepancies in the researchers' judgments were discussed with a third researcher, who made the final decision on inclusion.

Data extraction and quality assessment

Two researchers extracted the following data from the eligible literature: sample characteristics (age, sex, height, weight, and body mass index), outcome measures (VAS, AKPS), muscle isometric strength (hip abductor strength, hip external rotator strength and knee extensor strength). Should statistical plots be the only available data in a study and means and standard deviations not provided, the authors of the literature were contacted again to request more valid data. If no response was forthcoming, the data were extracted from the graphs of the studies via the Degitizer module of Origin (Pro2021, Origin Lab, USA). The quality of the included studies was evaluated via the PEDro scale, in addition to the list of inclusion/exclusion criteria for patients with PFP. The PEDro scale was used to assess the quality of the included studies on 11 items, including whether random assignment was made, whether concealed assignment was made, whether blinding was used and whether statistical comparisons between groups were made. The PEDro score was used to categorize the literature as either high-quality (HQ) or low-quality (LQ). Studies with a score of >6 were classified as HQ, whereas those with a score of ≤ 6 were classified as LQ. The PFP Diagnostic Checklist is a seven-item scale that determines the key inclusion and exclusion criteria for the diagnosis of PFP. Higher scores indicate a greater number of key criteria reported. The quality of the studies was independently evaluated by two researchers. In the event of a discrepancy between the two researchers' scores, a joint discussion with a third researcher was held to determine the final score.

Risk-of-bias assessment

The risk of bias for each study outcome was evaluated using the Cochrane Risk of Bias Tool, V.2 [18]. The two experimenters (ZZ, BZ) conducted an independent assessment of all the included RCTs. Each significant area of bias was evaluated in relation to the findings of the included studies. The signaling questions and criteria from the tool were employed to inform the domain-based risk-of-bias assessment. A domain-based risk-of-bias assessment was conducted, whereby the risk of distortion of outcome estimates was classified as either 'low', ' some concerns ' or 'high' risk of bias. Each outcome in the study was evaluated for overall risk of bias based on individual domains, according to the guidance provided by the tool. In instances of disagreement between the two researchers, consensus was reached through discussion.

Outcome measures

The outcome measures included visual analog scale (VAS), anterior knee pain scale (AKPS), maximum isometric contraction force of the hip abductor, maximum isometric contraction force of the hip external rotator and maximum isometric contraction force of the knee extensor. The visual analog score is a reliable, valid and responsive tool that is frequently employed as an outcome indicator for pain [19]. The scale comprises a bidirectional 10-cm line, with 0 cm representing "no pain" and 10 cm representing "worst pain imaginable". The endpoints of the line are located at either end of the scale [19]. The anterior knee pain scale (AKPS) is a self-report questionnaire that assesses the level of pain and function of the knee joint. It comprises 13 items, including claudication, weight-bearing capacity, walking, walking up and down stairs, squatting, running and jumping. The scores range from 100 (normal knee function and no pain) to 0 (severe knee pain and dysfunction). Lower scores indicate more severe pain or dysfunction [20]. The isometric muscle strength of the hip abductors, hip external rotators and knee extensors was quantified by performing successive isometric maximal contractions, with the data recorded using a force transducer or handheld dynamometer. The maximum value was selected for analysis as described previously [21].

Study analysis

In order for studies to be included in the meta-analysis, the following criteria must be met: (1) the study design must be a randomized controlled trial, a comparative controlled trial, or a cohort study. (2) The patients in the study must meet the inclusion criteria. (3) The study must employ a knee strengthening or hip strengthening training. (4) The study must provide clear outcome data. (5) The sample size must meet the requirements for statistical analysis. Subsequently, the study was deemed eligible for inclusion in the meta-analysis. The quality of the studies was assessed by the PEDro scale and the risk of bias was assessed using the RoB-2 tool and meta-statistical analyses were performed via Stata18 (STATA, USA; https://www.stata.com). The study metrics selected for the articles were continuous data, in which the included studies employed comparable outcome measures (VAS, AKPS, maximum isometric contraction strength of hip external rotators, maximum isometric contraction strength of hip abductors, and maximum isometric contraction strength of knee extensors). In experimental studies involving different intervention durations, the data were pooled at the conclusion of the intervention period. In these studies, the intervention periods were 3 weeks, 4 weeks, 6 weeks, 8 weeks and 12 weeks. All outcome measure scores were converted so that favorable results (pain reduction, functional improvement, strength changes, etc.) were entered as positive values into Stata18. As the measures and tools employed in each experiment differed, the standardized mean difference (SMD) was employed as the effect scale in this study, with confidence intervals (95% CI) utilized for each effect indicator. A meta-analysis was conducted via the randomized effects model (REM) DerSimonian–Laird method, given the considerable heterogeneity in research design, sample selection, intervention methods, measurement tools, and data collection across the experiments. A heterogeneity test (Q test, test level $\alpha = 0.05$) was conducted concurrently with the analysis. If the resulting P value was less than 0.05, heterogeneity was indicated between studies. In such cases, the magnitude of heterogeneity was quantified by combining it with the I^2. If the resulting I^2 value was less than 50%, it was considered low, whereas if the value was greater than 50%, it was considered high. To identify and mitigate the impact of heterogeneity on the results, a meta-regression analysis was conducted using the randomized effects model (REM) DerSimonian–Laird method. This analysis employed a univariate model, independently testing predictor variables such as sample, intervention time, frequency, age, weight and height to assess their individual contributions to the observed heterogeneity. A series of sensitivity analyses were conducted by removing individual papers one by one to test whether there was a significant effect of individual papers on the total effect size. If the effect was found to be significant and had a high impact on heterogeneity, the paper in question was excluded. Subjective tests for publication bias were conducted via funnel plots, and if publication bias was identified, Egger's test was employed to quantitatively determine the extent of bias. In this work, the standardized mean difference (SMD) and its 95%

confidence interval (CI) were employed as effect scales for the results. Furthermore, the significance level for all the statistical analyses was set at $P \leq 0.05$.

The level of evidence was guided by the recommendation made by Van Tulder et al. [22].

Strong evidence = based on results from multiple studies, including at least two HQ studies that are statistically homogeneous ($I^2 < 50\%$).

Moderate evidence = based on results from multiple studies, including at least one HQ study that is statistically heterogeneous ($I^2 > 50\%$) or from multiple LQ studies that are statistically homogeneous ($I^2 < 50\%$).

Limited evidence is based on results from multiple LQ studies that are statistically heterogeneous ($I^2 > 50\%$) or from one HQ study.

