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Commentary

Eccentric exercise in the prevention of patellofemoral pain in high-volume runners: A rationale for integration

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ABSTRACT

Patellofemoral pain (PFP) is a common overuse condition seen in high-volume runners, such as military recruits. Exercise is commonly prescribed, with benefit, for the rehabilitation of individuals with PFP. However, a substantial number of individuals with the condition do not achieve an optimal outcome, suggesting the condition can be difficult and complex. Given the challenging nature of the condition, and the risk of developing PFP in high-volume runners, it seems logical to investigate options for injury prevention. Eccentric exercise has been useful in the prevention of some pathologies so its utility in preventing PFP should be explored. Current evidence regarding prevention programs for PFP are limited. Preventative exercise programs for PFP have not been well described or reported, and questions remain regarding their effectiveness. Based on available evidence or lack thereof, and known physiological and clinical effects of eccentric exercise, suggestions for integration of eccentric exercise into PFP prevention programs are offered. Eccentric exercise may be useful for PFP prevention from a theoretical framework however additional longitudinal cohort studies would be useful in determining its utility.

Background

Patellofemoral pain (PFP) is a common overuse knee condition seen in runners. The etiology of PFP remains unclear but a number of modifiable and non-modifiable factors likely contribute to altered stress at the patellofemoral joint.[1,2] Interestingly, incidence rates in military recruits who notoriously are exposed to high-volume running programs, range from 9.7 to 571.4/1000 person years, with a point prevalence of 13.5%.[3] Given the high proportion of people with the condition, further inquiry into the prevention of PFP is warranted.

PFP may be related to decreased force production in the knee extensors and hip abductors, with eccentric contractions more prominently occurring during functional activities.[1] Specific to military recruits, quadriceps weakness may serve as a risk factor for developing PFP.[2] Some individuals with PFP have displayed significant hip abduction and knee extension eccentric strength deficits when compared to healthy individuals.[4] Nakagawa et al. discussed the role of eccentric quadriceps loading to dissipate force during the loading response phase of weight-bearing activities in order to properly control knee flexion.[5] Individuals experiencing PFP may avoid eccentrically loading their hip abductors and knee extensors due to weakness or to minimize pain. This can be problematic, as it may lead to muscle performance deficits, compensatory body mechanics during weight-bearing activities and subsequently exacerbate symptoms.[1] Neuromuscular control deficits are a critical component of the aforementioned compensatory movements, which can be reduced by improving muscle morphology and neural activity.[6] Importantly, rehabilitation of individuals with PFP should be based on individual clinical findings, as patellofemoral morphology and structural abnormalities on imaging are not consistently correlated to symptoms.[7,8]

Eccentric exercise (EE) has been well-described in the rehabilitation of conditions such as tendinopathy, but may also be helpful in the prevention of some injuries. For example, assuming good compliance, multifaceted programs including EE are beneficial in preventing hamstring strains.[9] EE may also be a beneficial component of anterior cruciate ligament tear prevention, although its isolated use in prevention is not well described.[10] These reports suggest there may be a protective effect of eccentric exercise in hip and knee injuries, so its application for the prevention of PFP may be reasonable.

Although recent studies support the use of exercise in treating PFP, there is little evidence regarding the effectiveness of exercise in the prevention of PFP. The purpose of this paper is review available evidence and discuss the possible role of eccentric exercise training in preventing patellofemoral pain, particularly as it relates to high-volume runners such as military recruits.

Exercise prescription for patellofemoral pain management

In the simplest terms, overuse conditions develop when tissue capacity is exceeded by the activity demand (Fig. 1). Exercise has been strongly recommended to manage PFP, with hip and knee directed interventions generally recommended over knee interventions alone.[1,11] Despite its high incidence and strong evidence in favor of exercise, PFP can be challenging to manage. One study using a 5–8 year follow up noted 57% of respondents with PFP reported an unfavorable outcome.[12] The authors noted higher self-reported disability and longer symptom duration correlated to worse long-term outcomes. Additionally, a number of psychosocial factors and altered central pain processing may play a role in symptom persistence and difficulty in managing the condition.[13,14]

A common approach to manage PFP is to reduce altered patellofemoral joint loading. Individuals with PFP typically complain of symptoms in positions of loaded or weight-bearing knee flexion, where compressive load of the patellofemoral joint is increased.[15] A recent

