CURRENT CONCEPTS IN BIOMECHANICAL INTERVENTIONS FOR PATELLOFEMORAL PAIN

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ABSTRACT

Patellofemoral pain (PFP) has historically been a complex and enigmatic issue. Many of the factors thought to relate to PFP remain after patients' symptoms have resolved making their clinical importance difficult to determine. The tissue homeostasis model proposed by Dye in 2005 can assist with understanding and implementing biomechanical interventions for PFP. Under this model, the goal of interventions for PFP should be to re-establish patellofemoral joint (PFJ) homeostasis through a temporary alteration of load to the offended tissue, followed by incrementally restoring the envelope of function to the baseline level or higher.

High levels of PFJ loads, particularly in the presence of an altered PFJ environment, are thought to be a factor in the development of PFP. Clinical interventions often aim to alter the biomechanical patterns that are thought to result in elevated PFJ loads while concurrently increasing the load tolerance capabilities of the tissue through therapeutic exercise. Biomechanics may play a role in PFJ load modification not only when addressing proximal and distal components, but also when considering the involvement of more local factors such as the quadriceps musculature.

Biomechanical considerations should consider the entire kinetic chain including the hip and the foot/ankle complex, however the beneficial effects of these interventions may not be the result of long-term biomechanical changes. Biomechanical alterations may be achieved through movement retraining, but the interventions likely need to be task-specific to alter movement patterns. The purpose of this commentary is to describe biomechanical interventions for the athlete with PFP to encourage a safe and complete return to sport.

Level of Evidence: 5

Keywords: Foot, hip, knee, rehabilitation, running

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BACKGROUND

Patellofemoral pain (PFP) has historically been a complex and enigmatic issue. Many factors have been identified to correlate with symptoms including variations in strength, flexibility, patellar tracking, quadriceps angle, and patellofemoral joint (PFJ) morphology. There are also known correlations with psychological factors such as depression, fear-avoidance, and anxiety which complicate the presentation further.[1]

Factors thought to relate to PFP often remain after patients' symptoms have resolved making their clinical importance difficult to determine.[2] Further complicating assessment, the pain source in PFP may involve multiple structures and is highly controversial.[2] As such, a thorough clinical assessment of an individual is paramount to fostering successful patient outcomes in this population. Although this commentary will explore biomechanical interventions for PFP, this pathology may be better understood in the context of the tissue homeostasis model.

HOMEOSTASIS MODEL OF PATELLOFEMORAL PAIN

In 2005, Dr. Scott Dye proposed a tissue homeostasis model for understanding PFP.[2] When any tissue is in homeostasis, it is maintaining a constant physiological condition of its internal environment. Although very successful at self-regulation, sufficient disruption of homeostasis can result in pathophysiologic processes. Instead of considering the presentation of PFP strictly from a perspective of structural failure, Dye suggested that the pathophysiologic processes that occur in response to sudden bouts of increased training loads or stressors should be seen as the true driver of symptoms.[2]

Homeostasis can be described as a zone, or "envelope of function", where the tissue is capable of tolerating loads.[2] It has been suggested that this zone is established through chronic loads to which the PFJ and related structures have adapted in response to consistent and incremental exposure.[3] Acute increases in training loads that exceed the established envelope of function are thought to disrupt homeostasis of the PFJ, ultimately resulting in pain. A central tenet of the envelope of function is that high PFJ loads are not inherently dangerous; rather loads that

exceed a tissue's conditioned capacity may be what are potentially injurious. Indeed, acute increases in training load that exceed chronic training loads appear to play a role in the development of many sports-related injuries.[3,4]

Once this homeostasis of the tissue is disrupted by sudden increases in training loads, the PFJ and associated structures may no longer tolerate levels of loading even during routine activities, such as descending stairs or previously well-tolerated running distances.[2] The goal of intervention at this point should be to re-establish homeostasis through a temporary alteration of PFJ loads, followed by incrementally restoring the envelope of function to the baseline level or, preferably, higher. The biomechanical interventions described in this commentary can be particularly helpful at temporarily reducing loads while trying to re-establish homeostasis of the PFJ.[6] Further, an understanding of the biomechanics of therapeutic interventions for PFP can also assist the clinician with planning a rehabilitation program that incrementally restores a patient's envelope of function. The purpose of this commentary is to describe biomechanical interventions for the athlete with PFP to encourage a safe and complete return to sport.