Very limited evidence is available on the basis of the results of one LQ study. Conflicting evidence = irrelevant pooled results based on multiple studies of unrelated quality that are statistically heterogeneous ($I^2 > 50\%$).

Results

Results of the search strategy

The process of literature screening and inclusion is illustrated in Fig. 1. Initially, a total of 1,496 relevant studies were identified from three databases: PubMed, WOS, and EBSCO. The initial screening phase involved analyzing titles and abstracts to eliminate studies that were not pertinent to the subject matter, as well as reviews, conference papers, and letters. Additionally, EndNote software was used to remove duplicates sourced from multiple databases. This process resulted in 71 studies being identified for further assessment. In the second stage of the screening process, 59 studies were excluded after a review of the full texts and the application of specific exclusion criteria. These criteria included the use of incompatible interventions, a lack of specification regarding the patient population, and the presence of incomplete data. Ultimately, 12 studies were deemed eligible for inclusion in the meta-analysis [13–15, 23–31]. Among these, nine

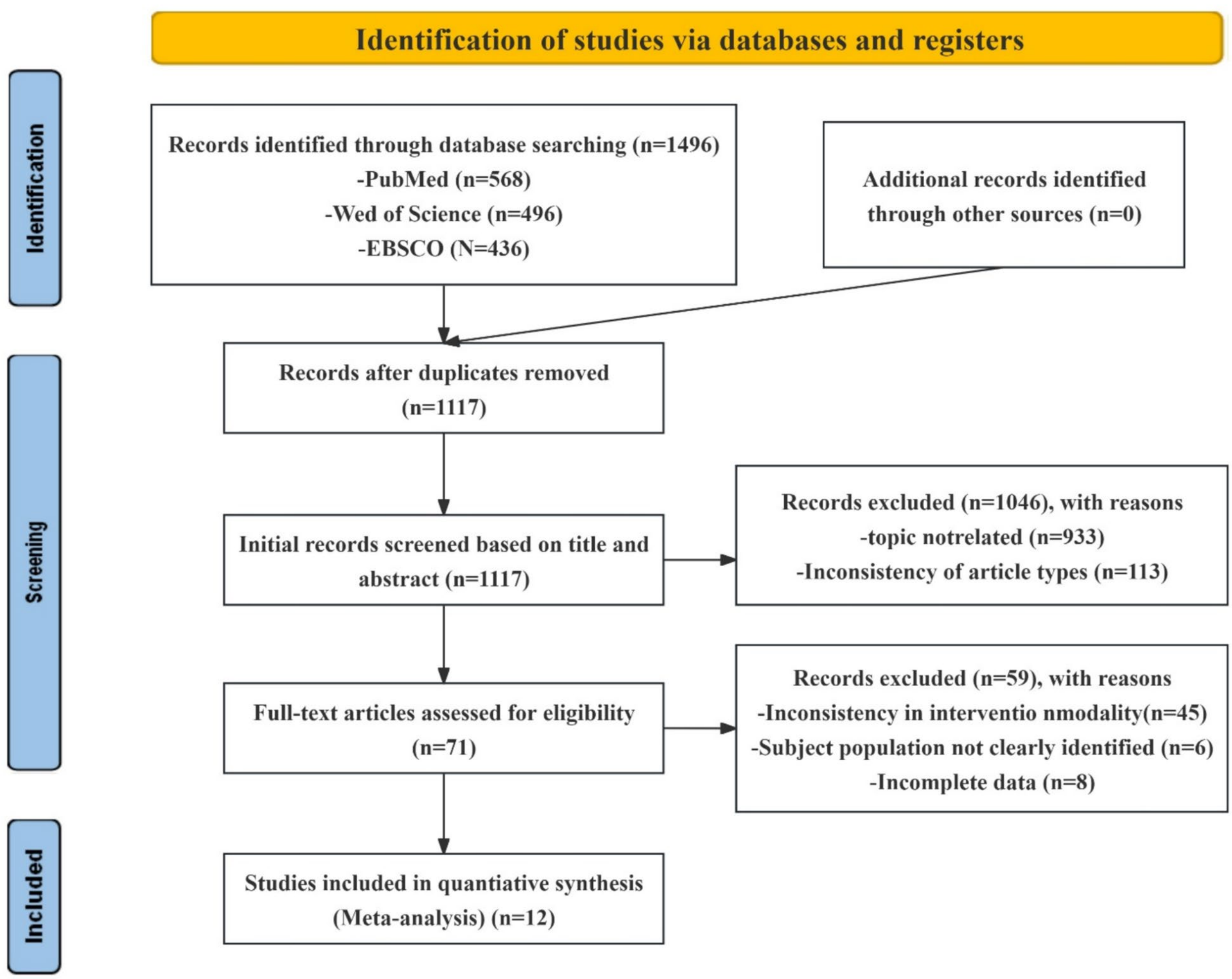

Fig. 1 Flow diagram of study selection using PRISMA

were randomized controlled trials, one was a comparative controlled trial, and two were cohort studies. For a more detailed overview of the screening process, please refer to Fig. 1. Further details on the included research literature, including sample size and participant demographics, can be found in Additional file 1. Details on the intervention and control group protocols, outcome measures and follow-up times can be found in Additional file 1.

Quality and risk-of-bias assessment

The results of the PFP Diagnostic Checklist and the PEDro Scale are presented in Additional file 1 and Table 1, respectively. All 12 studies achieved a score of 5 or above on 7 items of the PFP Diagnostic Checklist, indicating a high degree of consistency in the included literature with respect to the criteria for the diagnosis of PFP. The study was evaluated using the RoB-2 tool, which is designed to assess the risk of bias. A total of five data sets yielded results that were deemed to have some concerns, while four exhibited a low risk of bias and only one demonstrated a high risk of bias (Additional file 1). The most common sources of bias were found to the randomization process and deviation from intended interventions. The methodological quality of the included studies was assessed using the PEDro scale. The scores ranged from 3 to 10, with 10 indicating the highest quality and 3 the lowest. Among the 12 studies, seven were categorized as high quality (HQ; PEDro score > 6), while five were categorized as low quality (LQ; PEDro score ≤ 6). Specifically, one study scored 10, six studies scored 7–9, and five studies scored 3–6. A detailed breakdown of the PEDro scores for each included study is provided in Table 1.

Meta-analysis results

Effects of hip strengthening and knee strengthening on pain and function in patients with PFP

(1) Comparison of the effects of two training modalities on reducing pain scores in patients with PFP.

