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NON-OPERATIVE MANAGEMENT OF ANTERIOR KNEE PAIN (T BESIER AND M FREDERICSON, SECTION EDITORS)

Gait Retraining as an Intervention for Patellofemoral Pain

Irene S. Davis [1,2] · Adam S. Tenforde [1,2] · Bradley S. Neal [3] · Jenevieve L. Roper [4] · Richard W. Willy [5]

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Abstract

Purpose of Review Movement retraining in rehabilitation is the process by which a motor program is changed with the overall goal of reducing pain or injury risk. Movement retraining is an important component of interventions to address patellofemoral pain. The purpose of this paper is to review the methods and results of current retraining studies that are aimed at reducing symptoms of patellofemoral pain.

Recent Findings The majority of studies reviewed demonstrated some improvement in patellofemoral pain symptoms and overall function. However, the degree of improvement as well as the persistence of improvement over time varied between studies. The greatest pain reduction and persistent changes were noted in those studies that incorporated a faded feedback design including between 8 and 18 sessions over 2–6 weeks, typically 3–4 sessions per week. Additionally, dosage in these studies increased to 30–45 min during later sessions, resulting in 177–196 total minutes of retraining. In contrast, pain reductions and persistence of changes were the least in studies where overall retraining volume was low and feedback was either absent or continual.

Summary Faulty movement patterns have been associated with patellofemoral pain. Studies have shown that strengthening alone does not alter these patterns, and that addressing the motor program is needed to effect these changes. Based upon the studies reviewed here, retraining faulty patterns, when present, appears to play a significant role in addressing patellofemoral pain. Therefore, movement retraining, while adhering to basic motor control principles, should be part of a therapist's intervention skillset when treating patients with PFP.

Keywords Patellofemoral pain · Movement retraining · Gait retraining · Motor learning

This article is part of the Topical Collection on *Non-Operative Management of Anterior Knee Pain*

✉ Irene S. Davis
isdavis@mgh.harvard.edu

1 Department of Physical Medicine and Rehabilitation, Harvard Medical School, Boston, MA, USA

2 Spaulding National Running Center, 1575 Cambridge St, Cambridge, MA 02138, USA

3 Sports & Exercise Medicine, Queen Mary University of London, London, UK

4 Department of Health and Human Sciences, Loyola Marymount University, Los Angeles, CA, USA

5 School of Physical Therapy & Health Sciences, University of Montana, Missoula, MT, USA

Overview on a Physician's Perspective on Retraining

Patellofemoral pain (PFP) is one of the most common lower extremity injuries in recreational athletes [1]. It has been reported that over one-third of runners will experience chronic knee pain [2, 3]. Additionally, having PFP as a young adult can serve as a risk factor for knee arthritis later in life [4, 5]. PFP often presents itself without any further radiologic or other imaging features. Appropriately, PFP has been described as "one of the most vexatious clinical challenges in rehabilitative medicine" [6].

The medical treatment for PFP is typically non-surgical. Non-steroidal anti-inflammatory medications (NSAIDs), acetaminophen, and other oral medications are considered for pain relief. While steroid injections have been traditionally offered, there is limited evidence for their success and compelling evidence suggests that both steroid and anesthetic are chondrotoxic [7]. Further, there is only limited evidence for alternative forms of injection including hyaluronic acid or use of orthobiological agents (such as platelet-rich plasma or regenerative medicine techniques).

Physical therapy is the mainstay treatment for PFP. This typically involves exercise in various forms, bracing, taping, foot orthotics, and a gradual return to sport. However, there are instances when this approach does not successfully resolve symptoms, especially once an athlete begins to increase their running volume or activity. The return of symptoms generates frustration for both the athlete and physician. When the standard approach has failed, it may be because the underlying cause of the problem has not been addressed. Emerging evidence suggests gait retraining provides an effective intervention in the management of PFP. When an athlete fails to see a resolution in symptoms, despite measured gains in strength and flexibility with physical therapy, they may be receptive to a gait retraining approach.

Gait retraining entails a significant time commitment. A new gait pattern places different demands on the body requiring adequate strengthening in preparation. The retraining phase can last 4–6 weeks followed by 2–3 months of habituation and gradual increase in mileage and overall activity. Therefore, deciding to take this approach requires some shared clinical decision-making as to the best time to begin a retraining program. Time in the season, upcoming planned competitions, and the state of injury in readiness all factor into when to start retraining program. The athlete needs to be counselled regarding anticipated time to habituation in order to reduce risk for future injury. Recreational runners and beginner athletes may be more receptive to make these changes. Professional athletes often have schedules that require faster return to competition not allowing for the time needed to alter and habituate to a new gait pattern. Unless they are taking time off for their injury, these athletes are likely to be less amenable to gait retraining and more appropriate for standard courses of physical therapy. Therefore, the physician plays an important role in deciding which athletes are most appropriate for a retraining intervention.