BIOMECHANICAL OVERVIEW OF PATELLOFEMORAL PAIN

High levels of patellofemoral loads, particularly in the presence of an altered PFJ environment,[7] are thought to be a factor in either the development or chronicity of PFP.[8-10] A PFJ that has relatively low PFJ contact area[11] or diminished cartilage thickness and properties,[7,12] transfers greater loads to the subchondral bone.[8] Indeed, individuals with PFP demonstrate increased water content[13] and metabolic activity[14] in the subchondral bone of the patella. Therefore, clinical interventions often aim to alter the biomechanical patterns that are thought to result in elevated PFJ loads while concurrently increasing the load tolerance capabilities of the tissue through therapeutic exercise.

Interventions that address biomechanical loading of the PFJ should encompass multiple loading parameters. Clinicians should familiarize themselves with the sport-specific loading demands that their athlete
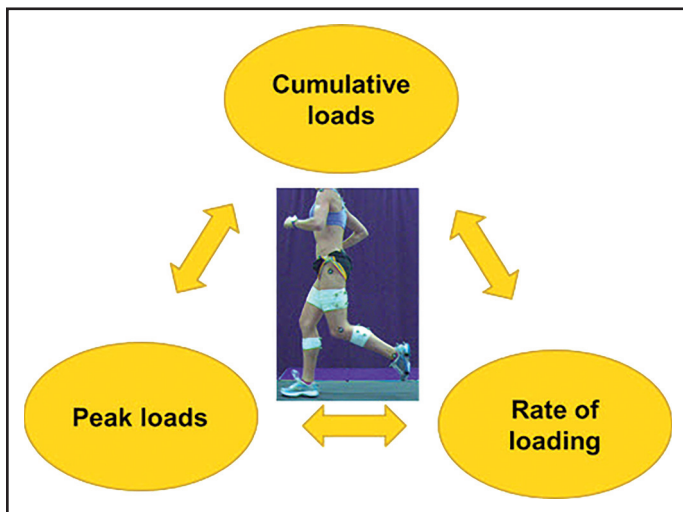
Figure 1. *The patellofemoral joint and related structures experience three aspects of loading a) the peak load per step, b) how quickly this load is applied (rate of loading and 3) the total accumulation of load during an activity. These metrics are important to consider in the development of rehabilitation programs for individuals with patellofemoral pain.*

with PFP may experience. Running, for instance, is a highly repetitive activity in which relatively high loads of 4-5.5 times body weight[15-17] are applied to the PFJ at a moderately high rate[18] (Figure 1). Thus, a rehabilitation program for the running athlete with PFP should include components that expose the extensor mechanism to high loads at a relatively moderate rate, with an emphasis on repetition. In contrast to running, the jumping athlete likely experiences PFJ reaction forces well in excess of 10 times body weight[19] applied at a much higher rate, but with fewer repetitions. A well-planned rehabilitation program for any athlete with PFP should reflect these sport-specific demands to ensure a durable return to sport.

CONSIDERING THE QUADRICEPS

Quadriceps weakness is an established risk factor for the development of PFP[20] across a variety of populations. Quadriceps weakness may be indicative of inadequate chronic training loads and, ultimately, a PFJ that has a relatively low envelope of function. Individuals who develop PFP have been found to have quadriceps strength deficits of 6-12% compared with healthy control participants[20-23] which are undetectable via manual muscle testing. As such, outcome measures documenting quadriceps strength in this population should utilize some form of dyna-

mometry during testing, either handheld (isometric) or isokinetic. Handheld dynamometry is a reliable measure of quadriceps strength (ICC = 0.72)[24] with even greater reliability when straps are used to stabilize the dynamometer (ICC = 0.96).[25] As clinicians in non-research settings typically lack access to isokinetic dynamometers, the use of an inexpensive handheld dynamometer is highly advisable in the assessment of quadriceps strength in athletes with PFP.

Progressive quadriceps strengthening is a foundation of rehabilitation of the athlete with PFP. In high quality studies, there is consistent evidence that progressive quadriceps strengthening improves symptoms and function in these patients.[26] Progressive quadriceps resistance exercises have been shown to reduce PFP by 44-90%.[26,27] While targeted strengthening of the vastus medialis oblique (VMO) is often prescribed, there is inconclusive evidence supporting its superiority to generalized quadriceps strengthening for the treatment of individuals with PFP.[26,28] Therefore, the authors of this commentary have considered the literature on generalized quadriceps strengthening and VMO-targeted strengthening together.