A total of eight studies [13–15, 24–26, 28, 31] analyzed the effects of hip strengthening training and knee strengthening training on pain scores in patients with PFP (Fig. 2). Moderate evidence (4 HQ and 4 LQ studies) that both types of strengthening training resulted in a reduction of patellofemoral joint pain in patients compared with the no intervention training group. In particular, hip strengthening training ($I^2 = 86.3\%$; SMD = −1.740, 95%; CI −2.212 to −1.267, $P < 0.001$) had a greater reduction effect than knee strengthening training did ($I^2 = 82.2\%$; SMD = −1.302, 95%; CI −1.75 to −0.86, $P < 0.001$).

(2) Comparison of the effects of two training modalities on improving knee function in patients with PFP.

Five studies [13, 15, 23, 28, 31] analyzed the effects of hip strengthening training and knee strengthening training on the knee function of patients with PFP (Fig. 3). Strong evidence (4 HQ and 1 LQ studies) suggests that both types of strengthening training improve knee function in patients compared to those receiving no intervention training. Hip strengthening training ($I^2 = 39.9\%$; SMD = 1.205, 95%; CI 0.968–1.443, $P < 0.001$) demonstrated a greater improvement in knee

Table 1 PEDro scale

Author	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	Total score
Almeida et al. [23]	1	1	1	1	0	0	1	1	1	1	1	8
Ferber et al. [24]	1	0	0	0	0	0	0	1	1	1	1	5
Hott et al. [15]	1	1	1	1	1	1	1	1	1	1	1	10
Khayambashi et al. [25]	1	0	0	1	1	0	1	1	1	1	1	7
Dolak et al. [26]	1	1	0	1	0	0	0	0	1	1	1	5
Hamstra et al. [27]	1	1	1	1	1	0	1	1	1	1	0	8
Saad et al. [28]	1	1	1	1	0	0	1	1	1	1	1	8
Khayambashi et al. [14]	1	0	0	1	0	0	0	1	1	1	1	5
Hansen et al. [29]	1	1	1	1	0	0	1	0	1	1	1	7
Tyler et al. [30]	1	0	0	0	0	0	0	1	1	1	0	3
Ferber et al. [13]	1	1	0	1	0	0	1	0	1	1	1	6
Bolgla et al. [31]	1	1	0	1	0	0	1	1	1	1	1	7

I = eligibility criteria specified, II = random allocation, III = concealed allocation, IV = similar at baseline, V = subject blinding, VI = therapist blinding, VII = assessor blinding, VIII = outcome measures obtained from > 85%, IX = treatment received as allocated, X = between-group statistical comparison, XI = point measures and measures of variability

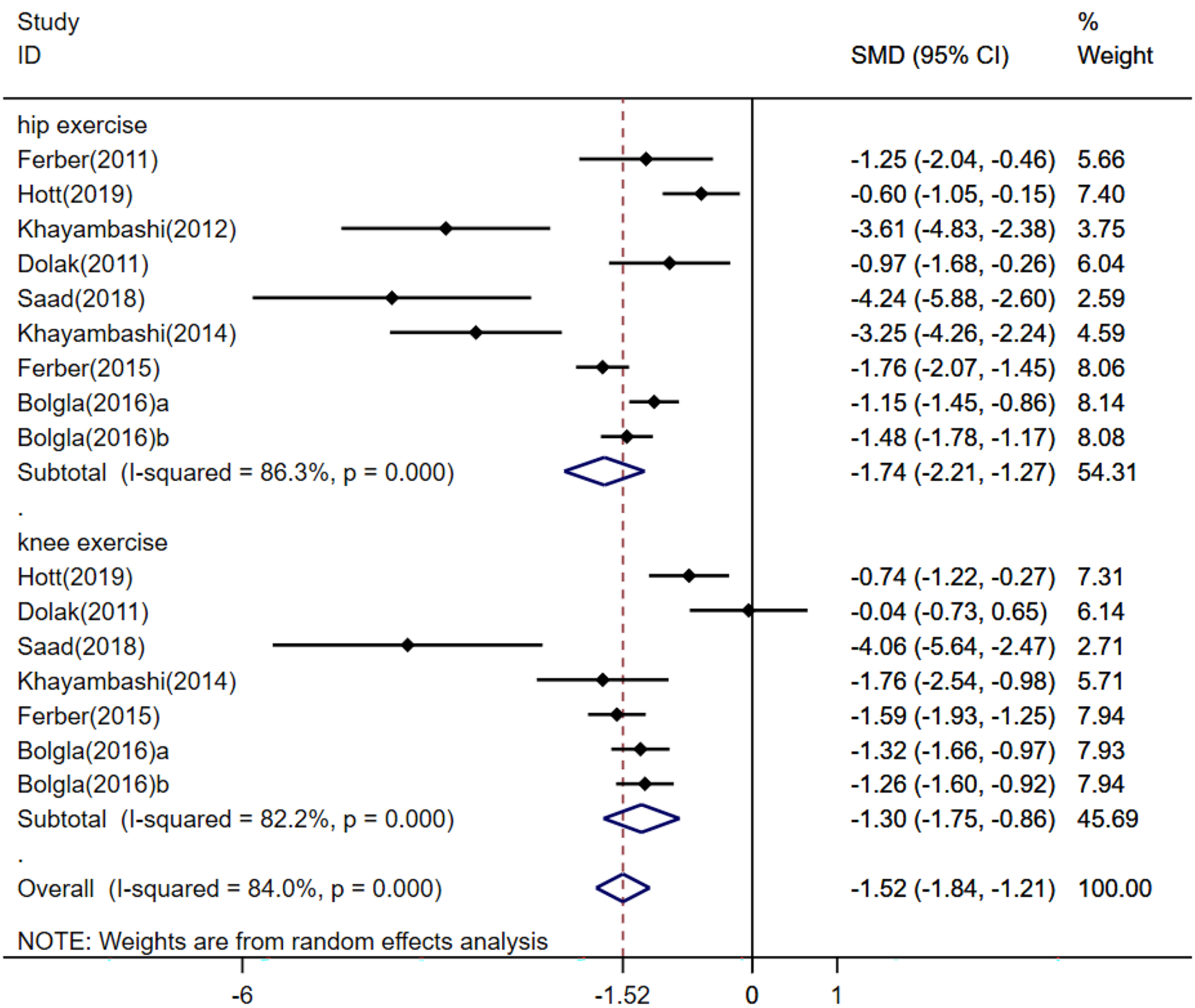

Fig. 2 Meta-analysis of the effects of hip strengthening training and knee strengthening training on VAS scores. **a**, **b** Represent data from different populations in the same literature. Bolgla [31] **a** represents male patients with PFP; Bolgla [31] **b** represents female patients with PFP

function than knee strengthening training ($I^2 = 47.7\%$; SMD = 1.023, 95%; CI 0.722–1.325, $P < 0.001$).

