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Running retraining to treat lower limb injuries: a mixed-methods study of current evidence synthesised with expert opinion

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ABSTRACT

Importance Running-related injuries are highly prevalent.

Objective Synthesise published evidence with international expert opinion on the use of running retraining when treating lower limb injuries.

Design Mixed methods.

Methods A systematic review of clinical and biomechanical findings related to running retraining interventions were synthesised and combined with semistructured interviews with 16 international experts covering clinical reasoning related to the implementation of running retraining.

Results Limited evidence supports the effectiveness of transition from rearfoot to forefoot or midfoot strike and increase step rate or altering proximal mechanics in individuals with anterior exertional lower leg pain; and visual and verbal feedback to reduce hip adduction in females with patellofemoral pain. Despite the paucity of clinical evidence, experts recommended running retraining for: iliotibial band syndrome; plantar fasciopathy (fasciitis); Achilles, patellar, proximal hamstring and gluteal tendinopathy; calf pain; and medial tibial stress syndrome. Tailoring approaches to each injury and individual was recommended to optimise outcomes. Substantial evidence exists for the immediate biomechanical effects of running retraining interventions (46 studies), including evaluation of step rate and strike pattern manipulation, strategies to alter proximal kinematics and cues to reduce impact loading variables.

Summary and relevance Our synthesis of published evidence related to clinical outcomes and biomechanical effects with expert opinion indicates running retraining warrants consideration in the treatment of lower limb injuries in clinical practice.

INTRODUCTION

Running as a means of exercise is popular for both recreation, and as a sport in its own right. However, running is not risk free. Injury incidence ranges from 19% to 78% among studies with follow-up periods between 1 week and 18 months.[1–2] Common running injuries include exertional lower leg pain, plantar fasciopathy, Achilles tendinopathy, calf pain, medial tibial stress syndrome, patellofemoral pain (PFP), iliotibial band syndrome (ITBS), patellar tendinopathy, hamstring injury including proximal tendinopathy and gluteal tendinopathy.[1] Proposed intrinsic factors for running-related injury include older age,[3] higher body mass index,[4] history of prior injury,[1] limb length discrepancy,[5] abnormal anatomical alignment[5] and foot posture,[6 7] and faulty foot loading patterns.[8 9] Proposed extrinsic factors include level of competition,[10] training accumulation,[11] shoe type[5] and training surface.[12] Multiple interventions have been developed in an attempt to mitigate these risks and treat injuries that develop, including exercise programmes to improve strength, neuromuscular control and flexibility,[13 14] footwear modification,[13 15] foot orthoses,[13 16 17] and taping techniques.[13 18] Despite extensive research in all areas, a lack of effective long-term treatment strategies remains a source of frustration for many runners and clinicians.

Alteration to running technique may help to treat running injuries by reducing load in certain muscle groups and joints.[19 20] This theory was tested by Davis[21] introducing the coaching concept of running retraining to treat lower limb injuries in a case series of five patients who reported pain reduction and maintained a changed running technique. The process involved (1) identifying any theoretical abnormal running mechanics which may be contributing to tissue overload; (2) establishing if running mechanics could be altered; and (3) facilitating the desired running mechanics changes and encouraging motor learning to ensure maintenance of any change. Despite nearly 10 years since the publication of this paper, only four small case series evaluating the effectiveness of running retraining interventions in reducing pain have been published.[22–25]

Biomechanical studies in asymptomatic populations have examined retraining strategies extensively (including altering step rate, strike pattern, hip and knee motion, trunk position, step width, and impact loading variables), and reported to change running kinematics, kinetics and electromyography. A recent systematic review by Napier *et al*[26] concluded a number of biomechanical variables can be altered by running retraining interventions. Additionally, they concluded the most effective strategy for reducing impact loading variables including vertical impact peak, and average and instantaneous loading rate was provision of real-time feedback related to kinetics and/or kinematics. However, the importance of these impact loading variables to injury are not supported by strong evidence, and the review by Napier *et al*[26] did not provide a synthesis of current published clinical outcomes, despite emerging evidence.[22–25]

Many interventions studied in previous running retraining research may not translate to clinical practice well, due to issues with practicality (eg, real-time three-dimensional (3D) motion analysis feedback), and the 'one size fits all' approach of associated methodology (eg, all participants transition from a rearfoot to forefoot strike). It also remains unclear how running retraining may interact with other interventions with an established evidence base such as exercise rehabilitation.[27–29] Given this lack of evidence to guide clinicians and researchers in the practical implementation of running retraining, consultation with those already prescribing running retraining in clinical practice may provide valuable insight. Such consultation is part of evidence-based practice, particularly where clinical trials are lacking.[30]

Our mixed-methods study had three objectives: (1) to systematically review and summarise the clinical and biomechanical evidence for implementing running retraining to treat lower limb injuries; (2) explore the clinical reasoning related to the use of running retraining by international experts; and (3) synthesise these elements to provide guidance for clinicians and researchers who seek to implement and evaluate running retraining interventions in the future.

METHODS

Systematic review

Inclusion and exclusion criteria

Running retraining was defined as 'the implementation of any cue or strategy to alter an individual's running technique'.[21] Studies evaluating other interventions in conjunction with running retraining were considered if the effects of retraining could be clearly delineated (eg, altering footwear combined with instruction of strike pattern, compared with altering footwear alone). Two streams of studies were sought:

1. Studies evaluating clinical outcomes (ie, changes to pain and/or function) following running retraining interventions in symptomatic running populations;
2. Studies evaluating changes to lower limb biomechanics (kinetic, kinematic or neuromotor) during running in symptomatic and asymptomatic populations.

Studies with less than 10 participants in total or in the running retraining intervention group were excluded. This criteria were applied to minimise the risk of potentially false-positive or false-negative findings influencing the evidence synthesis.

Search strategy

MEDLINE, EMBASE, CINAHL and Current Contents were searched in June 2015. The search strategy and results for each data base can be found in online supplementary file 1.

Review process

Titles and abstracts found during the initial electronic search were uploaded into Endnote X6 (Thomson Reuters, New York, USA), duplicates removed, and each screened for inclusion by two independent reviewers (DRB and BSN). To resolve disagreement about exclusion, a third reviewer (CJB) was available. Where necessary, the full text was retrieved.

Quality assessment

Two independent reviewers (CJB and DRB) evaluated the methodological quality of each included study using the Downs and Black quality index which consists of 27 items (maximum score of 28).[31] A third reviewer (BSN) was available to resolve any disagreements. Based on quality assessment scores, studies were categorised as high quality (≥20), moderate quality (17–19) or low quality (≤16). Owing to the lack of randomised controlled trials and high-quality studies identified, meta-analysis was not performed. However, where possible, similar findings were combined in results tables for various retraining interventions, and the quality of these associated studies subsequently used to determine the level of evidence for each finding based on a modified version of the van Tulder *et al*[32] criteria:

1. Strong=consistent findings among multiple studies including at least three high-quality studies;
2. Moderate=consistent findings among multiple trials, including at least three moderate-quality/high-quality studies or two high-quality studies;
3. Limited=consistent findings among multiple low-quality/moderate-quality studies, or one high-quality study;
4. Very limited=findings from one low-quality/moderate-quality study.

Semistructured interviews

Participants

Prospective interview participants were initially identified from author lists of running retraining-related literature. Experts were required to be actively participating in running retraining research, have at least 5 years clinical experience, and be prescribing running retraining regularly to treat patients with running injuries. It was felt that experts with a good blend of clinical experience and research knowledge would be able to provide the best information on the perceptions of current evidence (published and unpublished), and its external applicability for clinical practice. Sixteen international experts from the UK, the USA, Canada and Australia were included and interviewed. Among them were 11 physiotherapists, 2 physical therapists, 1 sports physician, 1 medical doctor and 1 running coach. Further details related to participant characteristics are detailed in online supplementary file 2. Ethical approval was granted by La Trobe University's Faculty of Human Ethics Committee (FHEC13/151). Each participant provided informed consent.

Interview process

One interviewer (JC) completed and recorded all interviews via Skype or in person where possible. Each was then transcribed for further analysis. The interviewer was a physiotherapist with 9 years clinical experience, and used running retraining interventions as part of their clinical practice. To facilitate discussion, a topic guide (see online supplementary file 3) was presented to each participant during the interview process. Content of the topic guide was based on a preliminary review of the literature and discussion between the research team.

Data analysis

Qualitative data were evaluated using a 'Framework' approach[33] by a physiotherapist (CJB) with experience in conducting interviews and evaluating data related to qualitative research. Each transcript was read to gain familiarity, and then a thematic framework was formed by mapping the ideas and opinions stated by the interviewees and combining these to generate themes and subthemes, subsequently tabulated with each interviewee being coded to enable anonymous quote attribution. Additional interviews were performed until data saturation, whereby no new themes were identified. An additional physiotherapist (PM) and sports physician (AF-M) also read through each interview transcript to reinforce the analysis. Of particular interest was information related to the current evidence base, appropriateness of running retraining to treat lower limb injuries, specific lower limb conditions and associated retraining strategies which may be effective in clinical practice, and the

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practical application of specific running retraining strategies and their interaction with other interventions. Triangulation was by means of respondent validation and performed by presenting each interviewee with the final themes, subthemes and accompanying findings, and requesting any free comment. Any new comment was added to the framework analysis.