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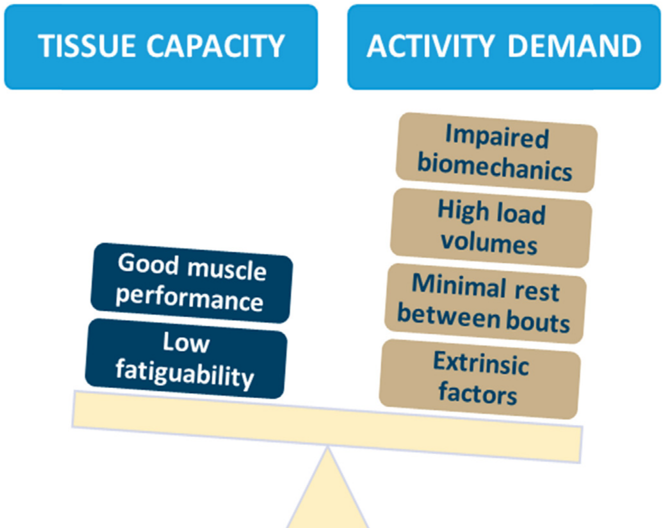


Fig. 1. Interplay between tissue capacity and activity demand in overuse conditions.

consensus statement offered a thorough biomechanical framework for the pathomechanical variables involved in PFP.[16] Underlying this biomechanical framework is the idea that altered kinetics and kinematics are causative variables in PFP. Theoretically, it would make sense that excessive femoral adduction and internal rotation or impaired muscle activation patterns may lead to aberrant stress patterns at the patellofemoral joint, subsequently leading to symptoms. Biomechanical impairments in proximal and distal factors have led to numerous studies investigating interventions such as hip and knee exercises and orthotic prescription to manage PFP.

Although altered kinematics and physical impairments at the body structures and function level can contribute to symptoms in persons with PFP, pain and self-reported disability are not always correlated to patellofemoral joint loading.[17] While targeted interventions to normalize biomechanical faults can be helpful in managing symptoms,[18,19] the complex presentation of PFP coupled with the high proportion of persistent symptoms suggests continued investigation into best practice in this population is warranted. As noted previously, EE has been helpful in reducing the frequency of soft tissue injuries in some cases. Although the mechanisms behind injury prevention are numerous, it is possible that eccentric loading increases tissue capacity to sustain greater strain before failure.[20] Few studies have investigated interventions to prevent the development of PFP or other joint related pathologies. In studies offering exercise for PFP prevention thus far, a lack of appropriate reporting makes it difficult to determine which exercises were offered, if the dosage was sufficient, or if participants would benefit from exercise alone. Prior to identifying the clinical utility of EE in the prevention of PFP, a review of relevant physiological mechanisms of EE is warranted.

Physiological mechanisms of eccentric exercise

To truly understand the potential benefit of eccentric exercise in the prevention of PFP, it would help to understand the physiological mechanisms of EE. By definition, eccentric muscle contraction is muscle activity that occurs when the force applied to the muscle exceeds the momentary force produced by the muscle itself.[21] The result is a lengthening action from work being done on the muscle, or 'negative work', and this absorbed mechanical energy can either be recovered and added to a subsequent concentric muscle contraction or be dissipated as heat.[21] It is hypothesized that eccentric muscle contractions elicit novel acute and chronic adaptive responses, compared to concentric or isometric contractions, due to its impact on a number of physiologic variables.[21,22] When chronically performed, the manifestations of these physiological adaptations include greater gains in strength, muscle mass, and neural adaptations[23–25] that could make it a valuable component for prevention programs.

EE has been shown to elicit increased force output at a lower level of activation for a given angular velocity when compared to concentric and isometric contractions.[25,26] While the exact mechanisms underpinning this increase in force production during EE are unclear, it has been hypothesized that the increase is mediated by increases in both the strain and number of attached cross-bridges.[21,27] Unlike concentric and isometric contractions during which only one myosin head is bound, the increased strain on a single myosin head during eccentric lengthening may enable activation of a second myosin head, leading to twice the number of active cross-bridges,[21] and thus greater force production capabilities. Additionally, previous research suggests that the hypertrophy adaptation to chronic eccentric training may be mediated by modifications of gene expression, resulting in both higher satellite cell activity and greater anabolic signaling.[21,25] Satellite cell proliferation increases the capacity for protein synthesis and allows for hypertrophy to occur.[28] This increase in satellite cell activity was found to occur in type II fibers after a maximal eccentric effort.[21]