Effects of hip strengthening training and knee strengthening training on lower limb biomechanics in patients with PFP

(1) Effects of hip strengthening training on hip abductor strength in patients with PFP.

As illustrated in Fig. 4, seven studies [13, 15, 23–26, 28] examined the impact of hip strengthening training on hip abductor strength in patients with PFP. Moderate evidence (4 HQ and 3 LQ studies) suggests that hip strengthening training significantly increase hip abduction strength in patients with PFP compared to those receiving no intervention training($I^2 = 65.8\%$; SMD = 0.848, 95%; CI 0.508–1.187, P < 0.001).

(2) Effects of hip strengthening exercises on hip external rotator strength in patients with PFP.

As illustrated in Fig. 5, a total of six studies [13, 15, 23, 25, 26, 28] investigated the impact of hip strengthening training on hip external rotator strength in patients with PFP. Moderate evidence (4 HQ and 2 LQ studies) suggests that hip strengthening training are more effective in increasing hip external rotator strength in patients with PFP compared to those receiving no intervention training ($I^2 = 68.6\%$; SMD = 0.780, 95%; CI 0.416–1.145, P < 0.001).

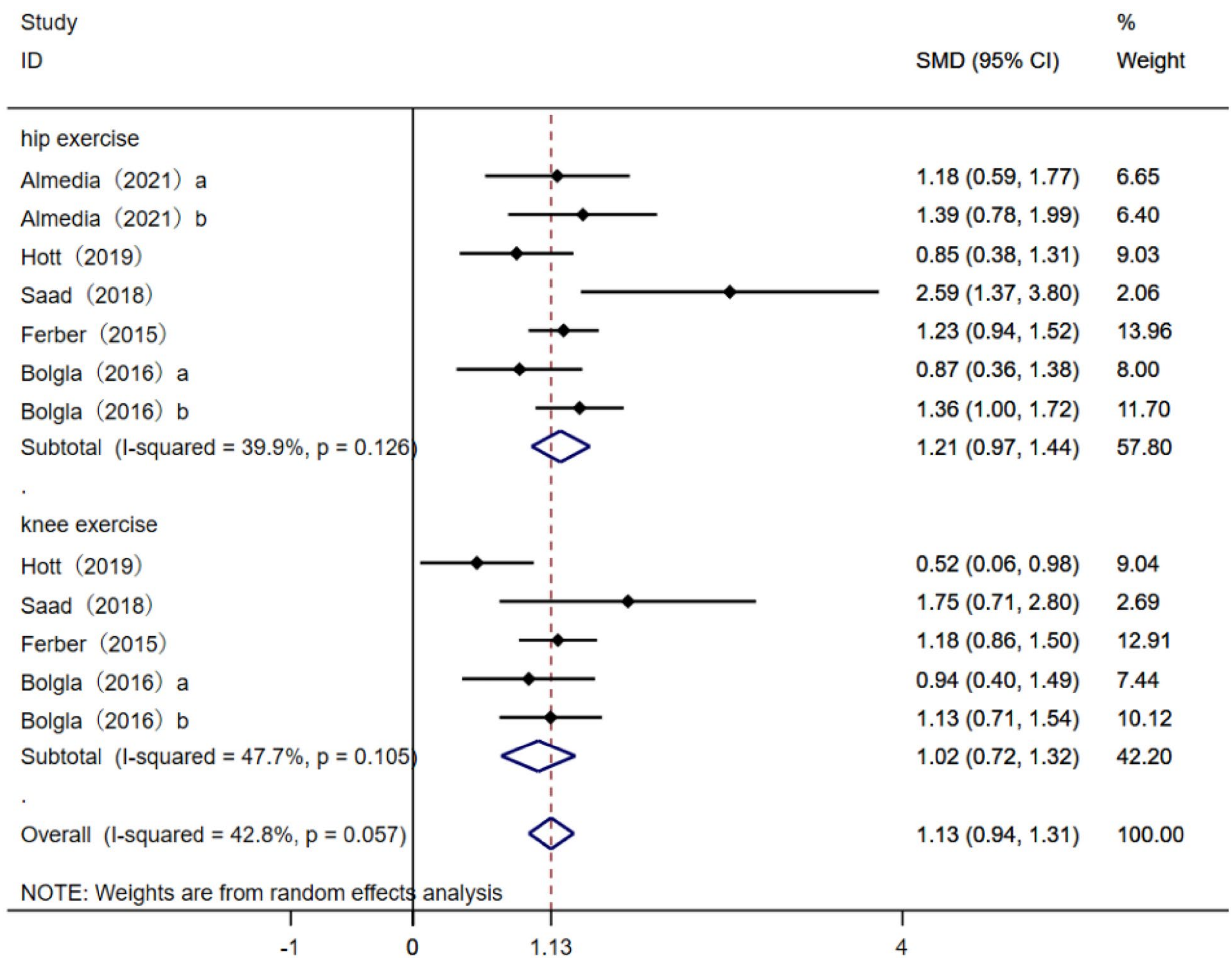

Fig. 3 Meta-analysis of the effects of hip and knee strengthening exercises on knee function in patients with PFP. **a**, **b** Represent data from different interventions and different populations in the same literature. Almedia [23] **a** represents strengthening training of the posterior lateral hip muscles; Almedia [23] **b** represents strengthening training of the anterior medial hip muscle groups

(3) Effects of knee strengthening exercises on knee extensor strength in patients with PFP.

A total of four studies [13, 15, 26, 28] were analyzed to determine the effect of knee strengthening training on knee extensor strength in patients with PFP (Fig. 6). Strong evidence (2 HQ and 2 LQ studies) suggests that knee strengthening training no difference improve knee extensor strength in patients with PFP compared to those receiving no intervention training. ($I^2=0\%$; SMD = 0.212, 95%; CI −0.014 to 0.439, $P=0.066$).

Examining sources of heterogeneity

A meta-regression analysis was conducted on the studies that included different outcome indicators to identify sources of heterogeneity. The results are presented in Table 2. The length of the intervention was found to be significantly negatively correlated with the change in the effect sizes of the VAS indicators for both hip strengthening ($P=0.025$, $R^2=54.61\%$) and knee strengthening ($P=0.036$, $R^2=87.00\%$). Body weight was positively correlated with the VAS score for knee strengthening ($P=0.046$, $R^2=100\%$); height was significantly negatively correlated with hip abductor height ($P=0.05$, $R^2=66.67\%$). Furthermore, in the heterogeneity analysis of the effect sizes of hip external rotator strength, the duration of the intervention was positively correlated with the effect size ($P=0.035$, $R^2=74.22\%$), and the weight ($P=0.014$, $R^2=100\%$) and height ($P=0.009$, $R^2=100\%$) were negatively correlated with the effect size.