Synthesis of review findings with expert opinion

For the purpose of synthesising evidence with expert opinion, retraining interventions discussed and suggested for various lower limb injuries were tabulated along with illustrative quotes and potential biomechanical rationale identified in the systematic review.

RESULTS

Search results

After screening title and abstract, full texts were obtained for 70 studies. The primary reason for exclusion on obtainment of full text was inadequate participant numbers (ie, less than 10 participants per group), and included six studies on step rate manipulation,[34–38] five studies on strike pattern comparison[36 39–42] including one in a PFP population,[41] one study on step width manipulation,[43] one study on cues to reduce hip adduction,[44] two studies on reducing impact loading variables[45 46] and three combination studies.[40 47–49] Additional reasons for exclusion included one combination study for absence of clinical or biomechanical analysis,[50] one combination study for including transition to minimalist footwear during gait retraining,[51] two step rate manipulation studies[52 53] for absence of statistical comparison of biomechanical differences and one step rate manipulation study[54] which combined hill running. A total of 46 studies met the inclusion criteria. A flow chart of the search results can be found in online supplementary file 1.

Quality assessment

Results of the quality assessment can be found in online supplementary file 4. Of the 46 included studies, 13 were high quality, 25 were moderate quality and 8 were low quality. Of particular note, no study attempted to blind the participants or assessors; only 6 studies[22 55–59] reported whether adverse events were experienced by participants, and 21 of the 46 studies did not report actual probability values. Additionally, 27 of the 46 studies lacked adequate justification of the statistical tests used to assess the main outcome data, commonly using parametric tests without describing whether the distribution of data was screened for normality prior to analysis. Accordingly, the use of parametric tests was considered inappropriate for such studies.

Evidence for clinical outcomes following running retraining

Four studies[22–25] investigating clinical outcomes were identified (table 1). Limited evidence indicates 6-weeks of visual (video) and verbal feedback to transition from rearfoot strike (RFS) to midfoot strike (MFS) or forefoot strike (FFS) and increased step rate can reduce pain[24 25] and compartmental pressures[24] in

Table 1 Clinical findings related to running-related pain in injured populations

Study (year)	Study design	Sample	Outcome measures	Intervention	Significant clinical results	Significant biomechanical results
PFP						
Noehren (2010)	Case series 1-month follow-up	10 female runners Running at least three times and 6 miles per week At least 20° peak hip adduction	Running-related pain VAS	2-weeks (eight sessions) of visual (real time 3D feedback) and verbal faded feedback to reduce hip adduction	↓ Pain following 2-week intervention and at 1-month follow-up	↓ Peak hip adduction following 2-week intervention and at 1-month follow-up ↓ Vertical impact peak and loading rates following 2-week intervention
Willy (2011)	Case series 3-month follow-up	10 female runners Running at least 10 km per week At least 20° peak hip adduction	Running-related pain VAS	2-weeks (eight sessions) of visual (mirror) and verbal faded feedback to reduce hip adduction	↓ Pain following 2-week intervention and at 1-month and 3-month follow-up	↓ Peak hip adduction and contralateral pelvic drop following 2-week intervention and at 3-month follow-up
Anterior exertional lower leg pain						
Diebal (2012)	Case series 12-month follow-up	10 military personnel diagnosed with compartment syndrome and indicated for surgery (fasciotomy) by an orthopaedic surgeon	Running-related pain VAS Running distance tolerated Intracompartmental pressures	6-weeks of visual (video) and verbal feedback to transition from RFS to FFS and increase step rate towards 180 per minute	↓ Pain during running and a reduction in postrunning compartmental pressures following 6-week intervention Improved 2 mile running time and SANE scores at 12-months follow-up No patient required a fasciotomy	↓ Step length and contact times ↓Peak vertical GRF, impulses, and weight acceptance rates ↑ Step rate (163–172)
Breen (2015)	Case series 12-month follow-up	10 runners (nine M, one F) presenting to sports medicine clinic with anterior exertional lower leg pain causing cessation of running	EILP questionnaire Global rating of change Running distance	6-weeks of individualised feedback to reduced ankle DF at foot strike (options included instructing MFS, increasing hip flexion, promoting earlier push off, and running more upright) Three sessions of retraining completed independently each week with two follow-up sessions	↓ Pain during running Eight participants running pain free over 30 min Improved EILP following 6-week intervention and at 12-month follow-up	↓ Ankle DF at foot strike ↓ Tibial angle (ie, more vertical) ↑ Peak hip flexion angle ↓ Stride length

3D, three-dimensional; DF, dorsiflexion; EILP, exercise-induced lower leg pain; F, female; RF, ground reaction force; M, male; PFP, patellofemoral pain; SANE, single assessment numeric evaluation; VAS, visual analogue scale.

patients with running-related anterior exertional lower leg pain.[24] Limited evidence indicates 2-weeks (eight sessions) of visual and verbal feedback to reduce peak hip adduction in female patients with PFP possessing more than 20° peak hip adduction can reduce pain at 1-month[22 23] and 3-month follow-up.[22]

Biomechanical effects of running retraining interventions

Forty-six studies evaluating the biomechanical effects of running retraining interventions met the inclusion criteria,[22–25 55–96] including evaluation of step rate manipulation (see online supplementary file 5); altering strike pattern (see online supplementary file 6); proximal retraining strategies (see online supplementary file 7); and modifying impact loading variables, contact time and stiffness (see online supplementary file 8). Nineteen studies[59–75 96] evaluated the biomechanical effects of step rate manipulation in isolation, with one including a symptomatic population,[75] and one also examining the effects of altering contact time.[70] Fifteen studies[56–58 76–82 90 92–94 96] evaluated the biomechanical effects of altering strike pattern, all in asymptomatic participants. Two studies evaluated the biomechanical effects of a retraining intervention combining transition from rearfoot to forefoot or midfoot strike pattern with other retraining interventions including an increase to step rate[24] and cues to alter proximal mechanics.[25] Three studies[55 83 95] evaluated the biomechanical effects of cues to reduce impact loading variables at foot strike. Four studies[84–87] evaluated the biomechanical effects of altering step width, but none of these included symptomatic participants. Three studies evaluated the biomechanical effects of cues to alter proximal mechanics,[22 23 88] with two aiming to reduce hip adduction,[22 23] and one to increase forward trunk lean.[88] One additional study[89] evaluated the biomechanical effects of a combination of retraining strategies on biomechanics, but this was excluded from further analysis due to poor transparency regarding the specific intervention used.

Expert opinion

Interview transcript analysis identified 10 sections with 29 themes and 75 subthemes. Three sections included 'current evidence base' (see online supplementary file 9.1; 2 themes, 9 subthemes), 'appropriateness of running retraining' (see online supplementary file 9.2; 1 theme, 4 subthemes) and 'specific conditions' (tables 2 and 3 and online supplementary file 9.3; 4 themes, 11 subthemes). Four sections were related to the practical application of running retraining strategies, including a reduction in overstride (ie, horizontal distance from foot strike to centre of mass (COM)) and increase in step rate (table 4; two themes, four subthemes); alteration to strike pattern (table 5; one theme, four subthemes); proximal retraining strategies (table 6; four themes, five subthemes); and approaches to modify impact loading variables, contact time and stiffness (table 7; two themes, four subthemes). Additional themes and subthemes included barriers and facilitators to running retraining implementation (see online supplementary file 10.1; 5 themes, 15 subthemes), the influence and relative importance of adjunctive interventions (see online supplementary file 10.2; 7 themes, 16 subthemes), and the potential for running retraining to prevent injuries or improve performance (see online supplementary file 10.3; 1 theme, 3 subthemes).

Synthesis of review findings with expert opinion

A summary of running retraining considerations discussed and potential biomechanical rationale identified in the systematic review are provided in tables 2 and 3.

DISCUSSION

There is limited evidence to support running retraining in the treatment of exertional lower leg pain[24 25] and PFP.[22 23] Additionally, the expert panel were advocates of running retraining for cases of chronic or recurrent injury, and where potential biomechanical deficiencies linked to injury can be established (see online supplementary file 9.2). Experts interviewed suggested lower limb injuries which may benefit from running retraining include (but are not limited to) exertional lower leg pain, plantar fasciopathy, Achilles tendinopathy, calf pain, medial tibial stress syndrome, PFP, ITBS, patellar tendinopathy, hamstring injury including proximal tendinopathy and gluteal tendinopathy (tables 2 and 3; and online supplementary file 9.3). Despite a paucity of current evidence in injured populations, there is substantial evidence for the immediate biomechanical effects of running retraining interventions in an uninjured population (see online supplementary files 5–8). Given the current state of evidence, this information is important to assist guidance of current clinical practice and future research, and is incorporated throughout the discussion.