Introduction to Retraining

The biomechanical etiology of PFP is multifactorial in nature [8•]. However, one important underlying factor is the magnitude of patellofemoral joint stress. Running is a common activity in overground sports and has been the primary sport in which PFP and gait retraining have been studied. It has been reported that runners with PFP exhibit greater peak patellar stress compared with healthy runners [9•]. Elevated patellofemoral joint stress may be due to higher patellofemoral joint forces [10] which can result from higher ground reaction forces. These increased stresses may also be the result of altered hip and knee kinematics which can, in turn, reduce the patellofemoral joint contact area [9•, 11•]. Some of the abnormal movement patterns that have been associated with PFP include increased hip adduction, internal rotation, and contralateral pelvic drop [12•]. Thus, interventions may aim to either alter these movement patterns or reduce ground reaction forces during running to reduce patellofemoral joint stress.

The most common intervention approach to changing abnormal movement patterns is strengthening the muscles that control those aberrant movements. However, studies that have involved strengthening report persistent symptoms in long-term follow-ups. For example, 5.7 years following a strengthening intervention for individuals with PFP, it was reported 80% continued to have pain and 74% had to reduce their physical activity [13]. This begs the question as to why strengthening, as an isolated intervention, fails in the long term. In order to address this, Willy et al. randomized 40 asymptomatic individuals with increased hip adduction into a hip strengthening group and a control group [14]. The 6-week progressive strengthening program was directed at the hip abductors and external rotators. Despite the significant increase in strength of these muscles following the intervention, there were no reductions in hip adduction, internal rotation, or contralateral pelvic drop during running. These are common movement disorders associated with PFP [12•]. These results by Willy [14] and others [15] suggest that strengthening alone does not change a movement pattern. Strengthening may provide the *capacity* to move differently, but reprogramming of the motor pattern through movement retraining is needed to alter the way a person moves.

Movement retraining in rehabilitation is the process by which a motor program is changed with the overall goal of reducing pain or injury risk. This retraining requires that the individual has the capacity both in terms of range of motion and strength to achieve the new movement pattern, as well as the endurance for it to persist. These pre-requisites should be met before beginning a retraining program. There are a number of motor learning principles that need to be adhered to in order to retrain a motor pattern. One of the most important features of a retraining program is the provision of some type of feedback. Feedback can take on many forms such as visual, auditory, or haptic. This feedback allows the individual to make the connection between, for example, what they see as correct movement and what that movement feels like. The participant must be given adequate practice/dosage to reinforce this motor pattern [16]. Finally, the feedback should be gradually removed such that the learner relies on their own intrinsic cues (proprioception, kinesthesia) associated with the correct movement pattern [16, 17]. This is commonly referred to as a faded feedback design.

The purpose of this paper is to review the methods and results of current retraining studies that are aimed at reducing symptoms of PFP. The studies will be presented in three groups: studies aimed at changing kinematics during running, studies directed at altering temporospatial characteristics during running, and retraining studies of functional movements such as stair negotiation and single-leg squat. The paper will end with a summary of these studies, their application to the clinic, and finally recommendations for future retraining investigations.

Kinematic Retraining Studies of Running

Kinematic gait retraining refers to cueing and provision of feedback for specific changes in joint or segment orientations to reduce loading on the patellofemoral joint during running. To date, kinematic gait retraining for PFP has been focused on (a) reducing hip adduction, (b) transition from a rearfoot strike pattern to a forefoot strike pattern, and (c) adopting a more forward trunk lean. The first strategy targets the kinematic influences of patellofemoral joint contact area whereas the latter two retraining strategies aim to reduce patellofemoral joint contact force.