Sensitivity analysis

A sensitivity analysis of studies incorporating outcome metrics revealed that data from studies incorporating metrics for VAS, AKPS, hip abductors, and hip external rotators did not significantly impact the results, and the

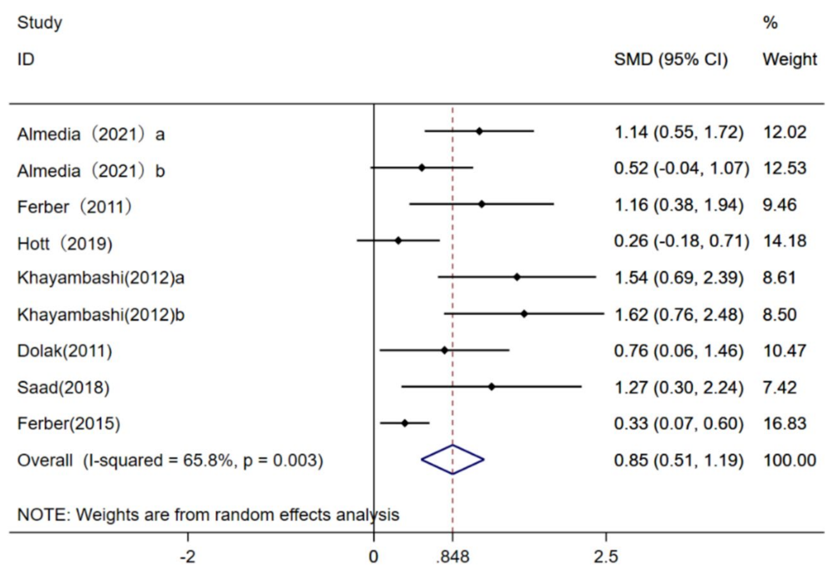

Fig. 4 Meta-analysis of the effects of hip strengthening exercises on hip abductor strength in patients with PFP. **a**, **b** Represent data from the same literature with different intervention modalities and different orientations of the hip joint. Khayambashi [25] **a** reported the muscle strength of the right hip abductors in patients with PFP, and Khayambashi [25] **b** reported the muscle strength of the left hip adductors in patients with PFP

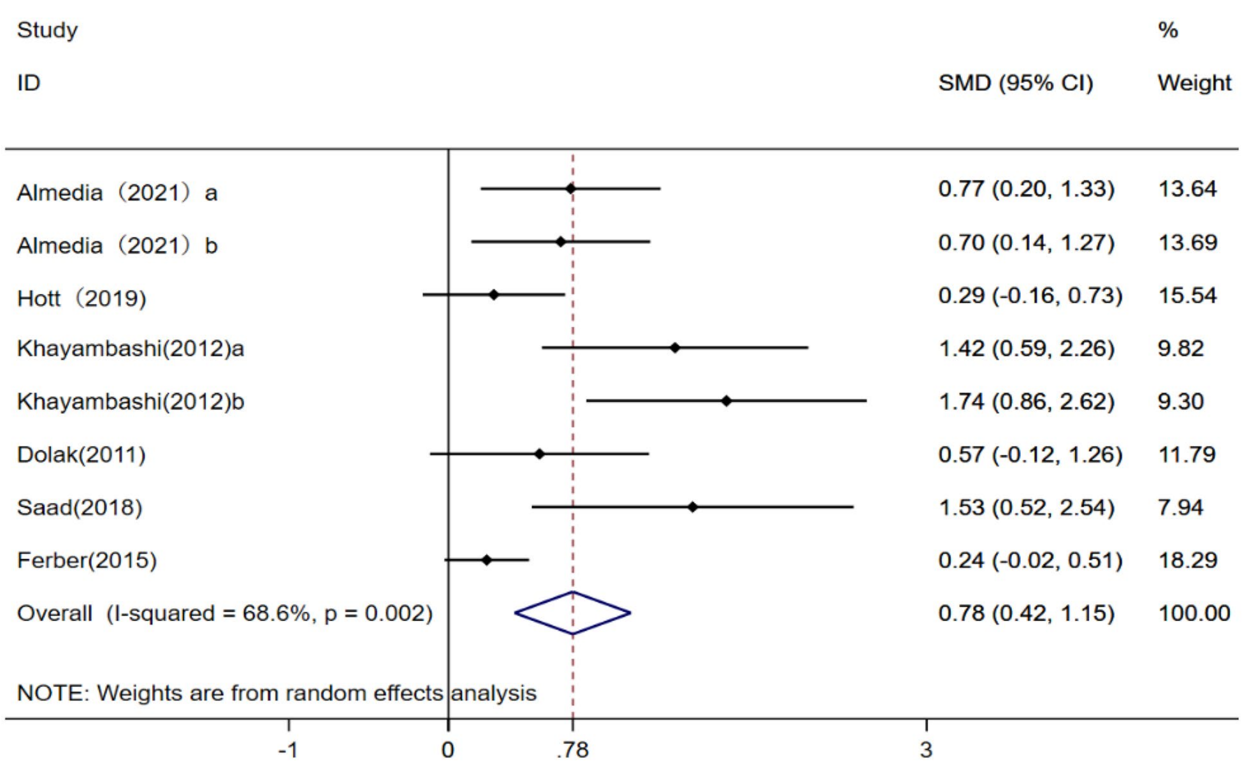

Fig. 5 Meta-analysis of the effect of hip strengthening exercises on hip external rotator strength in patients with PFP. **a**, **b** Represent data from the same literature with different intervention modalities and different orientations of the hip joint