The results of a quadriceps strengthening program may be enhanced through the use of patellar taping or bracing. The effect of patellar taping on PFJ kinematics and PFP remains somewhat controversial. Although the application of patellar tape results in large and immediate reductions in pain,[29] pain reductions occur with either directionally applied or non-directionally applied tape.[30] These findings are suggestive of a non-biomechanical mechanism for the reduction in pain that is often observed with patellar taping. Patellar taping may enhance the ability to perform quadriceps resistance exercises in individuals with PFP,[31] presumably by reducing pain-related quadriceps inhibition. Thus, patellar taping may enable greater PFJ loading during quadriceps resistance exercises that would ordinarily result in pain.[29] In support of this rationale, recent systematic reviews indicate that patellar taping enhances patient outcomes, but only in the first 12 weeks of rehabilitation[6,32] when pain would be expected to be the greatest. Patellar bracing may also have a similar influence on outcomes in individuals with PFP through the 6 and 12 week time points.[33] As such,

it appears that recovery from PFP may be bolstered by the addition of patellar taping or patellar bracing, but only in the first 6-12 weeks of a patellofemoral rehabilitation program.

THE QUADRICEPS STRENGTHENING PARADOX

Despite the consistent improvements in pain associated with quadriceps strengthening, the mechanism behind reported pain reductions is unclear. For instance, quadriceps strengthening exercises may potentially expose the PFJ to high reaction forces which are thought to exacerbate PFP. Conversely, it has been proposed that quadriceps strengthening may alter patellar kinematics, potentially increasing the contact area between the patellar and trochlear articular surfaces. To date, preliminary evidence suggests that eight weeks of quadriceps strengthening may result in increased contact area of the PFJ.[34] Thus, quadriceps strengthening may reduce PFJ stress by increasing the contact area of the PFJ.

Ultimately, the process of quadriceps strengthening, rather than the quadriceps strength gains that result, may reduce PFP by improving load tolerance of the patient and the PFJ structures. For instance, quadriceps strengthening results in a desirable increase in glucosaminoglycan content in articular cartilage of the knee.[35] In an animal model, eccentric quadriceps muscle contractions result in protective adaptations in distal femoral articular cartilage.[36] Taken together, these findings suggest that a loading program may increase the tissue quality of the articular cartilage of the PFJ. Emerging evidence also suggests that progressive loading of the PFJ may reduce local hyperalgesia[37] and may alter central pain processing in individuals with PFP.[38,39] Therefore, progressive quadriceps strengthening may improve a patient's envelope of function by enhancing load tolerance of the PFJ. Clearly, further study is necessary to better understand the mechanisms of pain reduction that are observed in individuals with PFP that result from a quadriceps strengthening program.

THE BIOMECHANICS OF QUADRICEPS STRENGTHENING

Prescription of quadriceps strengthening for the treatment of PFP requires a working knowledge of the biomechanics of various progressive resistive exercises. Specifically, clinicians should consider carefully the interactions between external moment arms, external and internal loads, knee joint angles and articular contact area of the PFJ when prescribing quadriceps strengthening exercises. In either open or closed kinetic chain, contact area of the PFJ is the lowest in the first 20 degrees of knee flexion and steadily increases as knee flexion increases.[11,40] Interestingly, the external moment arm acting on the knee also increases as an individual moves deeper into a closed kinetic chain squat. As a result, PFJ stress (the quotient of PFJ reaction force and PFJ contact area) increases fairly linearly from full knee extension to approximately 45 degrees of knee flexion during a squatting maneuver.[41,42] However, PFJ reaction forces increase rapidly from approximately 45 degrees to 100 degrees of knee flexion with either a squat or leg press[43] with a disproportionate lower rate of increase in PFJ contact area.[40] The net result is that PFJ stress is considerably higher when squatting and leg presses in knee flexion angles in excess of approximately 45 degrees when compared with squatting with comparatively less knee flexion (Figure 2 and 3A).[41] Thus in the early stages of rehabilitation of PFP, the PFJ is particularly well-suited to closed chain loads, in approximately the first 45 degrees of knee flexion.[41]