Conditions with limited empirical evidence

Limited evidence indicates that transitioning from a rearfoot to forefoot or midfoot strike pattern combined with increasing step rate, or altering proximal mechanics to facilitate hip flexion is effective in managing anterior exertional lower leg pain over a 6-week period, with positive clinical outcomes sustained for up to a year following the intervention[24 25] (table 1). This approach was strongly supported by experts interviewed, and further biomechanical support is provided by very limited to limited evidence demonstrating reduced tibialis anterior muscle activity[81 90] and forces[80] with a forefoot strike (see online supplementary file 6), and limited evidence indicating reduced tibialis anterior muscle activity[60] and ankle dorsiflexion[61 71 72] around the time of foot strike with increased step rate (see online supplementary file 5). Additional running retraining recommendations for anterior exertional lower leg pain included other strategies to reduce overstride (eg, altering proximal mechanics), with some experts suggesting this may be more important than changing the strike pattern, and cues to reduce impact loading variables which may reduce ankle dorsiflexion at foot strike[83] (see online supplementary file 8). Further research is needed to identify which running retraining strategies have the greatest effect on biomechanics and symptoms in individuals with exertional lower leg pain.

Limited evidence indicates visual and verbal feedback to reduce peak hip adduction in females with PFP possessing greater than 20° peak hip adduction is effective in its treatment,[22 23] with positive clinical outcomes sustained for up to 3 months post-intervention[22] (see table 1). This approach is generally supported by expert opinion (table 3), and recent prospective findings implicating excessive hip adduction as a risk factor for PFP.[97] Reducing overstride through various approaches including increasing step rate was also suggested as important in the treatment of PFP (table 3). Importantly, there is strong evidence indicating reduced patellofemoral joint (PFJ) stress/load,[68 75 96] moderate evidence indicating peak knee flexion,[66 68 75] and limited evidence indicating reduced knee power absorption,[63 66] internal knee extensor moments[63 71 73 75] and peak hip adduction[59 66] with an increased step rate (see online supplementary file 5).

Other suggested running retraining interventions for PFP included increasing forward trunk lean, which limited evidence

Table 2 Summary of running retraining considerations for foot and lower leg pathologies, including potential biomechanical rationale for retraining strategies

Retraining considerations	Illustrative quotes	Potential biomechanical rationale for retraining considerations
Anterior exertional lower leg pain		
Running retraining strongly advocated Consider increasing step rate,* strategies to reduce overstride and impact loading variables, and transitioning from rearfoot to forefoot or midfoot strike*	"It may just make a lot, a lot, a lot of sense to retrain someone who's got a compartment syndrome, A, because nothing else works and B, because once you start getting the calf working, they're going to absorb loads much better." (5) "(For anterior compartment syndrome) try and reduce that over-stride, getting weight more under their body, getting them to come often to a very almost heavy forefoot strike to start with just so you completely unload tib ant is often the best way to go and then eventually working them back towards a midfoot strike pattern." (6) "For example, if somebody presents with very acute anterior compartment syndrome, then I'm gonna want to switch into a forefoot position pretty quickly." (11) "My approach tends to be to try and change the kinematics of that whole leg with an outcome hopefully of changing Tib ant activity at footfall. I don't start by saying, I want you stop landing on your heel and running on your toes." (16)	*Transition from rearfoot to forefoot or midfoot strike**—limited evidence indicates ↓ muscle forces[80] and stance phase activation[81] of tibialis anterior *Increasing step rate**—limited evidence indicates ↓ ankle dorsiflexion at foot strike[61 71 72] and tibialis anterior muscle activity during late swing[60] *Cues to reduce impact loading variables*—limited evidence indicates ↓ dorsiflexion at foot strike[83]
Plantar fasciopathy		
Poor agreement among experts on whether running retraining can be effective and if so, the best way to implement, especially in relation to strike pattern Consider strategies to reduce overstride and impact loading variables (eg, vertical loading rate), increasing step rate	"If you switch to a more forefoot strike, then you'll increase the load on the plantar fascia, so (transitioning strike pattern) might not be the best option on the short term." (1) "I think it has a quite a big role and I think when we're talking about plantar fascia … I'd say that if you've got someone who's got a significant over-stride, then I would be looking at (correcting) that … Most commonly, you don't often see someone and think, "Oh god, that's a terrible forefoot strike pattern." We need to change that. It's often that it'll be at the other end of the spectrum. It's terrible that over-stride, heel strike, we need to change that." (5) "I know there's some evidence on loading rates and plantar fasciitis … but I'm not really convinced that there is a real strong rationale there." (8) "I will say I will promote better impact moderating behaviour for chronic one (plantar fasciopathy). First of all, increase cadence, doing less noise and more minimalist shoes … if it's not enough, I can play with the foot position, decrease the heel strike" (10) "Plantar fasciopathy is a tough one and I've not had good response to gait retraining on that one." (14)	*Cues to reduce impact loading variables*—limited evidence indicates ↓ VALR and VILR[55 83] *Increasing step rate*—limited evidence indicates ↓ VIP, VILR and VALR[59 67]
Achilles tendinopathy		
Running retraining advocated by some experts Consider strategies to reduce overstride, increase lower limb stiffness, and increase hip extension, and transition from a forefoot to rearfoot or midfoot strike	"I would be looking at other interventions and normalizing (reducing) that over-stride rather than actually going (from a rearfoot) to a forefoot run." (5) "Those crazy runners who have decided that barefoot running is for them and they've decided that they're gonna forefoot strike and they'll come in and they'll literally be toe striking … In which case, you just need to get them back to rearfoot striking and often they'll get a lot better." (6) "Clinically, we find that when you stiffen people up (reduce knee and ankle dorsi-flexion), we get a very good result in terms of their pain and their recovery with Achilles tendinopathy … I think it's related primarily as reducing the dorsiflexion moment." (9) "I targeted hip extension in my people who have calf Achilles problem." (15) "I would look at insertional Achilles as something that I need to rehabilitate and then through a graduated return to running-load management process to deal with (rather than focusing on running retraining." (15) "Sometimes, I'll even switch them (Achilles tendinopathy patients) to a heel strike … I'll just do like that gentle heel strike rather than mid and forefoot." (17)	*Increasing step rate*—limited evidence indicates ↓ ankle dorsiflexion at midstance[68] and ↓ soleus muscle forces during stance[68] *Transition from forefoot to rearfoot strike*—limited evidence for↓ plantar flexor impulse (force production);[79 92] and very limited evidence for ↓ gastrocnemius and soleus muscle forces[80]
Calf pain		
Strength and exercise approach may be more relevant than running retraining Consider increasing step rate and transitioning from forefoot to midfoot or rearfoot strike	"We believe there's perhaps too much contraction of the calf muscle or it's happening too quickly … We're trying to activate the big muscle (with retraining) there, the quads, hamstrings, etcetera and reduce the load." (9) "They often have strength deficit, particularly strength and endurance deficits initially … The formation of their SSC (stretch shortening cycle) calf ability, it's usually not great and that leads to their recurring injury problems." (11) "With those ones, I'd get best results from just really strengthening that calf up, lots and lots of calf raises … Get them pretty strong and then maybe do some plyometric stuff as well. So, you're improving the muscle's ability to handle force. Maybe rather than necessarily changing their gait too much." (12) "Have they (runners with calf pain) got an over pronounced forefoot strike addressing that? Are they running with a very low, slow cadence? Picking that up, getting them faster." (13) "I think there's a role (for running retraining in calf pain)." (16)	*Increasing step rate*—limited evidence indicates ↓ ankle dorsiflexion at midstance[68] and ↓ soleus muscle forces during stance[68] *Transition from forefoot to rearfoot strike*—limited evidence for↓ plantar flexor impulse (force production);[79 92] and very limited evidence for ↓ gastrocnemius and soleus muscle forces[80]

Continued

Table 2 Continued

Retraining considerations	Illustrative quotes	Potential biomechanical rationale for retraining considerations
Medial tibial stress syndrome		
Running retraining advocated by most experts Consider strategies to reduce impact loading variables and overstride, reduce hip adduction/IR and increase step width (address cross over gait), and increase hip extension	"I think it (running retraining) works pretty well within the medial tibial stress syndrome, to work on decreasing the impact force. Again, that's not a condition that I would push on a forefoot strike pattern because of the tension in the soleus … I would consider that mid-foot strike would be the best option on the short term." (1) "You'll get over-striding (in runners with medial tibial stress syndrome) because it's gonna really increase your impacts, your loading rates, also cross-over gait pattern. … Excessive hip adduction can really increase the bending moment in the tibia so that's the other mechanic that I really consider in addressing." (2) "Particularly MTSS, they tend to lack normal hip extension. So, it's usually more to do with the propulsive phase, rather than landing phase sometimes, so, it's a combination of both (you need to address)." (6) "If they're getting a lot of hip adduction, internal rotation, that's gonna increase torsional stress more distally so looking at trying to control that (in runners with medial tibial stress syndrome), if that's existent and that sometimes just changing hip mechanics, getting them to tighten their glutes, think about reducing hip adduction will also reduce the load." (6) "You wanna decrease the vertical loading rate (in runners with medial tibial stress syndrome) and for that you see, we increase the cadence and you change your shoes." (10) "The chronic group one—So those people who are coming in and giving you a three or four-year history of medial tibial stress syndrome … I'll use gait training reasonably early and reasonably constantly and I think, with some degree, success as well."(16)	*Increasing step rate*—limited evidence indicates ↓ ankle dorsiflexion at midstance[68] and ↓ peak tibial acceleration (limited);[61 65 69] and very limited evidence indicates ↓ tibial contact forces[64] *Cues to increase step width*—limited evidence indicates ↓ peak rearfoot eversion;[84 87] and very limited evidence indicates ↓ peak internal ankle inversion moment,[84] ↓ anterior tension, posterior compression and medial compression of the tibia,[87] and ↓ shear stress on the anterior, posterior, medial and lateral tibia[87] *Cues to reduce impact loading variables*—limited evidence indicates ↓ peak tibial acceleration[55 83 95]