Differing morphological adaptations of skeletal muscle eliciting hypertrophy have also been demonstrated following eccentric compared to concentric training.[23,29] Specifically, eccentric training has shown to result in greater increases in fascicle length mediated by an addition of sarcomeres in series when compared to concentric training, while concentric training has shown to result in greater increases in pennation angle mediated by addition of sarcomeres in parallel.[23,29] While both modes of resistance training may produce similar increases in hypertrophy, these differences in architectural adaptations suggest that structural remodeling is mode specific.[29] The increase in fascicle length due to EE may alter muscle function due to influences on force-velocity and force-length relationships, ultimately influencing muscle performance.[29,30] Specifically, it is hypothesized the increase in muscle fiber length results in an increased maximal shortening velocity of the muscle.[31] Furthermore, the addition of sarcomeres in series and thus fascicle length has been suggested to act as a protective mechanism from future bouts of eccentric contraction muscle damage and soreness due to this shift in the length-tension relationship.[29,32]

Given its importance to the muscle-tendon unit, morphological changes of tendinous tissue during exercise should also be considered. Resistance training has been associated with changes in tendon stiffness and modulus.[33,34] The degree of adaption is thought to be dependent on the magnitude of strain[35] and since EE elicits greater force output than other modes of contraction, it is logical that EE may promote these structural changes compared to other modes by affording greater loads on the tendon. Enhanced tendon capacity through strength training in healthy individuals may offset the demand placed on muscular tissue during activity, thereby reducing overuse risk, although additional research into this area is warranted.

While eccentric contractions produce more force than concentric or isometric contractions, they also have lower metabolic requirements resulting in the ability to perform EE with less energy costs for higher mechanical loads.[36] Thus, with eccentric programs, it may be possible to obtain higher session workloads, with less fatigue. Eccentric contraction uses typically four times less metabolic power to produce a given amount of negative mechanical power.[25,36] It is hypothesized that the mechanism eliciting lower metabolic requirements is that the cross-bridges do not complete a full cycle during eccentric contractions. Instead, they remain in an active state until they are forcibly detached and rapidly re-attached, requiring less ATP to maintain force.[27] Outcomes such as decreased muscle fiber fatigability, blood lactate accumulation, energy expenditure, and carbohydrate oxidation, lower perceived exertion, and higher fat oxidation have been shown to be a result of the lower metabolic costs during EE when compared to concentric exercise.[21,25] At the same absolute torque output, EE has also been shown to result in less cardiovascular demand (as measured by heart rate, mean arterial pressure, rate pressure product, systolic blood pressure, and diastolic blood pressure)[37] making it applicable for a variety of populations. It should be noted that while in-session fatigue during EE may be lower than other contraction types, higher energy expenditure has been shown to occur following EE for up to 48–72 h, hypothesized to be a result of the muscle damage that occurs during EE,[21] making adequate recovery periods between EE training a critical component of program design.

Compared to other contraction types, the neural strategies controlling eccentric contractions have shown to be unique, including a decrease in the number and size of motor units required during recruitment and lower and more variable motor unit discharge.[6,25] The greater force production capabilities with eccentric contraction, as previously mentioned, mean that fewer numbers of motor units are required for a given load.[21] Additionally, the motor unit discharge rate has been suggested as the primary contributor to increases in strength following eccentric training.[22] While the mechanisms behind these strategies are not completely understood, research suggests it involves a combination of supraspinal and spinal factors.[38] When compared to concentric contractions which appear to rely more on spinal-reflexive mechanisms, eccentric contractions have demonstrated production of greater excitability of the motor cortex.[6] This increase in cortical excitability occurs to counteract the inhibition at the spinal cord level, ultimately allowing the eccentric contraction to occur.[6] Considering these physiological mechanisms at local, spinal and supraspinal levels, EE may play an important role in improving tissue capacity for activity.