Female runners with PFP often demonstrate greater peak hip adduction [18–21] and hip internal rotation kinematics [22, 23] compared with uninjured female runners. While male runners with PFP demonstrate a different pattern of greater knee adduction, 17% of males demonstrate the female pattern of increased hip adduction [24], Increased hip adduction has been shown to increase lateral patellar tracking [25], leading to elevated lateral patellofemoral joint stress due to a reduction in patellofemoral contact area [26, 27]. Two case series of 10 participants with PFP and excessive hip adduction utilized visual feedback to improve hip mechanics. Noehren et al. [28] provided real-time feedback on the hip adduction angle during running over the course of 8 sessions of gait retraining. Sessions started at 15 min and increased to 30 min over the 8 sessions across 2 weeks. Feedback was provided on a video monitor placed in front of a treadmill that displayed the real-time kinematic curves of the runner's hip adduction. The feedback was faded over the last four sessions (Fig. 1). The persistence of the biomechanical and clinical outcomes was assessed at a 1-month follow-up. In a similar investigation, Willy et al. [29] used a full-length mirror to provide visual feedback on hip adduction during running, given that mirrors are available in most clinics. These authors asked runners to increase the distance between their knees and point their patellae straight ahead by activating their gluteal muscles. Again, 8 sessions of faded feedback retraining were conducted over 2 weeks with results being measured post training and at 1- and 3-month follow-ups. Participants in studies by both Noehren et al. [28] and Willy et al. [29] demonstrated reductions in peak hip adduction, internal rotation, and contralateral pelvic drop during running (Fig. 2). They also reported improvements in pain (scored via visual analog scale) and function [28, 29]. These changes largely persisted for 1 month [28, 29] and 3 months [29] after the retraining periods (Fig. 3—*Willy hip adduction curve*). At 3 months, Willy et al. reported that hip adduction regressed by 2° from the post-test. While this change was not significant, it suggests there may have been some drift towards the baseline measure. However, pain levels remained at post-retraining levels [29].

Transitioning to a forefoot strike pattern shifts some of the demand of the knee extensors to the plantar flexors [30], effectively reducing the patellofemoral joint stress. This transition can also eliminate the impact transient of the vertical ground reaction force, thereby reducing the vertical load rate. This load rate has been associated with PFP [31]. Three studies have used this forefoot strike transition to treat PFP. In a pilot study, 3 runners with PFP were provided real-time feedback from an insole sensor that provided an audible alarm when they landed on their heel [32]. The runners underwent 8 sessions of retraining over 2 weeks with a faded feedback design that incorporated a gradual reduction of audible feedback while run time increased. Post training, and at the 3-month follow-up, the runners exhibited lower vertical load rates and reduced knee pain and were able to return to the prior level of running. Using a randomized control design, Roper et al. [33] conducted a gait retraining program to transition to a forefoot strike in rearfoot strikers with PFP. Runners were randomized to either a retraining or a control group. Runners in the retraining group received both verbal and visual (via a mirror) feedback over the course of 8 retraining sessions, using a faded feedback design similar to Cheung et al. [29]. The control completed the same 8 sessions of treadmill running with a matched run time schedule [33], but without the verbal or visual feedback. Runners in the retraining group experienced large improvements in pain with 50% reductions in average patellofemoral joint stress during early stance phase. Importantly, the control group did not demonstrate reductions in knee pain at the conclusion of the sham intervention. Furthermore, these improvements persisted at the 30-day follow-up. Finally, dos Santos [34••] conducted a retraining study using faded verbal cuing to retrain six rearfoot strike runners with PFP to transition to a forefoot strike pattern. Following this retraining, patellofemoral joint stress was reduced by 27% and pain was reduced by 75% at the 6-month follow-up.

Adopting a forward trunk lean during running may also be a viable retraining strategy to reduce patellofemoral joint loads in individuals with PFP [35]. As part of the previously described study, dos Santos and colleagues [36••] instructed six runners with PFP to increase their forward lean. This was done by providing faded verbal cuing over 8 sessions. This approach resulted in a significant reduction in pain both at the post-training and at the 6 month follow-up. However, one concern with this study is that runners had relatively normal trunk lean at baseline (10.8°) which increased to 18° post

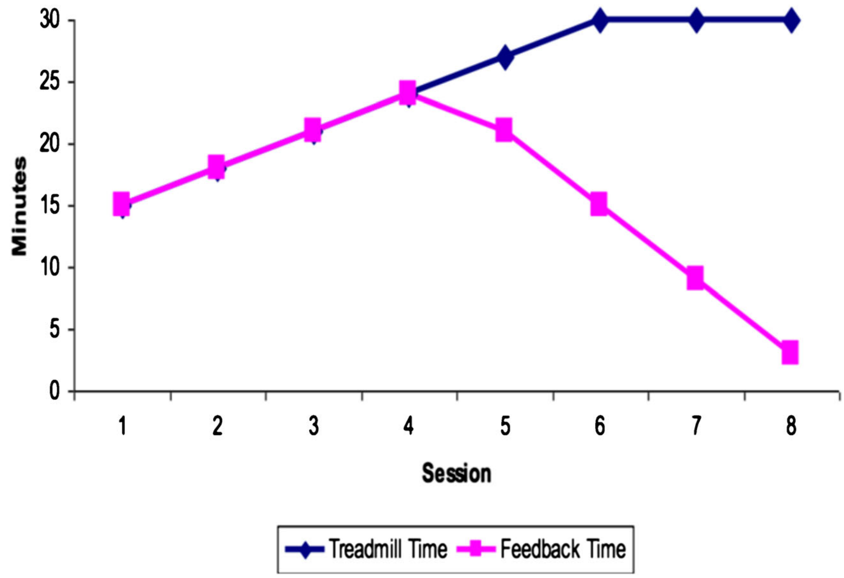

Fig. 1 Retraining schedule. Run time increases from 15 to 30 min over 8 sessions. Feedback is faded during the last 4 sessions

training. This amount of trunk flexion might be considered excessive and may result in secondary negative consequences.