*Retraining strategy part of successful case series intervention in this condition.
IR, internal rotation; VALR, vertical average loading rate; VILR, vertical instantaneous loading rate; VIP, vertical impact peak.

indicates will reduced PFJ stress;[88] and cues to reduce impact loading variables (see online supplementary file 8). Interestingly, transitioning from a rearfoot to a forefoot strike in runners with PFP did not emerge as a strong theme among experts, despite limited evidence indicating reduced peak and accumulative PFJ reaction force and PFJ stress when transitioning to forefoot striking.[94 96] Additionally, reductions in running-related pain have previously been reported in a small case series of three runners with PFP when transitioning to a forefoot strike.[41] Further research is needed to establish the potential therapeutic value of transitioning from rearfoot to forefoot striking in runners with PFP. Considering PFP is a multifactorial condition,[98] it is likely that a tailored retraining strategy is needed in a clinical setting, and further research is required to understand the interaction of running retraining strategies with other evidence-based interventions.[99]

Conditions with support for running retraining from expert opinion

Poor agreement exists among experts on the value of running retraining in plantar fasciopathy treatment (table 2). Running retraining suggestions included reducing overstride, increasing step rate and feedback to reduce impact loading variables, based on evidence linking high loading rates to plantar fasciopathy.[100] Supporting this proposal is limited evidence for reduced loading rates with cues to reduce impact loading variables[55 83] (see online supplementary file 8) and increase step rate[59 67] (see online supplementary file 5). Some experts recommended that transitioning from a rearfoot to a forefoot or midfoot strike to reduce loading rates[81] may assist in plantar fasciopathy treatment, while others suggested that this may be detrimental due to increased arch strain in forefoot compared with rearfoot strike running[79] (see online supplementary file 6). Further research on the effects of strike pattern manipulation in plantar fasciopathy is needed to provide clarity on these differing opinions.

Running retraining for Achilles tendinopathy and calf pain was cautiously recommended by some but not all experts interviewed (table 2), and adequate rehabilitation exercise was generally considered more important. Recommended retraining strategies for Achilles tendinopathy included reducing overstride and increasing step rate, which limited evidence indicates will reduced stance phase soleus muscle forces[68] and ankle dorsiflexion at midstance[68] (see online supplementary file 5). Additional considerations lacking supporting biomechanical evidence included reducing impact loading variables, increasing lower limb stiffness to reduce midstance ankle dorsiflexion, and increasing hip extension to reduce power requirements of the gastrocnemius-soleus complex during propulsion (see online supplementary file 8). Transitioning individuals with a pronounced forefoot strike to a rearfoot or midfoot strike was another proposed strategy for Achilles tendinopathy and calf pain (table 2), supported by very limited to limited evidence for reductions in plantar flexor impulses and internal joint moments,[79 92] and gastrocnemius-soleus muscle forces[80] (see online supplementary file 8). Running retraining strategies including reducing overstride and increasing step rate, reducing impact loading variables and transitioning strike pattern towards a midfoot strike was advocated by most experts for medial tibial stress syndrome (table 2). Additional consideration to reducing hip adduction and increasing step width was also suggested, which limited to very limited evidence indicates may reduce peak rearfoot eversion;[84 87] rearfoot eversion and forefoot dorsiflexion excursion;[87] peak internal ankle inversion moment;[84] and tension, compression and shear stresses on the tibia[86] (see online supplementary file 7).

Similar to PFP, cues to reduce peak hip adduction and internal rotation were recommended by some experts in the

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Table 3 Summary of running retraining considerations for knee and hip pathologies, including potential biomechanical rationale for retraining strategies

Retraining considerations	Illustrative quotes	Potential biomechanical rationale for retraining considerations
PFP		
Running retraining strongly advocated Consider increasing step rate, strategies to reduce overstride and impact loading variables, reduce peak hip adduction* and internal rotation, and promote more forward trunk lean	"Most common thing with patellofemoral would be over-striding and also medial collapse, particularly the females … Then the third one would be the one that I would call the very upright running posture with the trunk. The runners that tend to run like that, they tend to have very low hip moments and very high knee extensor moments. So for those folks, we'd work on some anterior trunk lean." (2) "Probably two major things which will lead to patellofemoral pain … there will be excessive hip adduction, internal rotation. So, that's something you often look to change. And the other thing will often be that the runner will be over-striding and landing with a particularly heavy heel strike." (6) "With patellofemoral, again we found that by changing those sagittal plane kinematics (reducing over-striding and increasing cadence), we noticed a change in frontal plane kinematics as well … some of that knee valgus and hip adduction was reduced as well." (9) "The one area that has the most evidence would be patellofemoral pain … if you see them banging really hard, over striding and hitting with those high impact forces, then you might try to soften those impact forces." (14)	*Cues to reduce hip adduction**—limited evidence indicates ↓ peak hip adduction and contralateral pelvic 3 months follow-up in a PFP population[22 23] *Increasing step rate*—strong evidence indicates ↓ peak PFJ stress/load including in a PFP population[68 75 96] and ↓ peak knee flexion[66 75 68]; and limited evidence indicates ↓ knee energy absorption,[59 63 66] and ↓ internal knee extensor moment[63 71 73 75] *Cues to increase forward trunk lean*—limited evidence indicates ↓ PFJ stress and reaction force, ↑ PFJ contact area, and ↓ internal knee extensor moment and knee flexion at time of peak PFJ stress[88] *Transition from rearfoot to forefoot strike*—limited evidence indicates ↓ peak and accumulative PFJ reaction force and PFJ stress[94 96]
ITB syndrome		
Running retraining advocated by some experts Consider strategies to reduce hip adduction and increase step width (address cross over gait)	"The pathomechanics (to change) would be medial collapse mechanics, excessive hip adduction and the other one would be cross-over gait pattern." (2) "We have success with people who have not had any success with the typical strengthening of their glutes and stretching of the IT band and rolling, form rolling. It's amazing! And all we do is (reduce) their hip adduction." (4) "We reduced tension within the ITB by, with a wider stance of gait. And sometimes I think you know, that does help … I found that the biggest change to ITB has been activating those big muscles. Again coming back to that high knee lift which then results in a greater activation, I think, of hip extensors of the opposite side." (9) "With IT band, it tends to be more dealing with the problems rather than the gait retraining component of it … I can think of a couple of patients that were—That crossed over and they got IT band. They would get IT band syndrome because they crossed over. And then in those cases, you do think about (promoting) maybe a little bit wider stride." (14)	*Cues to reduce hip adduction*—limited evidence indicates ↓ peak hip adduction and contralateral pelvic drop at 3 months follow-up[22 23] *Cues to increase step width*—very limited evidence indicates ↓ peak internal knee abduction moment,[84] ↓ internal knee abduction impulse,[84] ↓ ITB strain and strain rate,[85] and ↓ peak hip adduction[84 85]
Patellar tendinopathy		
Cautious recommendations for running retraining to assist by some Consider increasing step rate, strategies to reduce overstride and impact loading variables, and transition from rearfoot to forefoot strike	"You often find these individuals very different to patellofemoral pain where you'll get a greater hip adduction. They often have good hip control, but they do have the over-stride pattern where they're landing quite heavy on the heel (which should be changed). And essentially, they're just not absorbing any shock to their foot and ankle, it's all going straight to the knee, which means you're gonna load up the patellar tendon." (6) "Patellar tendinopathy … My first part of the treatment will be to protect the tendon if it's acute, I will say to the patient, okay, just increase the cadence, lowering the shoes so more minimalist shoes in acute condition, and be sure that you don't cause another problem in another place at the same time, less noise, and if it's not enough, forefoot striking." (10)	*Increasing step rate*—moderate evidence indicates ↓ peak knee flexion[66 68 75]; and limited evidence indicates ↓ knee energy absorption,[59 63 66] ↓ internal knee extensor moment,[63 71 73 75] ↓ patellar tendon force in midstance[68], and ↓ quadriceps (vastii) muscle forces during stance[68] *Transition from rearfoot to forefoot strike*—limited evidence indicates ↓ knee power absorption[92]
Hamstring, including proximal hamstring tendinopathy		
Running retraining generally advocated but some inconsistent beliefs regarding how, particularly in relation to trunk position Consider strategies to reduce over stride and impact loading variables, reduce anterior pelvic tilt and knee extension at foot strike, and increase swing phase hip and knee flexion	"Yep and I often see over-striders … I often see kinematically that they are, have got a very stiff knee strategy (which needs to be changed). (5) "Hamstring is always a classic over-stride pattern … Just changing that and getting them to try and often think about landing more softly, so that they land a lot more under their body" (6) "These guys at the foot strike position were leaning forward a bit too much and over-extending the knee. So if we reduce the knee extension at the foot strike and straighten the body up as well, perhaps that reduced the stretch or the tension within either the hamstring or some of those neural structures." (9) "I would be looking for anterior pelvic tilt, control of anterior pelvic tilt, and then maybe control of even internal rotation of the hip (with running retraining)." (14) "I think the high hamstring group often tend to, again, have really poor swing phase hip mechanics … The running mechanic that I might wanna look to (change) is actually trying to reinforce that capacity to have good hip-knee flexion during swing phase." (16)	*Increasing step rate*—limited evidence indicates ↓ hip energy absorption[63 66] ↓ peak internal hip extensor moment[66 71]