Eccentric exercise in the prevention of patellofemoral pain

Injury prevention is an important field, but is of particular importance for populations at high-risk for developing overuse conditions. In the military population, knee overuse injuries are the most common musculoskeletal conditions treated and contribute a significant amount of missed training time and treatment cost.[39] One study reported that among 449 trainees participating in Naval Special Warfare training, PFP accounted for 9.4% of reported injuries.[40] There are several possible factors that may contribute to the development of PFP, such as overtraining without proper rest, change in training habits, altered biomechanics, and decreased strength.[1,41] Pragmatically, offering formal individualized running analysis and subsequent targeted intervention in the prevention in PFP to all military members or high-volume runners is unrealistic. Identification of methods to increase strength to accommodate to the rapid increase in training could potentially reduce the incidence of overuse injuries. Using a low-cost program that can be widely used and adapted as necessary for specific task performance would be ideal.

Although strength deficits and pain are commonly correlated in PFP, causal relationships have not necessarily been established, further complicating the prevention and management of the condition.[1,39] To minimize time lost, militaries have worked to create screening methods to predict musculoskeletal injuries, such as PFP, as well as interventions to prevent them. Thus far, programs involving hip and knee strengthening have produced functional improvements and pain reduction in those with PFP, as well as a decreased prevalence among military recruits.[39] Other studies examining the role of strengthening the hip and knee musculature in the management of patients with PFP have found similar results, suggesting that this may be an effective intervention for improving pain and function for these patients.[42,43] Considering that it is unclear whether pain or strength deficits occur first, it is possible that strengthening could be utilized in a preventative manner for those participating in intense physical activity, such as high-volume runners and military recruits.

If strengthening the hip and knee musculature may be preventative for PFP, the optimal exercise prescription should be considered. As discussed earlier, eccentric training provides certain benefits over other types of muscle contraction.[44,45] Higher muscular forces can be produced during eccentric contractions, these contractions produce less fatigue and are more metabolically efficient. Because of the increased forces generated during this type of exercise, as well as the unique neural adaptations, greater strength gains are achieved via eccentric training and may be preferred in prevention programs emphasizing strength development.[44,45] Although training specificity should guide prevention protocols, Table 1 presents a number of possible exercises for high-volume runners which may increase tissue capacity and attenuate the substantial stress occurred in training. In the table presented, which is not intended to be prescriptive for all populations, activities in a prevention program might include a mixture of weight bearing and non-weight bearing activities that facilitate functional and isolation-based muscle recruitment of muscles commonly implicated with PFP. When considering the non-weight bearing exercises depicted in Table 1, the eccentric muscle demand may appear relatively low, although electromyographic (EMG) activity may be high, which can be helpful when initiating programs.[46] Increased participant effort and muscular output can be created by adding external load (e.g. leg weight or cable column), or having a partner add manual resistance. Specific exercise prescriptions will depend on the specific individual's ability and goals, and the American College of Sports Medicine has developed progression models for guidance.[47]

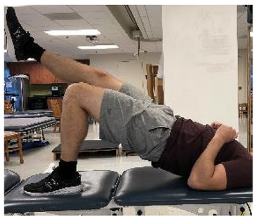
Although symptoms of PFP tend to be localized to the knee, it is important to have good muscle performance through the entire leg when trying to minimize the risk of developing the condition. Recruiting muscle groups while trying to minimize compensation can be more easily achieved in non-weight bearing positions. Replicating necessary muscle activity in positions of less demand may be a good starting activity. For example, in the presence of substantial gluteus medius weakness leading to pelvic drop in stance, frontal plane recruitment in non-weight bearing seems appropriate. In this case, side-lying hip abduction has considerable EMG recruitment, and may serve as a precursor or adjunct to other activities.[46] Though particular muscle group recruitment can be helpful, an emphasis should be placed on weight bearing, single limb and dynamic exercises to replicate the demands of running. Eccentric moments of the gluteal, quadricep and hamstring muscles in varying angles of knee flexion are common,[15] and should be incorporated in prevention programs.

While a theoretical framework regarding the role of eccentric strength training and the prevention of PFP is presented, available evidence describing effective implementation of EE for preventing PFP is scarce. However, there is support regarding the management of the condition, as well as the contributing factors, that suggests that this type of training could theoretically have a preventative role. The active population and military recruits share a similar mechanism of injury in which tissue capacity is exceeded by activity demands, usually in a rapid fashion without appropriate rest.[41,42] If strength deficits and biomechanical abnormalities could be addressed prior to engaging in this type of activity, or at least concurrently, then it is reasonable that strength training could be used in a targeted and specific manner toward prevention. Considering the eccentric role of the musculature involved in running, as well as the supported benefits of eccentric strength training, it is appropriate to incorporate this type of training when addressing strength deficits in persons with PFP. The authors of this commentary hope additional investigation into optimal prevention interventions is pursued.