Spatiotemporal Retraining Studies of Running

Spatiotemporal retraining consists of altering a runner's step rate/cadence to a set percentage above their baseline measurement [36••, 37, 38•]. This can be done easily using watch-based metronome applications and so is a simple intervention to employ. Studies have demonstrated that increasing step rate by 7.5–10% can acutely reduce peak hip adduction while also reducing the negative knee work by 27–34% [39, 40] and patellofemoral joint stress by 10–22% [41, 42]. Based upon these results in healthy individuals, increasing step rate has become one of the retraining interventions suggested for PFP.

Esculier and colleagues [37] conducted an RCT to compare gait retraining to increase cadence with education on load management and exercise targeting the hip and knee musculature. The study enrolled 69 participants, with 23 being allocated to one of three groups: education, education and

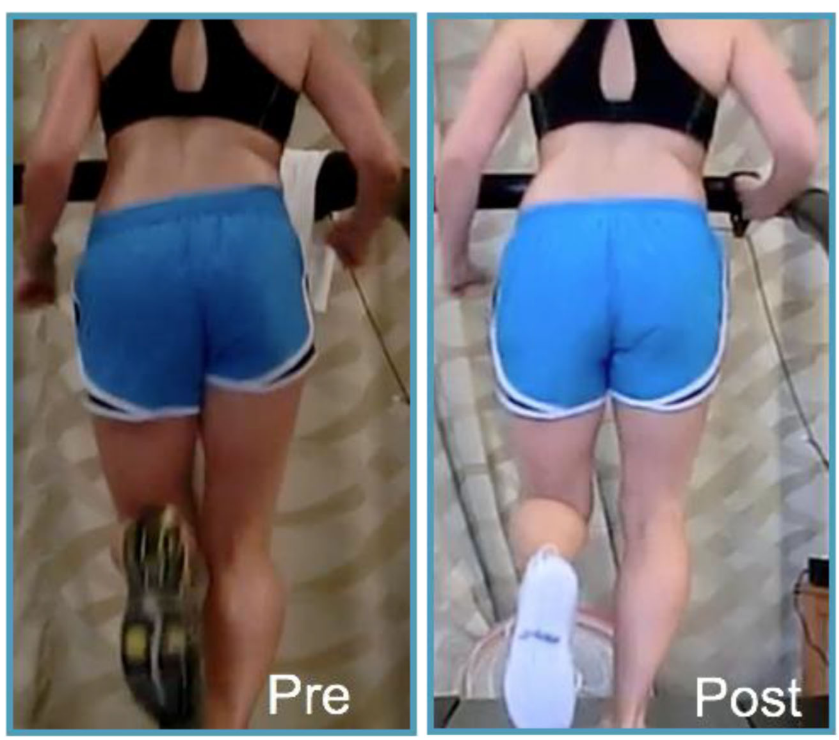

Fig. 2 Hip mechanics pre- and post-retraining. Note the reductions in hip adduction and contralateral pelvic drop following the retraining

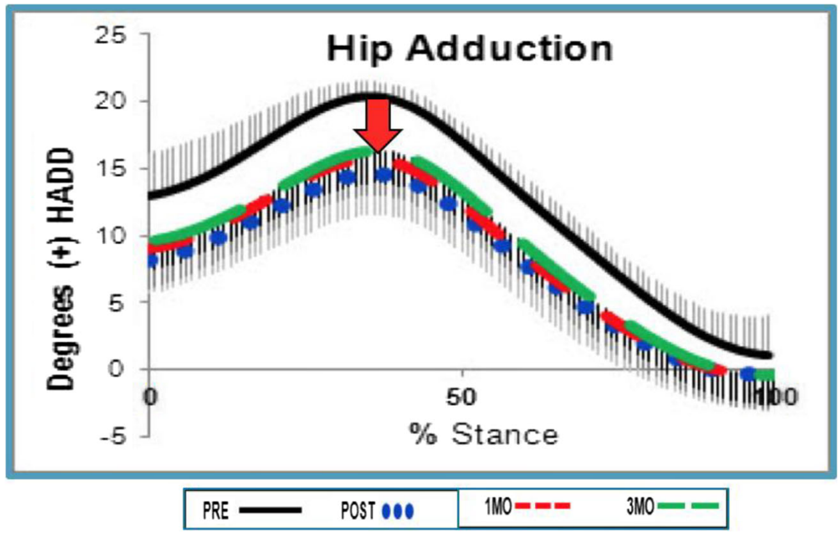

Fig. 3 Hip adduction reductions noted following retraining and at the 1- and 3-month follow-ups (Willy et al. 2012)