Continued

Table 3 Continued

Retraining considerations	Illustrative quotes	Potential biomechanical rationale for retraining considerations
Gluteal tendinopathy		
Running retraining advocated by most experts Consider reducing overstride and increasing step rate, and reducing hip adduction, internal rotation and contralateral pelvic drop	"(In gluteal tendinopathy) One (variable to change) would be over-striding and then the other one would be excessive hip adduction, specifically excessive pelvic drop." (2) "It's more just controlling that femoral internal rotation adduction and try to get them think about tightening their glutes, opening their knees up, and often that tends to make a big difference with them (gluteal tendinopathy patients)." (6) "I'm interested in what's happening through that sagittal plane (in runners with gluteal tendinopathy), but I'm really interested in what's happening through coronal plane and rotational as well. So I wanna decrease that hip adduction-internal rotation that's potentially compressing that tissue and I will do that through rehabilitation and I will, again, because I don't think rehabilitation on its own changes gait, and I'll also do that through gait modification." (16)	*Increasing step rate*—limited evidence indicates ↓ hip energy absorption,[63 66] ↓ peak internal hip extensor moment,[66 71] ↓ peak hip adduction[22 23] and ↓ gluteal muscle forces during stance[68]; and very limited evidence indicates ↓ peak internal hip abduction and external rotation moments[66] *Cues to reduce hip adduction*—limited evidence indicates ↓ peak internal hip abduction moment at 1-month follow-up,[22] and ↓ peak hip adduction and ↓ contralateral pelvic drop at 3 months follow-up[22 23]

*Retraining strategy part of successful case series intervention in this condition.
†Concurrent conflicting expert opinion regarding this retraining strategy.
ITB, Iliotibial band; PFP, patellofemoral pain.

treatment of ITBS (table 3), an approach supported by findings that greater peak adduction in female runners may be a risk factor for ITBS development.[101] Additionally, increasing step width to reduce cross-over gait (hip adduction at foot strike) was suggested (table 3), and this is supported by very limited to limited evidence for reduced peak internal knee abduction moment and impulse,[84] ITB strain and strain rate,[85] and peak hip adduction[84 85] (see online supplementary file 7). There were inconsistent beliefs regarding the potential for running retraining to assist in the treatment of patellar tendinopathy (table 3), with some cautious recommendations to consider reducing overstride, increasing step rate, reducing impact loading variables, and transitioning from a rearfoot to a midfoot or forefoot strike. Limited-to-moderate evidence indicating reduced patellar tendon forces in midstance,[68] internal knee extensor moments,[63 73 75] knee power absorption[63 66 96] and peak knee flexion[66 75 68] supports increasing step rate (see online supplementary file 5). Biomechanical rationale to support a transition from a rearfoot to a forefoot strike is less clear, with limited evidence indicating a reduction in knee power absorption,[82 92] but conflicting evidence related to internal knee extensor moment[80 92 93] (see online supplementary file 6). This, combined with potential increases to tissue stresses more distally with a transition to a forefoot strike (eg, increased ankle power absorption; see online supplementary file 6), indicate that caution may be needed when considering this strategy for patellar tendinopathy and other conditions. Considering comparable reductions in knee, loading can be achieved by increasing step rate by 10%[59]; this may be a safer approach.

Running retraining for hamstring injury including proximal hamstring tendinopathy was generally supported (table 3). Recommendations included cues to reduce impact loading variables and anterior pelvic tilt, along with various methods to reduce overstriding, including increased step rate and promoting more hip and knee flexion during swing. While there is a paucity of biomechanical evidence examining the effects of promoting increased hip and knee flexion, there are a number of considerations from the biomechanical literature relating to increased step rate. First, limited evidence indicates greater hamstring muscle forces[68] and activity during late swing[60] with increased step rate (see online supplementary file 5), which in theory may place greater load on the hamstring muscle or tendon. However, limited evidence also indicates increasing step rate may reduce hip energy absorption[63 66] and peak internal hip extensor moment[66 71] (see online supplementary file 5), and thus reduce hamstring muscle and tendon load during early stance. Further research evaluating the effects of increasing step rate on symptoms in individuals with hamstring injury is needed to clarify the importance of these various biomechanical changes.

When managing gluteal tendinopathy, running retraining strategies including reducing overstride, increasing step rate, and cues to reduce hip adduction/internal rotation and contralateral pelvic drop were generally advocated (table 3). We did not find any studies evaluating strategies specifically targeting contralateral pelvic drop, but very limited to limited evidence indicates visual and verbal cues to reduce hip adduction also reduces contralateral pelvic drop[22 23] and peak internal hip abduction moments[22] up to 3 months following a 2-week intervention (see online supplementary file 7). When increasing step rate, very limited to limited evidence indicates reduced gluteal muscle forces,[68] and hip energy absorption during stance;[63 66] peak internal hip extensor,[66 71] abduction[66] and external rotation[66] moments; and peak hip adduction[59 66] (see online supplementary file 7).

Practical application of running retraining

Addressing overstride and increasing step rate

Addressing the presence of overstriding was considered one of the most beneficial running retraining strategies (table 4), with experts frequently discussing the importance of the foot landing closer to a runner's COM. Despite strong recommendation from experts, evidence to support the importance of overstriding or horizontal distance between foot strike and COM to running injury is lacking. Defining what constitutes overstriding (eg, the distance which may lead to injury), how this relates to injury and how to address it should be priorities for future research. Increasing step rate will move foot strike closer to the COM,[66] and was suggested to be beneficial for many injuries. One key recommendation is that increases to step rate should be gradual (between 5% and 10% at a time) to ensure manageable changes and avoid excessive fatigue.[66] Experts proposed a range of cues to increase step rate, including metronomes, music and verbal cues (eg, 'take shorter faster steps'), and all could be considered clinically.

Table 4 Expert opinion related to practical implementation of strategies to reduce overstride and increase step rate