Quadriceps strengthening can also be achieved with open kinetic chain exercises. However, PFJ loads during open chain exercises are highly dependent on the configuration of force application. During open chain knee extension with a weight attached to the ankle, the external moment arm increases as the knee nears full extension. This loading configuration results in a highly variable level of external resistance throughout the knee extension motion (EXT-VR) as shown in Figures 2 and 3B. Thus, PFJ reaction forces increase rapidly as the knee nears full extension in the open chain[43] whereas PFJ contact area decreases precipitously. This loading scenario results in a large increase in PFJ stress in the last 20 degrees of knee extension, which is exactly opposite of what occurs during a squatting maneuver.[41] In contrast, a knee extension machine that uses a cable system applies external resistance in a fairly uniform manner throughout the knee range of motion, via a constant external moment arm (EXT-CR) as shown in Figure 2 and 3C.[41,44] Knee exten-
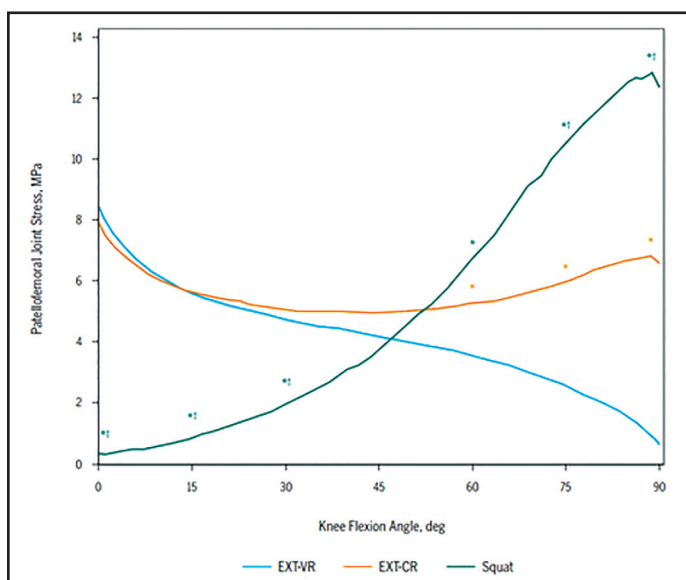
Figure 2. *Patellofemoral joint stress during three different types of quadriceps strengthening exercises: EXT-VR represents a free weight attached to the distal lower leg. EXT-CR represents a knee extension machine that applies constant resistance. Squat relates to a squatting maneuver. Patellofemoral joint strees is dependent on the external moment arm, amount of resistance and the direction of force application. Figure reprinted with permission from Powers CM, Ho KY, Chen YJ Souza RB, Farrokhi S. Patellofemoral joint stress during weight-bearing and non-weight-bearing quadriceps exercises. J Orthop Sports Phys Ther. May 2014; 44(5): 320-327.*

sion machines with constant resistance exhibits PFJ stress values in terminal knee extension that are proportional to those observed during the same range of motion with a knee extension with variable resistance.[41] Interestingly, a performing knee extensions between 90-50 degrees of knee flexion with a constant resistance configuration results in PFJ stress levels that are intermediate to PFJ stress estimated during closed chain squatting or open chain knee extension through the same range of motion.[41]

When selecting appropriate resistance levels, clinicians should keep in mind that large internal muscle forces often result from counteracting much lower external loads. Regardless of the sport, clinicians should seek to achieve activity-relevant quadriceps loads with therapeutic exercise in athletes with PFP prior to return to sport initiation. During running, for instance, peak vertical ground reaction forces are typically around 2.5 times body weight, yet the external moment arm acting on the knee is rather large. In contrast, the much smaller internal moment arm

of the quadriceps[45] necessitates peak quadriceps forces estimated at 5 times body weight during the stance phase of endurance-paced running.[46] Muscle forces of this magnitude are attainable with select rehabilitation exercises. Single leg squats performed to at least 65 degrees of knee flexion without added weight yields peak quadriceps forces of approximately 4-5 times body weight.[47] However, squats to this depth of knee flexion may result in pain in individuals with PFP[41] and peak knee flexion during running rarely exceeds 40-45 degrees,[47] Thus, clinicians should opt for added weight to a single leg squat to attain peak quadriceps that are relevant to running. Adding resistance to body weight exercises is absolutely required if a clinician wishes to attain peak quadriceps forces that are of same magnitude as those seen during jumping. For instance, a bilateral drop vertical jump results in peak quadriceps forces of 7 times body weight.[48]

Provided the added resistance is sufficient, open kinetic chain knee extension exercises can also generate peak quadriceps forces that are similar to forces noted during running and other activities. For instance, therapists may find it difficult to provide sport-relevant resistance between 45-90 degrees of knee flexion[41] with the EXT-VR load configuration. Once past the early stages of rehabilitation, the constant resistance supplied by a knee extension machine using the EXT-CR configuration may thus provide the best means to strengthen the quadriceps between 45-90 degrees of knee flexion in the athlete recovering from PFP (Figure 3C). For closed kinetic chain, exercises that involve squatting or leg presses between 0 and 45 degrees of knee flexion may be the best means to strengthen the quadriceps with moderate levels of PFJ stress. With either squatting or open chain knee extension exercises, clinicians should aim to incrementally increase the range of motion and level of resistance in response to improvements in pain in the patient to restore the envelope of function of the PFJ.