exercise, and education with gait retraining. The gait retraining group underwent five 10-min treadmill sessions over 8 weeks. However, it should be noted that the retraining group was mixed with rearfoot and forefoot strikers. Rearfoot strike runners who were unable to increase their cadence were then cued to use a forefoot strike pattern and land softer. Neither structured nor faded feedback was provided. All three groups demonstrated small, but similar, improvements in outcomes, including pain and function leading the authors to conclude that education alone may be adequate for the treatment of PFP. However, given lack of structured and faded feedback, the validity of the retraining design is questioned. Additionally, it is unknown whether the small reductions in pain noted with the 3 interventions exceeded "wait and see" since a control group was not included.

Neal and colleagues [38•] conducted a feasibility study and recruited 10 participants with PFP for a gait retraining program that focused on increasing step rate by 7.5%. The program included 3 sessions a week for 6 weeks, with feedback provided using a metronome in a faded design. Participants experienced a significant reduction in average pain and improvement in function post-retraining. Worst pain scores improved from 6.8/10 to 2.9/10, which was a significant improvement but indicated continued dysfunction. Additionally, 3/10 participants were unable to increase step rate by 7.5%. This suggests that not all patients may be able to increase their step rates sufficiently to reduce their pain.

Bonacci et al. [36••] conducted a feasibility RCT to investigate the effect of a 6-week gait retraining program to increase cadence by 10%. Sixteen participants were recruited and randomized to either a foot orthoses or a gait retraining group. Participants in the gait retraining group performed 10 gait retraining sessions over 6 weeks to increase their cadence and were also issued minimalist shoes. This program transitioned runners from 50/50% walk/run to 100% running over the course of the 10 sessions, with metronome feedback provided in a faded feedback design. Participants then ran on their own for the following 6 weeks. Participants in the gait retraining group experienced an 81% reduction in pain at the 6-week follow-up. While increasing cadence has been shown to reduce patellofemoral joint loads by 10–22% [41, 42], Sinclair et al. [43] reported that wearing a minimalist shoe reduced these loads by approximately 9%. Thus, the combined use of the minimalist shoe with increasing cadence makes it difficult to discern the direct cause of the reduction in pain and improvement in function.

Finally, dos Santos et al. [34••] used verbal cuing and a metronome, in a faded feedback design over 8 sessions, to increase the cadence of six runners with PFP by 10%. These authors found that pain was not significantly reduced post training, but later demonstrated a significant reduction at the 6 month follow-up.

Functional Movement Retraining

In addition to the work conducted on running, there is emerging evidence supporting efficacy of functional movement retraining interventions for other functional tasks in participants with PFP. These studies include a mix of both randomized controlled trials (RCTs) and case series.

Baldon et al. [44] implemented an RCT comparing traditional quadriceps strengthening intervention with and without additional facilitation of improved motor control of the lower limb, pelvis, and trunk. Participants were instructed to perform all exercises with neutral frontal plane alignment and a forward trunk lean. Three sessions per week were completed for 8 weeks, supervised by a single physical therapist. Participants in the motor control group demonstrated significant improvements in 3D kinematics during a single-leg squat task. This included decreased ipsilateral trunk lean, hip adduction, knee abduction, and contralateral pelvic depression excursion. Both groups demonstrated a reduction in average pain (during the previous week) post-retraining and at 3-month follow-up. However, significantly greater improvements were noted for the motor control group at both time points.

Rabelo et al. [45] conducted a similar RCT, assessing the effect of two interventions on a step down test in 34 women. The authors compared a traditional quadriceps and gluteal strengthening program with the same program with additional facilitation of improved motor control of the lower limb, pelvis, and trunk. Participants in the motor control group were instructed to correct these faults in their movement patterns during functional activities such as the single-leg squat and forward lunge. Three sessions per week were completed for 4 weeks, all of which were supervised by one of two physical therapists. Continual feedback was provided using both mirror and verbal cues. Both groups demonstrated reduced pain (measured using a numerical rating scale), but no differences between groups were noted for any of the follow-up points (4 weeks, 3 months, or 6 months). Those in the motor control group demonstrated a significant improvement in function at 3 months, reflected by a higher Kujala score. However, unlike with Baldon, this effect had washed out by the 6-month follow-up. Finally, there were no between-group differences in 3D kinematics during a step down task at any follow-up point. The superior results reported by Baldon et al. [44] may be due to the specificity of training. Their functional outcome test was a single-leg squat, the same task that was included in the motor retraining program. Willy and Davis [14] also identified improvements in a single-leg squat after a strengthening intervention that included single-leg squat training with verbal and visual feedback on alignment.