Themes Subthemes	Illustrative quotes
Strategies to reduce overstride	
Various methods of correcting overstride, including increased step rate	"It's getting people holding the hips over the landing foot (to reduce over-striding) … We can try and change those things constructively by simple cues like giving—lifting up through the hips, getting the right mobility exercises in place to try and deliver the mobility through the hips." (3) "The main thing that I'll do there is (increase) cadence (to reduce over-stride)." (5) "In terms of trying to change strike pattern or prevent that overstride it's more just thinking about landing softly is often enough." (6) "I find that cadence looks after overstriding in most cases." (8) "If you significantly change cadence with people, you tend to find the overstriding reduced. It's very difficult to overstride with a higher cadence, but I tend to use the cue of shorter, quicker, lighter steps." (11) "Perhaps trying to get hip flexion and knee flexion occurring, together is another way of reducing stride length." (12) "if you look, if your head's up and you can see your foot out in front of you, try and make your foot disappear, that's another thing, just for over striding." (14) "I might tell them to land their foot a little closer underneath their body rather than out so far out in front of them (to reduce over-striding)." (15)
Cues to increase step rate	
Step rate considerations and potential benefits Need to gradually increase step rate (cadence) and the relevance of working toward 180 steps per minute	"A lot a time, I've had a lot of success there just working with cadence (to manage running injuries)." (3) "Sometimes, the only cue you need to use is just get them to increase their cadence and it will change their strike pattern, it'll change their landing pattern, where they're landing relative to their centre of mass. And also, often change frontal and transverse plane motion of the hip as well." (6) "Even by altering step rate you can significantly alter the degree of forefoot or rearfoot pronation." (7) "Cadence again. It's probably a good thing for even for a foot problem, it's probably one of the key things you can do to decrease the load in general." (10) "Changing the cadence, we often observe positive changes in all of the things that we would like to see (to manage running injuries)." (11) "One of the issues with cadence is that it doesn't shift centre of gravity. So it is essentially the same movement pattern. It's just a bit truncated and it's just a bit faster." (13) "For cadence, it depends on what was the initial cadence of that person … If I have a runner coming in with a cadence of 145, which is extremely low, I try to bring that person to 180, it will not work for sure. So, usually I go through a couple sessions; first time I go up to 155, 160, and then go up again." (1) "I can subscribe also to the kind of "at 5% rule" (for how much to increase cadence)." (3) "I get them to download a metronome app, which you can download for free for your smart phone and get them to run at a beats-per-minute that matches what (step rate) they're running at naturally … Make sure they find what their beats-per-minute is and then increase it by five, and then if that feels comfortable, increase it by five again 'til you get them up to 170, 175, 180 in a progressive manner." (5) "Probably don't wanna change it (step rate) more than about 10%." (6) "I think we can increase cadence quite easily from five to ten percent." (9) "I am pretty sure that it's around the 180 that we can find the best protective biomechanics … So my range is between 170 to 190." (10)
Various methods to increase step rate	"Evidence tells us that it's easy for people to make five percent changes (to their step rate)." (14) "Some people, when you increase the cadence, they tend to increase the speed … So I think that the treadmill is the best place to do it (increase step rate)." (1) "People who like to run with ear buds and iPhones and that kind of thing, I recommend them to use some apps that it can plan for playing music that have that specific cadence (they are instructed to run at)." (1) "(I use) a device made by Garmin. It has real-time icon and step rate, so I use that. By looking at your step rate on the watch and real-time, that could be considered as external focus and that what I intend to work on most with them (to increase step rate)." (2) "I do use metronomes (to increase step rate). I think they're great tools." (3) "I used to try and use metronomes and songs and things like that a lot (to increase step rate) … Most people can do it without—just getting to think about faster step rate." (6) "You tell them and say, 'you need to take shorter strides'. (to increase step rate)." (8) "Some people are more visual, so they look the second on the board and I guess say its three sets per second, one, two, three, one, two, three, one, two, three, so I combine the visual with the auditory. And for most of the people, that works (to increase step rate)." (10) "I'm not fond of using music generally (to increase step rate) … if they've got music pumping through their ears, they're really not aware of how heavy or not that foot strike potentially is." (11) "Maybe music would be less noxious than the metronome (to increase step rate). I think I just don't really like the metronome. I find it kind of annoying." (15)

Strike pattern alteration

Experts proposed a range of potential benefits of strike pattern alteration, including both transition from rearfoot towards forefoot or midfoot (eg, knee injuries), and from forefoot towards rearfoot or midfoot strike (eg, Achilles tendinopathy and calf pain). However, caution was recommended when considering changing a runner's strike pattern, with a substantial adaptation period suggested if choosing to make alterations, especially towards a forefoot strike pattern (table 5). Additionally, potentially greater importance of other retraining interventions was stressed, including reducing overstride, which transitioning from a rearfoot to forefoot strike may be detrimental to.[81] Additionally, other interventions including proximal retraining strategies, increasing step rate,[61 71 72] and use of minimalist

Table 5 Expert opinion related to practical implementation of strike pattern alteration

Themes Subthemes	Illustrative quotes
Strike pattern implication and potential benefits	"For runners who are, I would say, big heel strikers and I would like to promote more forefoot or mid-foot strike pattern" (1) "With an anterior tibial compartment syndrome, I've seen great benefit from forcing someone on to the forefoot who is a real heavy heel striker but they need to take the time to do it." (3) "Once you start shifting to more of a forefoot, you have less stress in the proximal chain and then vice versa. So for that reason, it is a horses for courses type of approach in terms of what you shift, which way." (5) "If you get someone with a real forefoot strike pattern, you may go the other way (change from forefoot to rearfoot strike) … It's difficult for someone who is a real sort of natural forefoot runner. So I try not to change their natural pattern unless it's completely hideous." (5)
Potential dangers of changing foot strike	"(If forefoot striking) reduces the forces at the knee, which we know it does, then it would seem logical that there would be a potential decrease in the pain in that area." (14) "I think that if I just give the advice of someone to really change the foot strike, it could be dangerous." (1) "I'm not advocating a strong, a severe forefoot strike pattern but a mild one." (4) "They (runners who transition to a forefoot strike) tend to go very, very quickly and end up with delayed onset muscle soreness and Achilles tendinopathy or metatarsal stress fractures because they impose a kind of a novel loading environment on tissues that haven't had time to adapt." (8) "We found initially that we were promoting a fore foot strike. A lot of the guys were really suffering with calf pain during that adaption period." (9) "I think changing foot strike is quite a big intervention, and I think you often create problems from that." (12) "I never give a cue around foot strike. I think that's quite dangerous." (13)
Foot strike may change through other interventions—barefoot or minimal shoes, proximal focuses	"Talking about changing the foot strike pattern, usually I go more indirectly by changing the cadence and by asking to do less noise, less impact forces. If these strategies are not working, then I try the barefoot condition and or the minimal shoes if the person has minimal shoe already." (1) "We usually start with four sessions of retraining to get them off their heels (and onto forefoot striking) and we do them barefoot on our treadmill regardless of whether they're gonna run barefoot or not." (4) "One of the easier ways to change that foot strike was to increase flexion. So (encouraging) a slightly higher knee, gait if you like." (9) "I tend to find that if you work proximally, the foot strike looks after itself." (11) "If I had somebody who I thought was excessively dorsiflexed through mid to late swing phase, then I would try to give them a cue to be—To relax their ankle during swing phase rather than to think about landing on the ball of your foot when you hit the ground. So I'd still try and change swing phase mechanics to set up a change during landing phase." (16) "If you're landing closer to the centre of the mass, I'm seeing less of a heel strike, so I think I'm probably seeing a shift towards a mid-foot gait pattern." (16)
Importance of other running mechanics in comparison to strike pattern	"For me it's not about changing strike pattern … "You don't need to go down the path of changing it just because it is heel strike. As long as you're not overstriding." (5) "Try and change, not just their strike pattern, but also whereabouts their foot's landing relative to their centre of mass." (6) "First approach is to try and decrease vertical loading rates by looking at the cadence, where foot strikes relative to the centre of gravity, the actual foot strike pattern itself to a certain extent, but that's sort of less important." (13) "From the perspective of a stress fracture, I'd be thinking about impact. And I'd be thinking about—Well, what's causing that impact? Are they in fact over striding or do they have more vertical oscillation and they're just pounding down? Or do they have a really stiff knee, for instance, that could be causing that impact? So it's not always just strike position or foot strike pattern." (14) "I won't cue that (strike pattern) by primary cues around foot contact … I can't think of a case where my starting point is, "I want you to land on this part of your foot." (16)

footwear or barefoot running[102] were proposed to potentially have desired effects on foot strike.

Proximal retraining (cues to modify hip, pelvic and trunk mechanics)

A number of strategies additional to visual (3D motion feedback or mirrors) and verbal ('tighten your buttocks' and 'point your knees straight ahead') cues published in the literature were proposed to reduce hip adduction and internal rotation (table 6). Considerations to both internal (eg, squeeze gluteals) and external (eg, point knees forward) cues were apparent, but consensus was lacking regarding the most appropriate approach, and it is possible the most effective cue may be specific to the individual. A number of retraining interventions may indirectly reduce peak hip adduction, including increasing step rate[66] or step width.[84 85] Possible cues to increase step width used in the literature include both visual (taped lines on the floor)[84 87] and verbal instruction (eg, 'widen your stance').[85 86] Although verbal instruction may be easier to implement in clinical practice, experts stressed the need to ensure individuals do not 'overcorrect' (table 6). Further research is needed to determine the most effective cues for reducing hip adduction and increasing step width and its effect of running-related pain.

Reducing impact loading variables

Some experts considered kinetic variables, including joint forces, tibial accelerations and loading rates, may be more important in relation to injury than kinematic variables (table 4), although evidence to support this premise is lacking. Additionally, most clinicians lack the required equipment to directly measure kinetics during running. It was suggested that impact noise during running may be closely related to actual impact loading variables such as vertical loading rates, and therefore may be used as a proxy measure. Additionally, moderate relationships between sagittal plane kinematics and subsequent loading (kinetic) variables during stance of running were recently reported, including increased step rate, decreased vertical COM excursion, decreased foot inclination angle at foot strike, and reduced horizontal distance between foot strike and COM (ie, decreased overstride).[103] Considering these variables along with strategies to reduce impact noise may be a focus of

Table 6 Expert opinion related to practical implementation of proximal retraining strategies