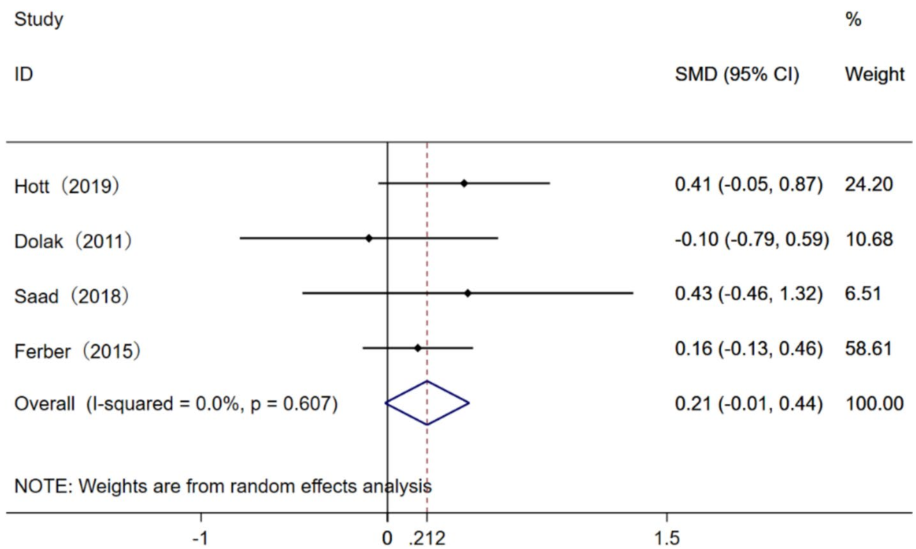

Fig. 6 Meta-analysis of the effect of knee strengthening exercises on knee extensor strength in patients with PFP

Table 2 Results of the meta-regression analyses of indicators in the included studies

Indicator	VAS		Hip abductor	Hip external rotator
	Hip exercise	Knee exercise	Hip exercise	Hip exercise
Intervention time	−0.520*	−0.572*	0.098	0.395*
Frequency	0.313	0.114	−0.053	0.174
Gender (female)	0.010	0.008	−0.009	−0.008
Sample	0.010	0.004	−0.009	−0.009
Age	0.131	0.193	0.010	−0.035
Weight	0.165	0.123*	−0.073	−0.123*
Height	15.134	14.294	−7.483*	−8.715*

Intervention time, height, and weight were associated with changes in the outcome indicators in the table and may be the main sources of heterogeneity in the articles

* Represents a significant difference between the independent variable and the dependent variable ($p < 0.05$)

results were relatively robust. Among the knee extensor indicators (Fig. 7-E1), the data of Hott et al. [15] and Ferber et al. [13] revealed a more pronounced effect on knee extensor heterogeneity. The effect sizes changed from 0.212 to 0.149 and 0.282, respectively; after deletion, the results were weakly stable.

Publication bias

A bias test for the inclusion of literature related to VAS indicators revealed the potential for publication bias. The funnel plot appeared asymmetric in the hip strengthening training study (Fig. 8-A1), and Egger's test ($P = 0.008$) revealed publication bias in the literature, which was corrected via the cut-and-patch method for data correction (Fig. 8-A2). Similarly, funnel plot asymmetry also appeared in the knee strengthening training study (Fig. 8-E1), and Egger's test ($P = 0.104$) was not statistically significant. The results of the AKPS-related studies revealed funnel plot asymmetry in both the hip strengthening and knee strengthening studies (Fig. 8-D1, D2). However, Egger's test did not yield statistically significant results ($P > 0.05$). The funnel plot for the hip abductor index demonstrated asymmetry (Fig. 8-B1). Egger's test ($P = 0.003$) indicated the presence of publication bias in the literature, and the data were corrected via the clipping and patching method (Fig. 8-B2). For studies related to the hip abductor muscle, asymmetry was observed in the funnel plot (Fig. 8-C1), and Egger's test ($P = 0.005$) indicated the presence of publication bias in the literature. Data correction was performed via the trim-and-fill method (Fig. 8-C2). For studies related to knee extensors, the funnel plot was asymmetric (Fig. 8-F1), and Egger's test ($P > 0.05$) was not statistically significant.

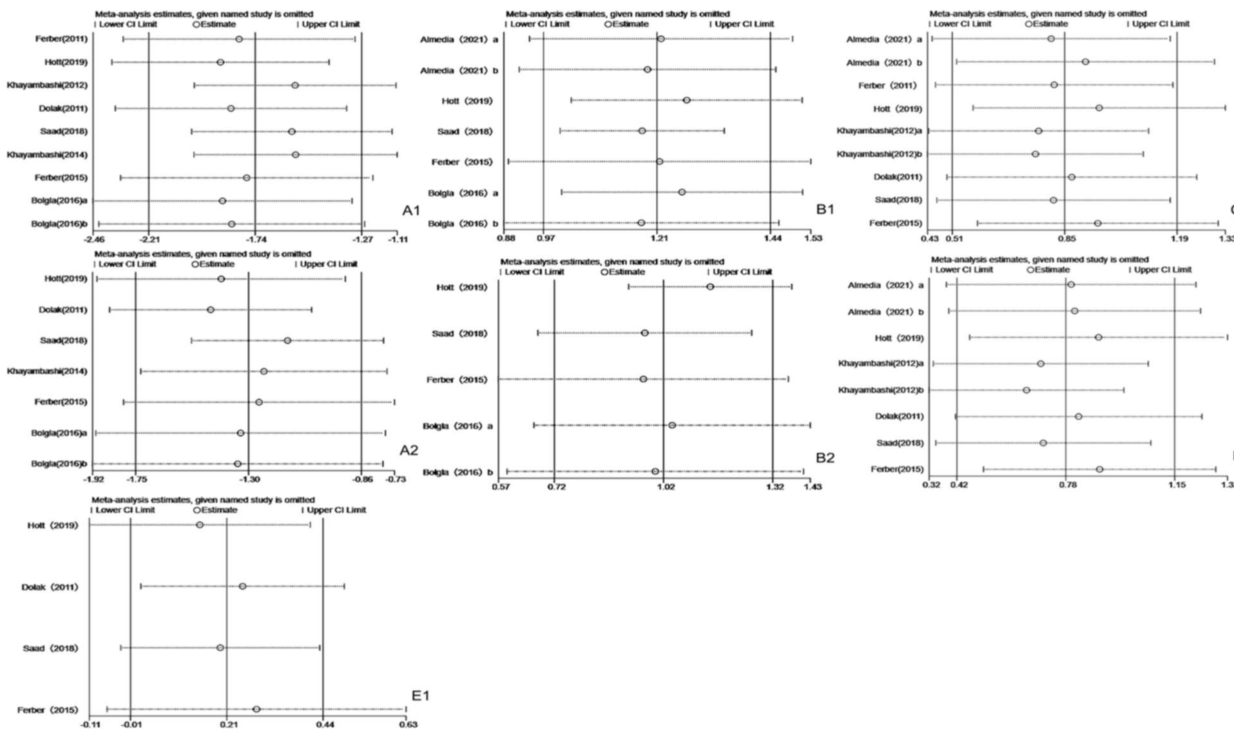

Fig. 7 Results of sensitivity analyses for each indicator in the included studies. A1 shows the results of the sensitivity analysis of the VAS indicators during hip strengthening training; A2 shows the results of the sensitivity analysis of the VAS indicators during knee strengthening training; B1 shows the results of the sensitivity analysis of the AKPS indicators during hip strengthening training; B2 shows the results of the sensitivity analysis of the AKPS indicators during knee strengthening training; C1 shows the results of the sensitivity analysis of the hip abductor indicators during hip strengthening training; D1 shows the results of the sensitivity analysis of the hip extensor indicators during hip strengthening training; and E1 shows the results of the sensitivity analysis of the knee extensor indicators during knee strengthening training