While RCTs are the strongest methodologic design, other types of studies have been used to examine the effect of retraining on functional activities. Salsich et al. [46•] conducted a feasibility study that involved twice-weekly sessions for 6 weeks. Twenty-five participants with PFP were provided with a variety of verbal and visual cues to ensure optimal kinematic alignment during functional tasks. These included single- and double-leg squats, ascending and descending stairs, and sitting and rising from a chair. The authors reported significant improvements in pain, function, and single-leg squat kinematics following the training. Liebbrandt and Louw [47•] used a comparable methodology to Salsich et al. [46•]. Eight participants with PFP (five females, three males) were provided with an individualized retraining program, to be completed four times per week for 6 weeks (one supervised, three independent sessions). The program was aimed at improving walking gait mechanics, squatting, and stair negotiation. Average pain was reduced by 3.6 points on a numerical rating scale (from 3.9 to 0.3) and seven out of the eight participants demonstrated improvement in their biomechanical outcomes during the functional activities. Finally, in a single case study of a female patient with PFP, Yemm and Krause [48] used functional retraining to reduce the frontal plane projection angle (i.e., hip adduction, internal rotation, knee valgus) during a single-leg step down. They provided mirror and verbal feedback continuously during 4 training sessions over 3 weeks. Immediately following the completion of the retraining period, PFP reduced from 4/10 to 1/10 and the frontal plane projection angle during the step down was reduced to normal. However, there was no follow-up to determine persistence of these changes.

Discussion

The results of the retraining studies for individuals with PFP are summarized in Table 1. The majority of these studies have been conducted in running and have focused on reducing hip adduction, increasing forward lean, transitioning to a forefoot strike pattern, and increasing cadence. A number of investigations have focused on improvement in functional activities such as walking, squatting, stair negotiation, and rising from a chair. Studies have all reported some improvements in mechanics, pain, and function. However, the degree of improvement was not consistent across studies.

Studies that adhered to motor control principles, such as utilizing a faded feedback design and providing adequate dosage appeared to have the greatest effect. For example, the greatest pain reduction and persistent changes over time were noted in those studies that included between 8 and 18 sessions over 2–6 weeks, typically 3–4 sessions/week [28, 29, 32, 33]. Additionally, dosage in these studies increased to 30–45 min during later sessions, resulting in 177–196 total minutes of retraining. In contrast, pain reductions were the least in studies where overall retraining volume was low and feedback was either absent or continual. For instance, Esculier et al. [37] only utilized verbal cuing, without faded feedback and which was limited to 5 sessions, 10 min in length (50 total minutes of retraining) over 7 weeks. Post-training running pain was 3.5/10 in the retraining group compared with 0.5–1.0/10 in previous retraining studies [29, 33, 49], where a faded feedback design was used. Additionally, the retraining group remained symptomatic at the 20-week follow-up (running pain VAS = 2.5), suggesting that treatment dosage was inadequate. While the functional training studies did demonstrate improvements, most were conducted using non-structured feedback or verbal cuing with no feedback. Many of these functional retraining studies did not include a follow-up to determine whether changes persisted. It is plausible that even greater results may have been achieved using a faded feedback protocol [50].

There have been a number of retraining studies involving healthy runners that have focused on altering mechanics associated with PFP that can further inform clinical interventions.

Table 1 Summary of narrative review for studies on movement retraining for patellofemoral pain