Themes Subthemes	Illustrative quotes
Trunk and pelvic position	
Various cues and beliefs related to trunk and pelvic position changes	"We would use a variety of cues to try and get the torso as upright as we can … resting your chin on the top of a wall whilst running and trying to imagine a hook through your nose lifting your head up to try to maintain that body position (can help a runner be more upright)." (7) "I'll be looking at sort of pelvic drop, rather than necessarily anterior posterior pelvic position per se … try to get them to focus on a high pelvis on the opposite side. So on the swing leg, so they're not letting it drop as they run." (12) "Cueing around lengthening spine, lifting chest, their sort of upper body postural shoulder girdle cues to get their core engaged, to get their pelvis stabilised and straightened up and to get them pushing their centre of gravity forward over their foot … That usually fixes all of the (running technique issues)." (13) "Tell them to stand up taller, they'll stop over striding and they'll hit the grounds more times per minute (ie, increase step rate)." (14) "Anterior pelvic tilt is hard and I tend to work (on correcting this) before I even get them up on the treadmill and gait retrain them, I tend to work on a more on a static position, so running in place, bridging. Trying to work on high knees, even getting into a plank position… Feel what it's like to have it in posterior pelvic tilt, have a tight abs and tight gluts, but then still be able to turn their feet over and then try to transfer it over to the treadmill." (14) "I haven't addressed forward lean (as part of running retraining). I haven't seen a lot of leaners in my experience." (15) "I will usually go through a process of giving people a sense of being tall and what that feels … I might talk about people being lifted by the top of their crown so they have a sense of tall … Once I've got people in that sense of tall —I'll either talk to people about being lifted up and slightly forward through the crown of their head or I will talk to people about subtly leaning forward from their ankles." (16)
Visual and verbal cues to reduce hip adduction	
Considerations and varying methods to change transverse/coronal plane hip and knee kinematics	"I've been working more on external focus of push their knees outwards (to reduce hip adduction) … It seems like the runners tend to get it much faster … They don't start getting some of these maladaptations that I saw previously when I had people really squeeze their glutes a lot." (2) "Their squeezing their buns and trying to get their knees apart (to reduce hip adduction) … you look at it frame by frame you can actually compare their pre and post and see a little more space between their knees so we give them that feedback." (4) "If I'm trying to change someone's femoral adduction, it will be something like try and maintain some distance between your knees." (5) "Trying to get them to think about tightening their glutes, sometimes think about tightening through their core (to reduce hip adduction and internal rotation." (6) "I usually start with sort of—kind of the usual ones (to reduce hip adduction) … keep your knees apart, you can say squeeze your buns … tell them to focus on something outside the body … your knees are headlights, your knees are flashlights, keep them pointed straight ahead." (8) "Look at what happens at the hip and the knee to make sure that they're actually creating it (space between their knees) by reducing hip adduction and internal rotation, rather than just bringing the feet apart and keeping their knees quite pinched in." (12) "would use mirror training (to reduce hip adduction and internal rotation). Other cues, I would kind of cue them to try to tighten the gluteals." (15)
Changing pelvic, hip and knee mechanics in the frontal/transverse plane through increased step rate and sagittal plane changes	"If you increase the cadence, you don't have much time to collapse your knee in, you don't have much time to do the pelvic drop, so I work a lot more with that." (1) "When we change sagittal plane kinematics, we notice a change in frontal plane kinematics (of the hip) as well." (9) "I mean, my experience again, it seems everything comes back to cadence … if we can improve that cadence by ten to 20 percent from the baseline level, then that usually looks after what's going on with (hip) internal rotation adduction, unless it's related to crossover gait." (11)
Increasing step width/hip abduction at foot strike	
Step width considerations and potential benefits	"Sometimes (a narrow) step width is an issue, you know, if they are crossing over for example, if they are scissoring, I'll give them some cues on foot placement, trying to run on a line or outside of a line (to increase step width)." (8) "You often get an affect of being quite narrow with the stride width on the rest of the chain. So you often see that (narrow step width is) accompanied by a hip adduction and maybe hip internal rotation." (12) "You just have to be careful (increasing step width) because you don't wanna go too wide because you can create a whole new set of other issues … When they're running occasionally on a treadmill it works a bit better to give them either a mirror or sort of cue them to sort of land with their feet a little farther apart, maybe more underneath their hip as compared to underneath their belly button, that cue has worked well (to increase step width)." (15) "Sometimes I will cue people to "Imagine that you're running on a train line. You wanna keep your feet a little bit wider," particularly if they have that negative cross over gait." (16)
Cues to increase hip extension	
Hip extension considerations	"You've gotta give them the underlying strength and flexibility in that terminal extension range … get them to drive through their hips when they're running. So drive through your hips so really try and extend your hip when you're running and that works (to increase hip extension) for some people." (5) "I tend to find if I ask people to actively extend their hip, then all they do is overextend their lower back and it doesn't tend to lead to positive change in the gait pattern, whereas if I ask them to apply positive downward pressure into the treadmill or the ground, they tend to get a nice hip extension that's appropriate for the speed of running." (11) "I do think if the extension is a tricky one to restore … I think you can do it by actually encouraging the patient to flex at the hip more, and as a consequence to that, they tend to naturally extend their hip more … but also they want to look at making sure they've actually got the range in the first place, if there is any restriction in the hip joint extension, or tightness in the hip flexor region, that's going to make you very difficult for them to get any extension." (12)

Table 7 Expert opinion related to practical implementation of modifying impact loading variables, contact time and stiffness

Themes Subthemes	Illustrative quotes
Cues to reduce impact loading variables	
On the importance of considering loading and impact forces	"So I put a lot of emphasis on (reducing) the loading rate (to manage running injuries)." (1) "I have a sense that many injuries are related to loading so we try to get everyone off their heels just because I know that reduces the rate of loading." (4) "I think loading rate anywhere is always a consideration and I think it's definitely related to injury wherever you're looking." (5) "I feel like injuries are the result of forces … We are trying to create a loading environment that promotes healing or prevents injuries." (8) "A lot of people believe that vertical loading rates are (important and) have been shown to be causally related, but I think the evidence is far too weak." (13)
Comparison of importance between loading (kinetics) and kinematics	"Any intervention that decrease the vertical loading rate and will promote better impact behaviour, it means forefoot striking, higher cadence, landing closer to the centre of gravity, more knee bend, all those interventions will decrease anterior compartment syndrome and all the knee pathologies, the hip pathologies and the lower back … I don't believe that kinematics is really linked with pathology." (10) "As far as I'm aware, really, it's the kinetics that cause injury, not necessarily kinematics." (11) "And obviously there's issues around that (just looking at movement) because you're not measuring forces. So you're making a lot of assumptions." (13)
Methods to measure and reduce impact loading variables in the clinic	"The rate of loading, I think, is directly correlated with the noise, with the sound when running." (1) "Some people use an increase in the cadence (to reduce impact) and I think that's a good broad global way to tell people who aren't gonna be followed closely." (4) "Running softly. I've heard that before. I've used that (to reduced impact loading variables). I don't, didn't find that was for me, one that has a lot of success with a lot people, they just struggle with exactly what to do when it comes to running softly." (5) "Probably the main measure of that (loading rate) clinically is—and the runner will say this—you can 'hear' the difference or 'feel' the difference." (6) "Talking to them about trying to land slightly softer as well as part of that. So they tend to, again, if you ask them to do that, it'll often shorten the stride, so the knee flexes a little bit, so they're not landing on a straight knee." (12) "Using those sort of cues around running softly, lightly, getting people to try and adjust their stride to decrease those impact forces." (13)
Cues to reduce contact time	
Consideration related to stiffness and an optimal range—implications to performance and injury	"Increase in the lower limb stiffness improves performance, power production, rate of force development, and therefore will improve significantly their running performance." (7) "Stiffness can be—can help you to become more efficient, more economical." (10) "If we can create more plantar flexion stiffness then we can see a more efficient motor unit." (11) "Kick your heels towards your butt and we like that one just because it reduces the inertial parameters of the swing … what it does is it allows people to use their hamstrings, get them a little bit more stiffness (to improve performance)." (14) "If I see the increased knee stiffness, I honestly encourage them to run softer so they can flex their knees a little bit more … Too much (stiffness) and you're really putting a lot on the tendons and the muscles. And too little of it is going through the skeletal systems." (15) "(Referring to stiffness) Some people might be Nerf balls, some people might be golf balls. And I think they are, and I think the evidence is really clear that they are very intrinsic tissue capabilities … Everybody doesn't have the same stiffness (in their) tendons." (16)

retraining interventions where clinicians seek to reduce impact loading variables.

Barriers and facilitators

Pain and irritability may prevent the implementation of running retraining in the early stages of rehabilitation (see online supplementary file 10.1 which summarises expert discussion of barriers and facilitators to running retraining implementation). Inconsistent beliefs related to whether a runner should be allowed to run in pain or not were evident. Importantly, experts suggesting running-related pain could be allowed, believed so only if pain was minimal (eg, 3/10). This fits with previous research in Achilles tendinopathy, which indicates that continued sports participation with minimal pain did not impair rehabilitation outcomes if guided by a similar pain monitoring model.[29] An additional consideration is that pain reduction may provide vital feedback to aid compliance to running retraining interventions.[104] Other key potential barriers discussed included muscle function capacity, joint flexibility and skeletal structure. Further research is needed to determine how these variables impact on biomechanical and clinical outcomes with running retraining. Fatigue resulting from running retraining was suggested to limit how much could be changed at once (eg, magnitude of step rate increase), and the duration runners may be able to maintain these changes. However, it was suggested that fatigue associated with running retraining was likely to diminish with habituation.