TREATMENTS FOR PROXIMAL CONTRIBUTIONS TO PATELLOFEMORAL PAIN

Female athletes with PFP often demonstrate greater hip adduction, hip internal rotation, and contralateral pelvic drop during sporting tasks.[6,49-51] These
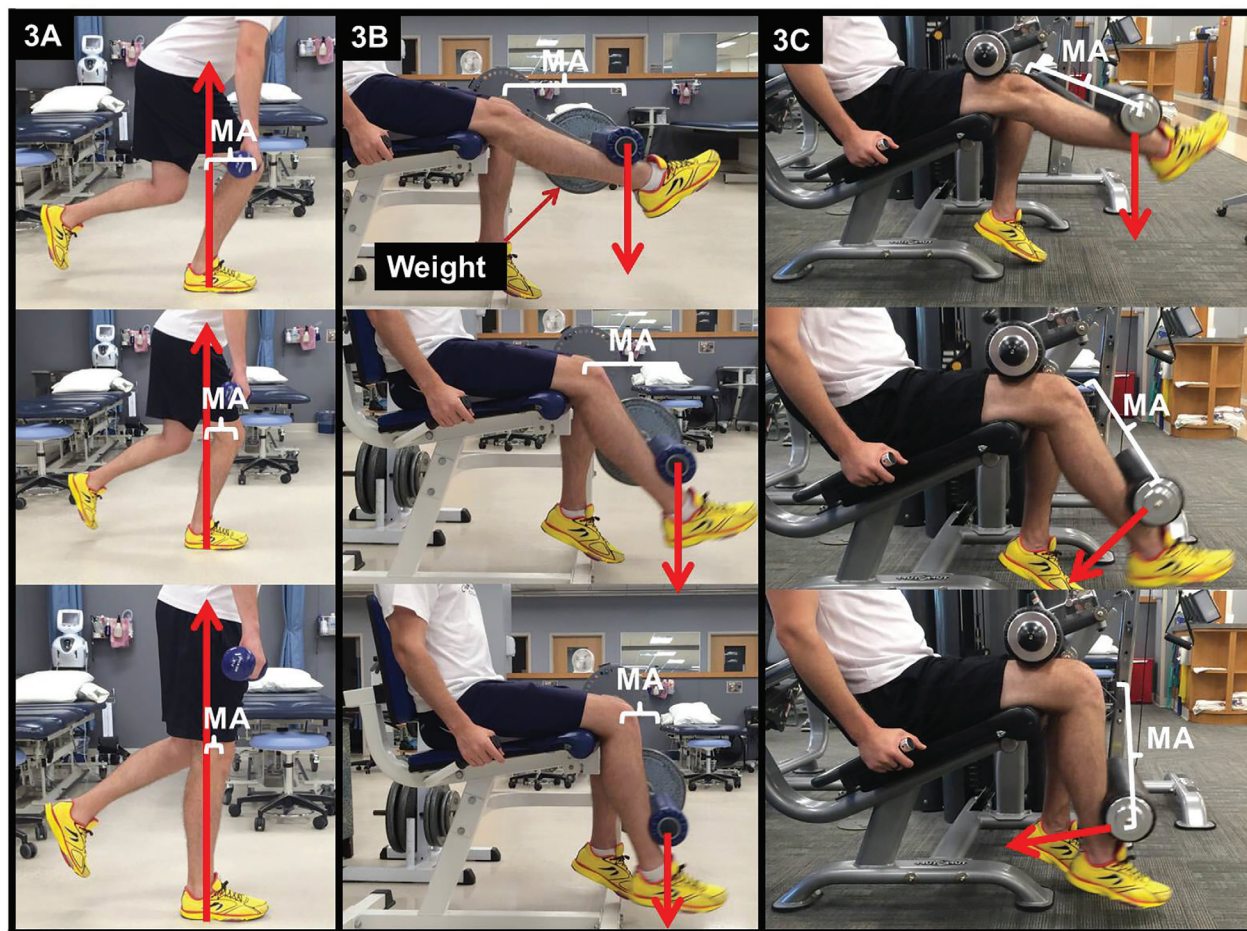
Figure 3. *The interaction between external loads and the external moment arm during common quadriceps strengthening exercises. Figure 3A: During the single leg squat, the external moment arm (MA) increases as the depth of the squat also increases resulting in increasing quadriceps forces and patellofemoral joint stress through 90 degrees of knee flexion. Corresponds with "Squat" in Fig. 2. Figure 3B: Patient performing open chain knee extension with a weight mounted at the levle of the lower leg (non tap figure). The external moment arm (MA) increases as the knee extends, resulting in increasing quadriceps forces and patellofemoral joint stress as the knee nears full extension. Corresponds with "EXT-VR" in Fig. 2. Figure 3C: During open chain knee extension on knee extension machine with a cable and weight stack system, the external moment arm (MA) remains constant throughout the range, resulting in relatively stable quadriceps forces and patellofemoral joint stress. Corresponds with "EXT-CR" in Fig. 2.*