Author/type	*n*	Age (years)	Sex	Protocol	Retraining time	Feedback type	Feedback frequency	Post-retraining follow-up	Biomechanical outcomes	Functional outcomes	VAS pain* pre (*x*/10)	VAS pain post (*x*/10)	VAS pain follow-up (*x*/10)
Running—kinematic FB													
Cheung and Davis 2011/ case series	3	26–32	3 F	2 weeks, 8 sessions	Increasing 15–30 min	Pressure insole in heel	Continual first 4 sessions, then faded	12 weeks	Loading rates reduced	PF pain score reduced Kujala improved	3.1	1.7	1.4
Dos Santos et al. 2019/ RCT (no true control)	18	18–35	9 F, 9 M	Control 2 weeks, 8 sessions	Increasing 15–30 min	Verbal, metronome	Continual first 4 sessions, then faded	24 weeks	Plant flex, Forward trunk lean increased	VAS-A reduced, AKPS improved	5**	2.5**	1**
Noehren et al. 2011/ case series	10	18–35	10 F	2 weeks, 8 sessions	Increasing 15–30 min	Kinematic curves for hip ADD	Continual first 4 sessions, then faded	4 weeks	Pk HADD, HIR, Contr. Pelvic drop reduced, VALR and VILR reduced	VAS-R reduced, LEFS improved	5.0	0.5	0.0
Roper et al. 2016/ RCT	16	18–44	11 F, 5 M	2 weeks, 8 sessions	Increasing 15–30 min	Mirror for foot strike pattern	Continual first 4 sessions, then faded	4 weeks	Knee Add, PF Stress reduced	VAS-R reduced	5.3	1	1
Willy et al. 2012/ case series	13	18–35	13 F	2 weeks, 8 sessions	Increasing 15–30 min	Mirror for hip ADD, IR	Continual first 4 sessions, then faded	12 weeks	Hip Add, Int Rot and CPD reduced	VAS-R reduced, LEFS improved	4.5	0.5	0.5
Running—cadence FB													
Bonacci et al. 2018/RCT (no true control)	16	18–40	12 F, 4 M	6 weeks, 10 sessions	20% weekly training vol.	Minimalist running shoes coupled with Metronome	Continual first 4 weeks, then faded	6 weeks	Cadence increased	VAS-W reduced, AKPS improved	1.8	----	0.4
Esculier et al. 2017/ RCT (no true control)	69	18–45	43 F, 26 M	8 weeks, 5 sessions	10 min/session	Verbal instruction in FFS or cadence	Continual	12 weeks	Cadence increased, AVLR and PFJ avg. load rate reduced	VAS-R reduced, KOS-ADLS improved	6.1	3.5	2.5
Neal et al. 2018/ case series	11	18–45	6 F, 4 M	6 weeks, 18 sessions	Increasing 10–30 min	Metronome for cadence	Continual first 3 sessions, then faded	None	Pk Knee flex, Pk Hip add, Pk Hip Int Rot reduced, cadence increased	NPRS-A reduced	3.0	0.9	----
Functional activities—walking, squatting, stair climbing													
Baldon et al. 2014/ RCT (no true control)	31	18–30	31 F	8 weeks, 24 sessions	90–120 min	Verbal instruction	Continual	12 weeks	Trunk lean, Hip Add and Knee Abd reduced	VAS-W reduced, LEFS improved	6.6	1.4	0.9
	8	18–37	5 F, 3 M	6 weeks, 6 sessions with	Not reported	Verbal	Continual	None	Knee flex, Ankle ROM and Hip	AKPS and LEFS improved in	3.9	0.28	---

Table 1 (continued)

Author/type	n	Age (years)	Sex	Protocol	Retraining time	Feedback type	Feedback frequency	Post-retraining follow-up	Biomechanical outcomes	Functional outcomes	VAS pain* pre (x/10)	VAS pain post (x/10)	VAS pain follow-up (x/10)
Liebbrandt and Louw 2018/case series				PT, plus 18 home ex sessions					Int Rot increased,	only 2 participants, NPRS-A decreased			
Rabelo et al. 2017/ RCT (no true control)	34	25.6	34 F	4 weeks, 12 sessions	Increasing 40–60 min	Verbal, mirror	Continual	24 weeks	Ipsilateral trunk lean increased	AKPS improved, NPRS-A decreased	6.1	2.0	1.3
Salsich et al. 2018/case series	25	22	25 F	6 weeks, 12 sessions, plus daily home ex	45 min/session	Verbal, visual, tactile	Individualized schedule: continual initially, faded	16 weeks	Hip add and med/lat rotation reduced, Knee med/lat rotation increased	VAS-C reduced, PSFS increased	2.2	1.8	0.5
Yemm and Krause 2015/ case study	1	19	1 F	3 weeks, 4 sessions	Not reported	Verbal, mirror	Continual	None	Reduced medial collapse	VAS-C reduced	6	1	---

*VAS/NPRS pain descriptors—*R*, running pain; *C*, current pain; *W*, worst pain over past week; *A*, average pain over past week