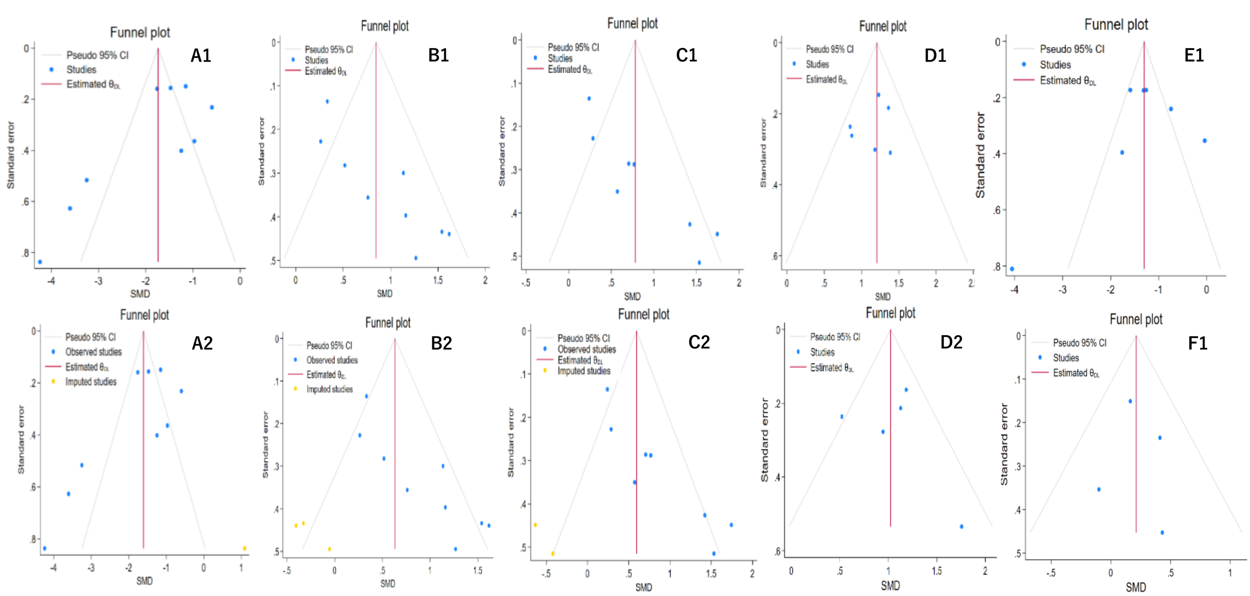

Fig. 8 Publication bias funnel plot

Discussion

The study included 12 studies [13–15, 23–31] of varying quality, comprising 9 randomized controlled trials, 1 comparative controlled trial, and 2 cohort studies. The meta-analysis aimed to compare the effects of hip strengthening training and knee strengthening training on reducing pain and improving knee function in patients with PFP. Additionally, the meta-analysis investigated the impact of these two strengthening trainings on lower limb biomechanics in PFP patients. Moderate evidence suggests that hip strengthening training are superior to knee strengthening training in reducing PFP patients pain [13–15, 24–26, 28, 31]. Strong evidence indicates that hip strengthening training are more effective than knee strengthening training in improving knee function [13, 15, 23, 28, 31]. Moderate evidence shows that hip strengthening training significantly increase hip abduction strength [13, 15, 23–26, 28] and hip external rotator strength [13, 15, 23, 25, 26, 28] in PFP patients compared to those receiving no intervention. Furthermore, strong evidence suggests that knee strengthening training do not significantly differ from no intervention in enhancing knee extensor strength in patients with PFP [13, 15, 26, 28]. In conclusion, these findings may assist clinicians in selecting appropriate rehabilitation methods for PFP patients.

Analysis of heterogeneity between studies

To explore the source of heterogeneity in the studies, a meta-regression analysis, sensitivity analysis and a publication bias test were performed. Despite these efforts, the results still exhibited some heterogeneity. The meta-regression analysis revealed that intervention time was negatively associated with the effect on hip VAS scores but positively associated with hip external rotator strength. These findings suggest differing adaptation mechanisms. Pain relief, as measured by VAS, often occurs in the early stages of rehabilitation due to neuromuscular adaptations, reduction in inflammation, and changes in pain perception. Prolonged intervention periods may lead to diminishing returns as these processes plateau over time [32, 33]. In contrast, improvements in hip external rotator strength are positively associated with intervention time, reflecting the cumulative benefits of mechanical loading and progressive adaptation in the musculature. Prolonged training promotes structural and functional changes such as hypertrophy, increased motor unit recruitment, and enhanced neuromuscular coordination [34, 35].

Upon conducting sensitivity analyses for the various outcome indicators, it was determined that with the exception of the knee extensor indicator, which exhibited relatively weak stability of the results, the exclusion of any individual study had a more limited impact on the combined effect size of the remaining outcome indicators. The results of the meta-analyses for the remaining outcome indicators were highly robust.

Effects of lower limb strengthening training on the pain and activity function of PFP patients

Currently, improving pain and functional activity in patients with PFP is a primary focus of clinical research [36]. This review provides moderate evidence [13–15, 24–26, 28, 31] that hip strengthening exercises have a significant effect on reducing pain in patients with PFP. While this review does not directly demonstrate the specific mechanism by which improvements in hip abductor and external rotator strength reduce pain, the review results indicate a positive impact on patellofemoral joint biomechanics, consistent with the findings of Mascal et al. [37]. Simultaneously with hip strengthening exercises, lower limb movement patterns[38] and increased ankle flexibility [39] also experience varying degrees of strengthening, potentially contributing additional positive effects in reducing patellofemoral pain. Across the eight studies included in this review [13–15, 24–26, 28, 31], involving a total of 328 patients, the average baseline pain score was 5.8 points, which decreased to 2.4 points after intervention, representing a 68% change in pain score. According to Ostelo et al. [40], the minimum clinically important change in pain is 1.5 points (or a 30% improvement from baseline), suggesting that the intervention program of hip strengthening exercises may have clinical significance in alleviating patient pain.