Of the studies providing limited evidence for running retraining to reduce pain,[22–25] two evaluated a programme including eight sessions of up to 30 min over a 2-week period,[22 23] another used 18 sessions over 6-weeks[24] and one used just 3 sessions over 6-weeks.[25] Three[22–24] of these four approaches are unlikely to reflect clinical practice due to associated costs they would entail, and are more intensive then those proposed by experts interviewed. The optimum number of sessions and time frame suggested to facilitate required changes varied among experts, and it was suggested this may be different for each runner. Some runners may be able to make clinically significant changes immediately, while others may take many months due to barriers such as pathology and associated pain, weakness, flexibility deficits, and intrinsic motivation. Importantly, experts highlighted these barriers may need to be addressed concurrently or prior to attempts to retraining running technique. Variable beliefs exist regarding the potential for changes as a result of running retraining to become habitual. Although few studies have explored this, limited evidence indicates a reduction in both peak hip adduction and running-related pain at 1–3 months follow-up can be achieved in females with PFP.[22 23] Further longer term studies are needed to determine if habituation from running retraining interventions in injured runners can be facilitated.

Limiting cues to one or two at a time was recommended. Additionally, an individual response to cues is considered likely, meaning clinicians need to be able to adapt and tailor cues to ensure desired biomechanical changes. Video analysis and feedback may assist compliance, allowing visualisation of running technique before and after the running retraining. Use of mirrors was suggested by some experts to assist reductions in hip adduction and knee valgus, and changes to trunk position and strike pattern. However, this was not recommended by all experts interviewed. With just one study published supporting the use of mirrors in running retraining,[22] further research is needed to establish their usefulness, along with other forms of clinically feasible biofeedback.

Undertaking running retraining on a treadmill was suggested to be practically easier than overground, although potential limitations in carry over to overground running gait were acknowledged. Vertical ground reaction forces have been reported to be similar between conditions.[105] However, treadmill running has been reported to decrease peak and range of knee flexion,[106–111] decrease ankle dorsiflexion range of motion, velocity and peak,[111 112] and increase peak rearfoot/ankle eversion[110 111 113] when compared with overground running. Further research is needed to establish to what extent clinical and biomechanical effects of running retraining on a treadmill translate to overground running.

Adjunctive interventions

Experts highlighted that running retraining is only part of the solution for the treatment of running injuries (see online supplementary file 10.2 which summarises expert discussion of adjunctive interventions during running retraining implementation). The importance of concurrently addressing muscle function and flexibility deficits was frequently discussed. References were made to both strength and motor control, with the latter being considered by some to be more important to an individual's ability to make changes to running technique. Manual therapy to address soft tissue flexibility and joint mobility restrictions was also considered as a potential adjunctive intervention by some experts. Further research to establish the impact of addressing muscle function and flexibility deficits through exercise and manual therapy on running retraining outcomes is needed.

The influence of footwear on injury and running retraining appears to be a divisive topic. While some experts believed footwear had minimal impact on outcomes, others considered footwear as vitally important. Those emphasising the importance of footwear generally promoted a more minimalistic approach, to assist in reducing impact loading variables and overstride, and transitioning towards a midfoot or forefoot strike. Importantly, caution and slow transition towards minimalist footwear was encouraged if choosing to implement this as an intervention, which is supported by recent evidence indicating an increased risk of pain and injury,[114] and foot bone marrow oedema[115] during 10–12-week transition periods. Barefoot running was suggested by some experts to potentially facilitate increased step rate, a more forefoot or midfoot strike, and reduced impact loading variables. Biomechanical rationale supports this premise,[102] but importantly, some experts suggested barefoot running may be injurious if the transition is too fast or running retraining is not concurrently implemented. The interaction of barefoot running and footwear modification with running retraining interventions requires investigation.

Substantial supporting evidence for the effectiveness of foot orthoses to treat lower limb injuries exists.[16 17] However, the perceived value of foot orthoses in running injury treatment varied among experts, with some considering them only as a 'last resort'. Additionally, those advocating their use generally saw them as only a temporary solution or a tool to facilitate desired running retraining strategies. Taping was viewed in similar light, with its value perceived to be in reducing symptoms in the short term and facilitating desired running retraining changes.

Prevention, performance and ideal running pattern

Some experts suggested running retraining may play a role in injury prevention, although a lack of available evidence to guide implementation exists (see online supplementary file 10.3 which summarises expert discussion of prevention, performance and and ideal running pattern in relation to running retraining). One commonly discussed approach was reducing impact loading variables such as vertical loading rates, indicating research to investigate the merits of this may be warranted in the future. When discussing running performance and economy, experts suggested acute changes may reduce running economy. However, some, but not all experts, suggested that economy may then improve over the first couple of months, with possible improvements to performance in the longer term with interventions such as increasing step rate.

Beliefs related to the presence of an ideal running pattern in relation to both injury and performance were inconsistent, with some experts suggesting this to be individual to each patient. Others stated certain running characteristics could be considered better than others for all runners, including higher step rates and a forefoot/midfoot strike. The topic of strike pattern is controversial, with the recent growing interest of barefoot running leading to a strong promotion of rearfoot runners to transition to a forefoot strike to both treat injury and improve performance.[116] Considering the lack of evidence to support this notion in relation to injury[102] and performance,[42 79] further research is needed on this topic.

Limitations and future research directions

This study provides what might be reported as a biased sample of 'experts' because we selected those who use and study running retraining. A sports biomechanics researcher or clinician who has moved away from this area of research because he/she feels it is not effective would not be included among our 'experts'. The topic guide (see online supplementary file 3) used to facilitate discussion between the researcher and interviewee was based primarily on literature included in the systematic review, which may have biased discussions towards topics with current biomechanical evidence. To address this, the topic guide included scope for and encouraged discussion of clinical reasoning regarding interventions lacking evidence.

Initial evaluation and framework analysis was completed by an experienced physiotherapist with more than 5 years' experience of providing running retraining as a specialist focus in clinical practice (CJB), which is another potential source of bias. To remove one level of bias, data accuracy and interpretation were checked by an additional researcher with qualitative research experience (PM), and two other researchers were also involved (AF-M and JC). Validity of qualitative findings was then further strengthened through triangulation of findings via respondent validation.

Only 5 of 46 studies included investigated an injured population, limiting the clinical applicability of findings from the evidence synthesis. We believe randomised controlled trials of running retraining efficacy in symptomatic populations are justified on the basis of current evidence. Such trials should also consider evaluating potential clinical predictors and biomechanical mechanisms, which may help tailor running retraining interventions to individuals and specific conditions. Other priorities highlighted by experts include development of technologies to provide more efficient feedback, developing options to allow mobile monitoring of compliance, and investigating the interaction of running retraining with other evidence-based interventions (see online supplementary file 9.1).

Summary

Expert clinical reasoning has been combined with a comprehensive evidence synthesis to guide clinicians and researchers who seek to implement and evaluate running retraining in the treatment of lower limb injury. Various options require consideration, including strategies to reduce overstride and increase step rate, altering strike pattern, reducing impact loading variables, increasing step width and altering proximal kinematics. Currently, limited evidence supports the effectiveness of transition from rearfoot to forefoot strike and increase step rate or altering proximal mechanics in individuals with anterior exertional lower leg pain, and visual and verbal feedback to reduce hip adduction in females with PFP. According to current expert opinion, other lower limb injuries which may benefit from running retraining include plantar fasciopathy, Achilles tendinopathy, calf pain, medial tibial stress syndrome, ITBS, patellar tendinopathy, proximal hamstring tendinopathy and gluteal tendinopathy. Tailoring approaches to each injury and individual is likely to be required to optimise outcomes, and running retraining should only be considered part of the solution when managing running injuries.

Key messages

Tailoring running retraining strategies to each injury and individuals is needed to optimise outcomes.

What are the findings?

- There is limited evidence for running retraining in the treatment of patellofemoral pain and anterior exertional lower leg pain.
- Based on sound biomechanical rationale, running retraining may assist in the treatment of lower limb injuries including exertional lower leg pain, plantar fasciopathy, Achilles tendinopathy, calf pain, medial tibial stress syndrome, patellofemoral pain, iliotibial band syndrome, patellar tendinopathy, hamstring injury including proximal tendinopathy and gluteal tendinopathy.
- The running retraining options that clinicians and patients might consider in clinical practice include strategies to reduce overstride and increase step rate, altering strike pattern, reducing impact loading, increasing step width and altering proximal kinematics.
- Substantial evidence exists for the immediate biomechanical effects of running retraining interventions in uninjured populations.

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Contributors CJB conceived the study concept and design. DRB, BSN and CJB completed literature searching. CJB and DRB completed quality assessment. CJB completed evidence synthesis. JC completed all interviews. CJB, PM and AF-M were responsible for qualitative data analysis and initial interpretation. All authors contributed to interpretation of findings, manuscript write up and final approval.

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Running retraining to treat lower limb injuries: a mixed-methods study of current evidence synthesised with expert opinion

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