mechanics are thought to reduce PFJ contact area, ultimately resulting in an increase in PFJ stress.[50] Real-time magnetic resonance imaging studies suggest relative lateral tracking of the patella as the femur adducts and internally rotates during a squatting or step down maneuver in females with PFP.[52-55] Contralateral pelvic drop is thought to increase tension in the lateral patellar retinaculum[56] via the iliotibial band,[57] potentially contributing to lateral patellar tracking.

Recent literature has evaluated interventions designed to address the proximal mechanisms of PFP. Proposed interventions to address the proximal mechanism contribution to PFP aim to reduce contralateral pelvic drop and reposition the femur, via reduced hip adduction and medial rotation. Smartphone applications and open source movement analysis software provide the means to readily analyze an athlete's mechanics in the clinic. During running, close proximity of the medial femoral condyles during midstance (Figure 4), known as a "reduced knee window,"[58] is suggestive of excessive hip adduction and hip internal rotation of the stance limb. Results of movement analyses can assist with clinical decision making in developing targeted rehabilitation programs.

Reduced posterolateral hip strength is often observed in individuals with PFP.[1,59] As the posterolateral hip musculature controls contralateral pelvic drop, hip

Figure 4. *Runner with patellofemoral pain demonstrating reduced space between the medial femoral condyles i.e., reduced knee window, suggestive of high levels of hip adduction and hip internal rotation of the right lower extremity.*

adduction, and hip internal rotation, it is not surprising that hip strengthening is often prescribed for the treatment of PFP.[6,60,61] Interestingly, posterolateral hip strengthening does not appear to reduce excessive proximal mechanics in either asymptomatic[62,63] or symptomatic individuals.[64,65] While these findings might be surprising, prospective data fail to support deficits in posterolateral hip strength as a risk factor for the future development of PFP.[59] In fact, data from two large prospective studies suggest that individuals who go on to develop PFP actually had *greater* posterolateral hip strength.[21,66] As reduced hip strength is observed in individuals with active PFP, but not before pain develops, hip strength deficits may actually be the result of PFP, rather than the cause of PFP.[59] Also noteworthy, posterolateral hip strength is not a strong predictor of frontal and transverse plane hip mechanics during running or stepdown maneuvers.[67]

There is a growing body of evidence of moderate to high quality that supports the prescription of posterolateral hip strengthening for the treatment of PFP.[6,74] Hip strengthening programs result in moderate to large reductions in PFP with moderate to large improvements in function in the short- to medium-term.[74] To date, only one study has evaluated long-term outcomes after a hip strengthening program for PFP.[69] At one-year post-intervention, Fukuda and colleageus reported that individuals who completed a hip and quadriceps strengthening program demonstrated greater improvements in PFP and lower limb function compared with quadriceps strengthening alone.[69] Evaluating interventions for PFP that employ hip strengthening can also be challenging as the quadriceps are also loaded during most hip strengthening exercises, such as step ups or single leg squats.[68] Future study that delineates hip strengthening and quadriceps strengthening exercises is needed to better understand the mechanism(s) of pain reduction noted after these rehabilitation programs. As proximal strengthening does not appear to alter proximal mechanics, non-biomechanical mechanisms may explain the reduction in PFP that is widely reported with rehabilitation programs that employ hip strengthening.

When approached from a tissue homeostasis perspective, long-term correction of proximal mechanics may not be required. As higher levels of hip adduction[75] and internal rotation[76] increase PFJ stress, these mechanics may hinder recovery from PFP. However, precipitating factor in the development of PFP in many athletes may be the application of load beyond the amount that the PFJ has been conditioned to tolerate. For example, a runner may have always had elevated hip adduction and internal rotation, yet the actual culprit for the development of PFP may be increasing running mileage faster than the PFJ and associated structures can adequately adapt. Along these lines, an athlete who runs with greater levels of hip adduction and hip internal rotation may be more susceptible to rapid changes in training loads than a runner who does not exhibit similar mechanics. Thus, the promising clinical outcomes of proximal exercise interventions for PFP may be better explained as simply the systematic conditioning of the PFJ and supportive musculature

to tolerate more load rather than actually changing hip frontal and transverse plane mechanics.[62]