Conclusions

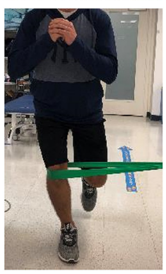
High volume runners frequently suffer from overuse musculoskeletal disorders such as PFP. With PFP, numerous muscle performance impairments have been linked to the development and persistence of symptoms and exercise is frequently effective in the management of the condition. Eccentric exercise, from a theoretical construct, appears to be useful in building tissue capacity to prevent overuse conditions such as PFP, although well-performed prospective studies are required to confirm or deny its effectiveness.

Table 1
Suggested exercises for eccentrically loading muscles implicated in patellofemoral pain.

Exercise		Technique	Functional Relevance
NON-WEIGHT BEARING TASKS			
Quadruped Alternating Upper and Lower Extremities		Stabilizing body on hands and knees, participant slowly raises one arm and the opposite leg Emphasis is placed on avoiding excessive lumbopelvic rotation	Facilitates proximal stability while reciprocal extremity motion is present, as is noted with running
Single Leg Bridge		Laying on back, training leg bent and contralateral limb straight Participant raises trunk from table and slowly lowers back to the bed	Recruits gluteal muscles and quadriceps in training limb Recruits quadriceps on contralateral limb
Side-lying Hip Abduction		Laying on side, participant raises training limb towards ceiling Care is taken to avoid excessive lumbopelvic rotation or hip flexion Limb slowly lowered back to the table	Electromyography activity of the gluteus medius is high Strengthens muscles involved in frontal plane hip and pelvic stability
Straight Leg Raise		Laying on back, contralateral knee bent After isometrically activating the quadriceps to keep a straight leg, the limb is raised and slowly lowered down	Isolation exercise of the quadriceps Various muscle activity (isometric, concentric, eccentric) similar to functional tasks
WEIGHT-BEARING TASKS			
Double Leg Squat		Standing equally on both legs, the participant slowly lowers their body towards the ground	Eccentric loading of the quadriceps to build strength while replicating the loading phases of running gait
Hip Hikes		Standing on the training limb, keeping the knee relatively straight, the participant slowly lowers the contralateral limb towards the floor Emphasis is placed on avoiding transverse plane deviations	Eccentrically activating the gluteus medius in stance Replicates stance phase gluteal activity of walking and running gait
Single Leg Deadlift		Standing on training limb with knee slightly flexed Without changing knee angle, participant slowly lowers trunk towards the floor while the contralateral limb moves back to counterbalance	Emphasizes stance limb stability Eccentrically recruits gluteal and hamstring muscles

(*continued on next page*)

Table 1 (*continued*)

Exercise		Technique	Functional Relevance
			
Single Leg Squat		Standing on the training limb, the participant slowly lowers their body Emphasis is placed on avoiding excessive frontal plane deviation of the trunk or femur	Eccentrically activating the quadriceps Self-awareness of frontal plane control Replicates position of foot strike through stance
Single Leg Squat with Resistance for Hip External Rotation		Start in single limb stance with resistance band around knee Participant slowly squats down maintaining neutral knee position, avoiding frontal plane deviation	Eccentric quadriceps loading Resistance facilitates co-contraction of proximal muscles active during stance phase of running

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This revised manuscript is being submitted for exclusive review by the Sport Medicine and Health Science journal, and is not under review elsewhere.

Authors' contributions

All authors (BF, DB, LW, DJ) were involved equally in the concept, development, writing and final submission approval processes of this manuscript.

Ethical approval

The appropriate IRB was contacted and deemed this work exempt from review.

Conflict of interest

The authors have no conflicts of interest, financial or otherwise.