**Estimated from graph

Futrell et al. [51•] conducted an RCT retraining study to compare transition to a forefoot strike pattern with increasing cadence by 7.5%. This study included a faded feedback protocol, as well as a 6-month follow-up. Another strength of this study was that a distraction test was used during all running assessments to reduce performance bias. The authors assessed the effect on vertical load rate and reported a 50% reduction in the forefoot strike group that persisted at the 6-month follow-up. In contrast, a small, but insignificant, reduction in vertical load rate was seen in the cadence group. In a more ecologically based study, Willy et al. [40] randomized 30 runners with high vertical load rates into a retraining or control group. The retraining group was trained to increase their cadence by 7.5% using self-controlled faded feedback from a wireless accelerometer and running watch over 8 outdoor running sessions. Runners in the retraining group reduced their load rates by 18% (and their hip adduction by approximately 3°). These studies together suggest that, while cadence may be effective, transitioning to a forefoot strike pattern may be the most effective way to reduce vertical load rates [34••, 51•].

Chan et al. have conducted the only retraining study of healthy individuals which includes a 1-year follow-up of injuries. The authors randomized 320 healthy runners into a control and retraining group [52••]. The retraining group was provided 8 sessions of faded feedback (over 2 weeks) on their vertical ground reaction force during treadmill running and asked to eliminate their impact peak by landing more softly. The control group did the same amount of running, but were given no instructions nor feedback. While the investigators did not measure the associated change in mechanics, transitioning to a forefoot strike pattern is the most effective way to eliminate the impact transient. Therefore, it is likely that many of the subjects used this strategy. The retraining group significantly reduced their vertical load rates, while the control group did not. More importantly, the retraining group experienced a 62% reduction in running-related injuries over the 1-year follow-up period [52••]. Interestingly, there was over a fourfold increase in the number of individuals experiencing PFP in the control group compared with the retraining group (4 vs 18). This suggests that this intervention had a preventative effect for PFP.

Tibial shock has also been used as feedback to reduce vertical load rates in healthy runners. Bowser and colleagues [53•] found a 32% reduction in tibial shock with an associated 25% reduction in vertical load rates following a 2-week, 8-session program using a faded feedback design. These reductions were maintained at the 1-, 6-, and 12-month follow-up, the longest retraining follow-up to date. Clansey et al. [54] also used tibial shock feedback as a means to reduce load rates. In contrast to Bowser, these authors conducted 6 20-min sessions over 3 weeks (2 sessions/week) providing *continual* feedback on tibial shock. They did note significant reductions of 31% for tibial shock and 18% for load rates post training. However, these changes did not persist at the 1-month follow-up, perhaps due to inadequate dosage and continual nature of the feedback.

There are significant limitations to some of the retraining studies to date. A number of these studies did not incorporate a control group, and thus, one cannot be sure that improved symptoms and function were not simply due to the passage of time. Some of the studies had very low participant numbers, limiting statistical power and making extrapolation of the results difficult. Furthermore, some studies addressed retraining mechanics that were not identified to be faulty. Retraining should be focused on subjects demonstrating the specific fault being addressed. For example, it is not advised to retrain runners to further increase their trunk lean or hip adduction if these mechanics are within normal limits. Teng and Powers noted a 7.4% decrease in patellofemoral joint stress when acutely increasing forward lean from an upright 4° forward lean to an average self-selected lean of 7° [55]. While patellofemoral joint stress reduced an additional 6% when flexing from 7 to 14°, this amount of lean might be considered excessive. Similarly, increasing cadence in runners with normal step rates should also be done with caution so as not to result in abnormally high turnover rates. Another limitation to these studies is that the majority involved female cohorts. While females are twice as likely to experience PFP compared with males, males still sustain this injury. Therefore, there is a need to further understand the effect of retraining on males with PFP. Adherence to motor control principles, such as adequate dosage and practice and faded feedback, is needed for true motor learning to occur. This adherence likely contributes to the persistence of the changes. Therefore, additional longer term follow-up studies (beyond 3–6 months) are needed to determine whether changes that are made with retraining truly persist.

In summary, faulty movement patterns have been associated with PFP. Studies have shown that strengthening alone does not alter these patterns, and that addressing the motor program is needed to effect these changes. Based upon the studies reviewed here, retraining faulty patterns, when present, appears to play a significant role in addressing PFP. Therefore, movement retraining, while adhering to basic motor control principles, should be part of a therapist's intervention skillset when treating patients with PFP.

Compliance with Ethical Standards

Conflict of Interest Irene S. Davis, Adam S. Tenforde, Bradley S. Neal, Jenevieve Roper, and Richard W. Willy declare that they have no conflict of interest.

Human and Animal Rights All reported studies/experiments with human or animal subjects performed by the authors have been previously published and complied with all applicable ethical standards (including the Helsinki declaration and its amendments, institutional/national research committee standards, and international/national/institutional guidelines).

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