MOVEMENT RE-EDUCATION FOR THE TREATMENT OF PFP

When attempting to restore tissue homeostasis, reducing PFJ loads through movement re-education may be particularly helpful in the early to intermediate stages of rehabilitation. Recent work suggests that various mechanics associated with PFP are modifiable with the use of motor learning techniques. As a premise for movement re-education for the proximal mechanism of PFP, individuals with PFP demonstrated delayed onset and reduced duration of gluteus medius activation.[77,78] Thus, currently described movement re-education interventions for the proximal mechanism aim to alter the neuromuscular control of the gluteal musculature in an effort to control proximal mechanics, if implicated. In contrast to hip strengthening, movement re-education has been shown to reduce proximal mechanics during running and other functional tasks, such as step descent or a single leg squat.[49] Providing mirror and verbal feedback, for instance, has been shown to be effective at reducing contralateral pelvic drop, hip adduction and hip internal rotation during a single leg squat.[62] Interestingly, changes in proximal mechanics during a single leg squat did not transfer to running.[62] Thus, patients are able to achieve improved control of proximal mechanics during common therapeutic exercises may not necessarily transfer these movement skills to an unrelated task, such as running. These findings suggest that changes in lower extremity mechanics require a motor learning component and that movement retraining likely needs to be task-specific.

The movement re-education literature for the treatment of PFP has largely focused on retraining running gait. Proximal mechanics[79,80] have been targeted in published gait retraining studies with runners with PFP. Realtime kinematic[80] or mirror feedback,[79] coupled with verbal cueing, result in reductions in hip adduction and contralateral pelvic drop in female runners with PFP (Figure 5). These reductions in proximal mechanics were accompanied by improvements in reported pain and lower limb function that were associated with large effect sizes.[49] Importantly, these previous investigations targeted females with PFP who also demonstrated

Figure 5. *Open source software and a webcam can be used to provide real-time feedback on frontal plane running mechanics. This video technique is useful if the treadmill has a large controller console that prevents the runner from seeing their reflection in a full-length mirror.*

a proximal mechanism during running. This criterion for enrollment in the respective studies underscores the importance of a targeted intervention in response to a thorough clinical gait analysis.[58]

Cueing a modest increase in step rate (cadence) during running has been shown to reduce PFJ contact forces and stress in individuals with and without PFP.[16,81-83] Clinically, most runners find that employing modest increases in running cadence is a relatively easy skill to learn. An increase in step rate by 5-10% over preferred levels reduces PFJ loads in part by decreasing peak knee flexion and quadriceps forces during the stance phase of gait.[16,81] Again, a clinical gait analysis is highly recommended in determining runners who would benefit the most from an increase in step rate. Specifically, runners who exhibit high amounts of vertical oscillation of the estimated center of mass between flight phase and mid-stance, have footfalls that are far in front of the estimated center of mass, and reach high levels of knee flexion during stance phase may benefit the most from an increase in step rate.[81,84] An increase in step rate also results in a reduction in peak hip adduction, albeit smaller in magnitude than the aforementioned kinematic and mirror feedback

studies.[85,86] Thus, running with increased step rate primarily reduces PFJ forces through a reduction in quadriceps forces rather than a large effect on lateral tracking of the PFJ.

Adopting a forefoot strike pattern during running has also been suggested as a means to reduce PFJ loads.[82,87] However, clinicians should be aware, that conversion to a forefoot strike increases the demand of the ankle plantarflexors while reducing demand of theknee extensors. Adopting a forefoot strike pattern has been shown to result in 11% greater Achilles tendon forces per step, which equates to an additional 47.7 times body weight impulse loading of the Achilles tendon per mile of running.[88] Because adopting a 5-10% increase in running cadence reduces PFJ loads by 10-20%[16,82] while also *reducing* Achilles tendon loads,[89] cueing an increase in running cadence may be preferred over adoption of a forefoot running pattern.

Clinical reasoning should guide movement re-education prescription. If frontal and transverse plane hip mechanics are thought to be the main biomechanical factor contributing to a runner's current PFP, then visual feedback to cue reductions in these mechanics are warranted. If sagittal plane running mechanics are primarily implicated in a runner's PFP, then cueing an increase in step rate during running may be the most effective gait modication. Clinically, cueing a reduction in proximal mechanics can easily be done with a full-length mirror or with a live video stream. Similarly, cueing an increase in steprate can be accomplished via matching the rhythm of a metronome[82,86] or in response to real time feedback from commercially available wrist mounted running computers[85] that calculate step rate via an accelerometer mounted in a footpod or within the device itself (Figure 6).