References

1. Willy RW, Hoglund LT, Barton CJ, et al. Patellofemoral pain. *J Orthop Sports Phys Ther*. 2019;49(9):CPG1–CPG95. https://doi.org/10.2519/jospt.2019.0302.
2. Neal BS, Lack SD, Lankhorst NE, Raye A, Morrissey D, van Middelkoop M. Risk factors for patellofemoral pain: a systematic review and meta-analysis. *Br J Sports Med*. 2019 Mar;53(5):270–281. https://doi.org/10.1136/bjsports-2017-098890.
3. Smith BE, Selfe J, Thacker D, et al. Incidence and prevalence of patellofemoral pain: a systematic review and meta-analysis. *PloS One*. 2018;13(1), e0190892. https://doi.org/10.1371/journal.pone.0190892.
4. Boling MC, Padua DA, Alexander Creighton R. Concentric and eccentric torque of the hip musculature in individuals with and without patellofemoral pain. *J Athl Train*. 2009;44(1):7–13. https://doi.org/10.4085/1062-6050-44.1.7.
5. Nakagawa TH, Baldon Rde M, Muniz TB, Serrão FV. Relationship among eccentric hip and knee torques, symptom severity and functional capacity in females with patellofemoral pain syndrome. *Phys Ther Sport*. 2011;12(3):133–139. https://doi.org/10.1016/j.ptsp.2011.04.004.
6. Lepley LK, Lepley AS, Onate JA, Grooms DR. Eccentric exercise to enhance neuromuscular control. *Sport Health*. 2017;9(4):333–340. https://doi.org/10.1177/1941738117710913.
7. Fick CN, Grant C, Sheehan FT. Patellofemoral pain in adolescents: understanding patellofemoral morphology and its relationship to maltracking. *Am J Sports Med*. 2020 Feb;48(2):341–350. https://doi.org/10.1177/0363546519889347.
8. van der Heijden RA, de Kanter JL, Bierma-Zeinstra SM, et al. Structural abnormalities on magnetic resonance imaging in patients with patellofemoral pain: a cross-sectional case-control study. *Am J Sports Med*. 2016;44(9):2339–2346. https://doi.org/10.1177/0363546516646107.
9. Goode AP, Reiman MP, Harris L, et al. Eccentric training for prevention of hamstring injuries may depend on intervention compliance: a systematic review and meta-analysis. *Br J Sports Med*. 2015 Mar;49(6):349–356. https://doi.org/10.1136/bjsports-2014-093466.
10. Arundale AJH, Bizzini M, Giordano A, et al. Exercise-Based knee and anterior cruciate ligament injury prevention. *J Orthop Sports Phys Ther*. 2018 Sep;48(9):A1–A42. https://doi.org/10.2519/jospt.2018.0303.
11. Crossley KM, van Middelkoop M, Callaghan MJ, Collins NJ, Rathleff MS, Barton CJ. Patellofemoral pain consensus statement from the 4th International Patellofemoral Pain Research Retreat, Manchester. Part 2: recommended physical interventions (exercise, taping, bracing, foot orthoses and combined interventions). *Br J Sports Med*. 2016;50(14):844–852. https://doi.org/10.1136/bjsports-2016-096268.
12. Lankhorst NE, van Middelkoop M, Crossley KM, et al. Factors that predict a poor outcome 5-8 years after the diagnosis of patellofemoral pain: a multicentre observational analysis. *Br J Sports Med*. 2016;50(14):881–886. https://doi.org/10.1136/bjsports-2015-094664.
13. Maclachlan LR, Collins NJ, Matthews MLG, Hodges PW, Vicenzino B. The psychological features of patellofemoral pain: a systematic review. *Br J Sports Med*. 2017 May;51(9):732–742. https://doi.org/10.1136/bjsports-2016-096705.
14. De Oliveira Silva D, Rathleff MS, Petersen K, Azevedo FM, Barton CJ. Manifestations of pain sensitization across different painful knee disorders: a systematic review including meta-analysis and metaregression. *Pain Med*. 2019;20(2):335–358. https://doi.org/10.1093/pm/pny177.
15. Neumann D A. Kinesiology of the Musculoskeletal System: Foundations for Physical Rehabilitation, third ed. Elsevier. 2017.
16. Powers CM, Witvrouw E, Davis IS, Crossley KM. Evidence-based framework for a pathomechanical model of patellofemoral pain: 2017 patellofemoral pain consensus statement from the 4th International Patellofemoral Pain Research Retreat,