In recent years, numerous studies have compared the therapeutic outcomes of hip strengthening training with those of knee strengthening training. However, the conclusions reached have not been consistent [13–15, 26, 28, 31]. In this study, we sought to evaluate the results of the intervention of hip strengthening training versus standard knee strengthening training [13–15, 26–29, 31]. Both types of strengthening training were found to improve pain (VAS) and function (AKPS) in patients with PFP, with significant therapeutic effects. A comparison of the magnitude of the effect sizes of the two intervention modalities revealed that hip strengthening training was superior to knee strengthening training in improving the VAS and AKPS scores, which is consistent with the findings of Baldon et al. [41]. However, a meta-analysis by Na et al. [16] revealed no significant difference between the results of the two interventions, which is inconsistent with the results of the present study. The main difference between this review and the study by Na et al. lies in the analytical approach employed. Na et al. designated their experimental and control groups as hip strengthening and knee strengthening groups, respectively, whereas this review classified its experimental groups as different strengthening regimens (hip strengthening, knee strengthening), with all control groups receiving no intervention. This discrepancy in analytical methodology may have contributed to the differences observed between the two studies' findings. Another reason for this discrepancy may lie in the different baseline levels of the patients, which may influence the efficacy of different intensive training regimens. A study comparing the success rates of different PFP treatment modalities [42] revealed that patients with PFP who experienced more pain at baseline but were still able to maintain a high level of function may benefit from hip and core strengthening. A review of the baseline characteristics of the patients included in the study revealed that the mean preintervention VAS score was 5.9, and the AKPS score was 72.9. These findings suggest that patients may benefit more from hip strengthening than from knee strengthening.

Effects of lower limb strengthening training on the lower limb biomechanical characteristics of PFP patients

A review of the literature revealed that the majority of patients with PFP exhibit abnormal hip muscle function [43]. Hip strengthening exercises have been demonstrated to be an effective means of increasing hip muscle strength, relieving PFP and improving knee function. They have also been established as the basis of objective treatment for patients with PFP [44]. Moderate evidence [13, 15, 23–26, 28] shows that hip strengthening exercises were significantly efficacious in enhancing the strength of both hip abductors and external rotators. The current body of research indicates that patients with PFP tend to exhibit reduced hip muscle strength [45, 46]. Ireland et al. [46] reported a 26% reduction in hip abductor strength and a 36% reduction in hip lateral rotator strength in female patients with PFP compared with their healthy counterparts. Similarly, Souza et al. [45] reported that patients with PFP presented 14% and 17% lower hip abductor and hip lateral rotator strengths, respectively, than healthy individuals did. Hip muscle strength (abductor and external rotator) clearly plays a pivotal role in maintaining knee and pelvic stability [47]. Hip abductors and external rotators act in a synergistic manner to eccentrically control hip internal rotation [48, 49]. Strengthening of the hip abductors serves to reduce the degree of abnormal lateral internal rotation of the femur and prevent increased contact pressure between the lateral patella and lateral femoral condyle [50]. Furthermore, strengthening of the hip external rotator limits the rotation of the femur around the tibia, thereby preventing dislocation of the knee joint. This also maintains the biomechanical balance between the hip extensors and lateral rotators, ensures stable loads on the ligaments and subchondral bone, and protects the patellofemoral joint, thus preventing knee dysfunction to a certain extent [45].

It is commonly accepted that quadriceps weakness and muscle imbalance are among the primary causes of increased stress in the patellofemoral joint [5]. Strong evidence suggests that knee strengthening training do not significantly differ from no intervention in enhancing knee extensor strength in patients with PFP [13, 15, 26, 28]. The stabilization of their strength may be attributed to the presence of pain, which impedes the full activation of the knee extensors. A review study [51] demonstrated that patients with PFP exhibited significantly reduced quadriceps activation. Furthermore, the study revealed that the efficacy of hip strengthening training was superior to that of knee strengthening training, potentially due to the absence of notable improvements in the strength of the knee extensors. As the sole dynamic stabilizing structure of the patella, increased muscle strength of the quadriceps enables better maintenance of the patellar sliding trajectory and enhancement of knee joint stability [52]. The medial and lateral femoral muscles work in concert to stabilize the patella by maintaining a balance between the two in terms of activation level and time. This prevents lateral patellar excursion and abnormal changes in patellofemoral joint pressure; maintains knee joint stability; and improves pathological changes in pain, dysfunction, and patellofemoral cartilage in patients with PFP [53].

Research limitations and prospects

Several limitations should be considered when interpreting the results of this review. During the screening process of included articles, only English-language trials were included, which may have limited the generalizability of the findings. Additionally, significant heterogeneity was observed for some outcome measures during the meta-analysis. Further analysis using meta-regression revealed that intervention duration and sample characteristics were particularly heterogeneous. Future studies should consider the impact of sample characteristics, interventions, intervention duration, and other potential variables that may influence outcomes. Including trials from multiple languages to minimize language bias would also be beneficial. This could help reduce heterogeneity and improve the interpretability and consistency of the results.

Conclusion

The results of this study demonstrate that hip and knee strengthening training have a positive effect on pain reduction and on enhancing knee function in patients with PFP and are effective in improving lower limb biomechanics. Although the number of available studies is limited, the evidence from moderate evidence suggests that hip strengthening training are more helpful than knee strengthening training in improving pain and function in patients. Future research should focus on comparing specific different types of strengthening training programs to identify the most effective ones. In addition, research should focus on combining hip strengthening with other rehabilitation methods, for example, with knee strengthening training. Clinicians should use hip strengthening as one of the primary training interventions when treating patients with PFP.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40001-025-02347-3.

Supplementary material 1

Acknowledgements
Not applicable.

Author contributions
All the authors contributed to the study conception and design. Data collection and analysis were performed by Z.Z.Y., Z.B.S and Y.Y.H. The first draft of the manuscript was written by Z.Z.Y., while Z.Z.Y. and S.Y.P. helped revise the manuscript. All the authors commented on previous versions of the manuscript. All the authors read and approved the final manuscript.

Funding
The authors have not received a specific grant for this research from any funding agency in the public, commercial or not-for-profit sectors.

Availability of data and materials
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Author details
[1]College of Physical Education and Health, East China Normal University, Shanghai 200241, China. [2]Key Laboratory of Adolescent Health Assessment and Exercise Intervention of Ministry of Education, East China Normal University, Shanghai 200241, China. [3]Department of Physical Education, College of Education, Zhejiang University, Hangzhou 310058, China.

Received: 1 September 2024 Accepted: 30 January 2025
Published online: 08 February 2025

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