THE ROLE OF FOOT ORTHOSES IN THE TREATMENT OF PATELLOFEMORAL PAIN

While there appears to be some support for the use of foot orthoses for the treatment of PFP,[90] the biomechanical rationale supporting their use is less clear. For instance, a 6° medially wedged orthosis did not reduce peak frontal plane kinematics or joint moments of the knee or hip in runners with and without PFP.[91] Interestingly, greater standing calcaneal eversion posture was not predictive of any changes in frontal plane hip or knee mechanics in

Figure 6. *Commercially available running computer enables the real-time calculation of running cadence (step rate).*

response to orthotics.[91] Despite these findings, foot orthoses, combined with exercise therapy, resulted in improved outcomes over six weeks in individuals with PFP compared with exercise therapy alone.[90] In an interesting clinical trial, Lewinson and colleagues randomized runners with PFP to either medially or laterally wedged foot orthoses. Regardless of foot orthoses assignment, both groups of runners reported 33% reductions in PFP after six weeks of using the foot orthoses during routine training runs.[92] Non-uniform reductions in frontal plane knee moments during running with the foot orthoses were observed across the cohorts.[92] These data, considered along with aforementioned studies, suggest that foot orthoses may enhance short term outcomes in PFP rehabilitation programs, but clinical results may be due to either individualized responses or non-biomechanical mechanisms. Patients with PFP who experience a reduction in pain with the use of foot orthoses may be able to tolerate greater levels of resistance during therapeutic exercises, potentially improving their envelope of function.

BIOMECHANICAL CONSIDERATIONS FOR RETURN TO SPORT

As described previously, peak quadriceps loads associated with an athlete's sport of choice are readily achieved with targeted resistance exercises. How-

ever, a progressive return to sport program is necessary to replicate the rate of loading and cumulative loads that are experienced by the PFJ during sporting tasks. For example, slow jogging is associated with a knee angular velocity in excess of 500 deg/sec with much higher velocities associated with faster running and jumping.[93] Knee angular velocities of this magnitude are difficult and potentially unsafe to simulate clinically with isokinetic knee extension devices. Similarly, sport-specific cumulative PFJ loads can be equally difficult to achieve with resistance training alone. For instance, running just 1 km alone requires approximately 800-1000 steps.[17] Thus, progressive return to sport programs are necessary to specifically mimic the loading rate and cumulative demands of a sport in order to fully restore the athlete's envelope of function.

Sample return to sport programs are readily available in the literature to assist clinicians in objectively guiding an athlete's return to jumping or running sports. Progressive jumping programs are available for the jumping athlete that advance jump repetitions, depth and height of jumps as well as progressing from bilateral to single leg jumps as symptoms allow.[94] Typically, return to running programs progress run:walk ratios in response to patient-reported discomfort.[95,96] While return to running programs are often based on time or distance, consideration of the number of loading cycles per training session may better quantify cumulative knee loads. Quantifying loading cycles in return to running programs can easily be done with a wearable activity monitors or running computers. PFJ loads during running are not different between overground and treadmill running.[17] Thus, treadmills may offer greater convenience and the advantage of enhanced control of running speed and number of loading cycles when compared to overground running. Individuals recovering from PFP may also benefit from running at a faster speed as opposed to slow jogging. Faster paced running requires shorter stance times and fewer steps to travel a given distance, resulting in lower cumulative PFJ loads when compared with jogging.[97] Therefore, running athletes recovering from PFP may have greater success with bouts of moderately fast- to fast-paced running for a prescribed number of steps rather than focusing on slow jogging for a set amount of time.

To guide clinical decision making, a criterion-based progression should be implemented that evaluates pain during activity and in the 24 hours after the return to sport session. There are no formal guidelines available for acceptable pain in athletes with PFP completing a return to sport program. Care should be taken during return to sport tasks to avoid acute aggravation of knee pain, which can increase hyperalgesia in individuals with PFP.[37] Thus, it is the authors' recommendation that pain should remain at or below 2/10 on the visual analog scale during return to sport activity, with trace to absent pain after the activity session.

CONCLUSION

The mechanisms of PFP are complex and enigmatic. The presentation may be best described by considering a tissue homeostasis model. Biomechanical interventions that reduce PFJ loading may be most helpful during early rehabilitation to allow progressive quadriceps strengthening as tissue homeostasis is re-established.

Biomechanical considerations should include the entire kinetic chain including the hip and the ankle, however the beneficial effects of these interventions may not be the result of long-term biomechanical changes. True biomechanical alterations may be achieved through movement retraining, but the interventions must be extremely specific to the desired task.

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