Manchester, UK: part 3. *Br J Sports Med*. 2017;51(24):1713–1723. https://doi.org/10.1136/bjsports-2017-098717.
17. De Oliveira Silva D, Willy RW, Barton CJ, Christensen K, Pazzinatto MF, Azevedo FM. Pain and disability in women with patellofemoral pain relate to kinesiophobia, but not to patellofemoral joint loading variables. *Scand J Med Sci Sports*. 2020;30(11): 2215–2221. https://doi.org/10.1111/sms.13767.
18. Neal BS, Barton CJ, Gallie R, O'Halloran P, Morrissey D. Runners with patellofemoral pain have altered biomechanics which targeted interventions can modify: a systematic review and meta-analysis. *Gait Posture*. 2016;45:69–82. https://doi.org/10.1016/j.gaitpost.2015.11.018.
19. Davis IS, Tenforde AS, Neal BS, Roper JL, Willy RW. Gait retraining as an intervention for patellofemoral pain. *Curr Rev Musculoskelet Med*. 2020;13(1):103–114. https://doi.org/10.1007/s12178-020-09605-3.
20. LaStayo PC, Woolf JM, Lewek MD, Snyder-Mackler L, Reich T, Lindstedt SL. Eccentric muscle contractions: their contribution to injury, prevention, rehabilitation, and sport. *J Orthop Sports Phys Ther*. 2003;33(10):557–571. https://doi.org/10.2519/jospt.2003.33.10.557.
21. Douglas J, Pearson S, Ross A, McGuigan M. Eccentric exercise: physiological characteristics and acute responses. *Sports Med*. 2017;47(4):663–675. https://doi.org/10.1007/s40279-016-0624-8.
22. Douglas J, Pearson S, Ross A, McGuigan M. Chronic adaptations to eccentric training: a systematic review. *Sports Med*. 2017;47(5):917–941. https://doi.org/10.1007/s40279-016-0628-4.
23. Reeves ND, Maganaris CN, Longo S, Narici MV. Differential adaptations to eccentric versus conventional resistance training in older humans. *Exp Physiol*. 2009;94(7): 825–833. https://doi.org/10.1113/expphysiol.2009.046599.
24. Roig M, Macintyre DL, Eng JJ, Narici MV, Maganaris CN, Reid WD. Preservation of eccentric strength in older adults: evidence, mechanisms and implications for training and rehabilitation. *Exp Gerontol*. 2010;45(6):400–409. https://doi.org/10.1016/j.exger.2010.03.008.
25. Hody S, Croisier JL, Bury T, Rogister B, Leprince P. Eccentric muscle contractions: risks and benefits. *Front Physiol*. 2019;10:536. https://doi.org/10.3389/fphys.2019.00536.
26. Fang Y, Siemionow V, Sahgal V, Xiong F, Yue GH. Distinct brain activation patterns for human maximal voluntary eccentric and concentric muscle actions. *Brain Res*. 2004;1023(2):200–212. https://doi.org/10.1016/j.brainres.2004.07.035.
27. Linari M, Lucii L, Reconditi M, et al. A combined mechanical and X-ray diffraction study of stretch potentiation in single frog muscle fibres. *J Physiol*. 2000;526 Pt 3(Pt 3):589–596. https://doi.org/10.1111/j.1469-7793.2000.00589.x.
28. Bazgir B, Fathi R, Rezazadeh Valojerdi M, Mozdziak P, Asgari A. Satellite cells contribution to exercise mediated muscle hypertrophy and repair. *Cell J*. 2017;18(4): 473–484. https://doi.org/10.22074/cellj.2016.4714.
29. Franchi MV, Reeves ND, Narici MV. Skeletal muscle remodeling in response to eccentric vs. Concentric loading: morphological, molecular, and metabolic adaptations. *Front Physiol*. 2017;8:447. https://doi.org/10.3389/fphys.2017.00447.
30. Timmins RG, Shield AJ, Williams MD, Lorenzen C, Opar DA. Architectural adaptations of muscle to training and injury: a narrative review outlining the contributions by fascicle length, pennation angle and muscle thickness. *Br J Sports Med*. 2016; 50(23):1467–1472. https://doi.org/10.1136/bjsports-2015-094881.
31. Bodine SC, Roy RR, Meadows DA, et al. Architectural, histochemical, and contractile characteristics of a unique biarticular muscle: the cat semitendinosus. *J Neurophysiol*. 1982;48(1):192–201. https://doi.org/10.1152/jn.1982.48.1.192.
32. Morgan DL, Talbot JA. The addition of sarcomeres in series is the main protective mechanism following eccentric exercise. *J Mech Med Biol*. 2002;2:421–431, 03n04.
33. Magnusson SP, Narici MV, Maganaris CN, Kjaer M. Human tendon behaviour and adaptation, in vivo. *J Physiol*. 2008;586(1):71–81. https://doi.org/10.1113/jphysiol.2007.139105.
34. Maganaris CN, Chatzistergos P, Reeves ND, Narici MV. Quantification of internal stress-strain fields in human tendon: unraveling the mechanisms that underlie regional tendon adaptations and mal-adaptations to mechanical loading and the effectiveness of therapeutic eccentric exercise. *Front Physiol*. 2017;8:91. https://doi.org/10.3389/fphys.2017.00091.
35. Kaux J, Drion P, Libertiaux V, et al. Eccentric training improves tendon biomechanical properties: a rat model, 093494.155. *Br J Sports Med*. 2014;48(7):617. https://doi.org/10.1136/bjsports-2014-093494.155.
36. Abbott BC, Bigland B, Ritchie JM. The physiological cost of negative work. *J Physiol*. 1952;117(3):380–390. https://doi.org/10.1113/jphysiol.1952.sp004755.
37. Overend TJ, Versteegh TH, Thompson E, Birmingham TB, Vandervoort AA. Cardiovascular stress associated with concentric and eccentric isokinetic exercise in young and older adults. *J Gerontol A Biol Sci Med Sci*. 2000;55(4):177. https://doi.org/10.1093/gerona/55.4.b177.
38. Duchateau J, Enoka RM. Neural control of lengthening contractions. *J Exp Biol*. 2016; 219(Pt 2):197–204. https://doi.org/10.1242/jeb.123158.
39. Kollock RO, Andrews C, Johnston A, et al. A meta-analysis to determine if lower extremity muscle strengthening should Be included in military knee overuse injury-prevention programs. *J Athl Train*. 2016;51(11):919–926. https://doi.org/10.4085/1062-6050-51.4.09.
40. Kaufman KR, Brodine SK, Shaffer RA, Johnson CW, Cullison TR. The effect of foot structure and range of motion on musculoskeletal overuse injuries. *Am J Sports Med*. 1999;27(5):585–593. https://doi.org/10.1177/03635465990270050701.
41. Duvigneaud N, Bernard E, Stevens V, Witvrouw E, Van Tiggelen D. Isokinetic assessment of patellofemoral pain syndrome: a prospective study in female recruits. *Isokinet Exerc Sci*. 2008;16(4):213–219.
42. Baldon Rde M, Serrão FV, Scattone Silva R, Piva SR. Effects of functional stabilization training on pain, function, and lower extremity biomechanics in women with patellofemoral pain: a randomized clinical trial. *J Orthop Sports Phys Ther*. 2014; 44(4):240–251. https://doi.org/10.2519/jospt.2014.4940. A1-A8.
43. Van Tiggelen D, Witvrouw E, Coorevits P, Croisier J, Roget P. Analysis of isokinetic parameters in the development of anterior knee pain syndrome: a prospective study in a military setting. *Isokinet Exerc Sci*. 2004;12(4):223–228.
44. Roig M, O'Brien K, Kirk G, et al. The effects of eccentric versus concentric resistance training on muscle strength and mass in healthy adults: a systematic review with meta-analysis. *Br J Sports Med*. 2009;43(8):556–568. https://doi.org/10.1136/bjsm.2008.051417.
45. Enoka RM. Eccentric contractions require unique activation strategies by the nervous system (1985) *J Appl Physiol*. 1996;81(6):2339–2346. https://doi.org/10.1152/jappl.1996.81.6.2339.
46. Distefano LJ, Blackburn JT, Marshall SW, Padua DA. Gluteal muscle activation during common therapeutic exercises. *J Orthop Sports Phys Ther*. 2009;39(7): 532–540. https://doi.org/10.2519/jospt.2009.2796.
47. American College of Sports Medicine. American College of Sports Medicine position stand. Progression models in resistance training for healthy adults. *Med Sci Sports Exerc*. 2009;41(3):687–708. https://doi.org/10.1249/MSS.0b013e3181915670.

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