ACTIVE & SAFE

Evidence Summary: Running

Christian A. Clermont, MSc

Version 1

February 2018

BC INJURY research and prevention unit

The British Columbia Injury Research and Prevention Unit (BCIRPU) was established by the Ministry of Health and the Minister's Injury Prevention Advisory Committee in August 1997. BCIRPU is housed within the Evidence to Innovation research theme at BC Children's Hospital (BCCH) and supported by the Provincial Health Services Authority (PHSA) and the University of British Columbia (UBC). BCIRPU's vision is *to be a leader in the production and transfer of injury prevention knowledge and the integration of evidence-based injury prevention practices into the daily lives of those at risk, those who care for them, and those with a mandate for public health and safety in British Columbia.*

Author: Christian Clermont

Editors: Sarah A Richmond, Amanda Black

For any questions regarding this report, contact:

BC Injury Research and Prevention Unit
F508 – 4480 Oak Street
Vancouver, BC V6H 3V4
Email: bcinjury1@cw.bc.ca
Phone: (604) 875-3776
Fax: (604) 875-3569
Website: www.injuryresearch.bc.ca

Suggested Citation:

Clermont C, Black A, Richmond SA, Pike I, Babul S. *Evidence Summary: Running*. Active & Safe Central. BC Injury Research and Prevention Unit: Vancouver, BC; 2018. Available at http://activesafe.ca/.

UBC BC Children's Hospital Research Institute

Evidence synthesis tool

SPORT:	Running	**Target Group:**	Adults, Adolescents, & Children

Injury Mechanisms:	Lower-limb musculoskeletal running-related injuries			
Incidence/Prevalence	**Risk/Protective Factors**	**Interventions**	**Implementation/Evaluation**	**Resources**
Adults (Overall Injuries) Based on a systematic review from van Gent et al. (2007), the incidence of lower extremity running-related injuries has been reported to be between 19.4 and 79.3% of all runners, depending on which study and how a running-related injury is specifically defined. In a retrospective case-control analysis of 2002 running injuries by Taunton et al. (2002), the most common site of running-related injuries are the knee (42.1% of all injuries), foot/ankle (16.9%), lower leg (12.8%), hip/pelvis (10.9%), achilles/calf (6.4%), upper leg (5.2%), and lower back (3.4%) (Taunton et al., 2002). More specifically, the top five most common overuse running-related injuries are patellofemoral pain syndrome, iliotibial band syndrome, plantar fasciitis,	**Overall Injuries** **Risk Factors** Gender differences: Prospective research by Ryan, Elashi, Taunton, and Koehl (2014) demonstrates females have a lower normalized injury rate than male runners (4.46 vs. 6.86 RRIs/1000 training sessions) resulting in a relative risk of 0.67 [95% CI: 0.32-1.40] compared to men. The most significant risk factor was previous lower limb injury and incomplete rehabilitation, where half of runners reporting a running-related injury had previously sustained an injury to the same anatomical area, and 42% of runners who had a previous injury and sustained another injury declared themselves as not 100% rehabilitated. A prospective cohort study by Buist, Bredeweg, Lemmink, van Mechelen, and Diercks (2010) found higher BMI, especially in male novice runners to have a hazard risk ratio of MSK injury= 1.15 [95% CI 1.05 – 1.26]. A clinical review by Vincent and Vincent (2013) also discuss higher BMI being a	There is a lack of effective long-term prevention strategies for running-related injuries (Barton et al., 2016). Nevertheless, based on the risk factors associated with running-related injuries, researchers and clinicians have developed some evidence-informed strategies to prevent or minimize the risk of running injuries, particularly for new or novice runners. **General Advice for Appropriate Start-to-Run Programs for Novice Runners** For new runners, especially those who are overweight and obese, Vincent and Vincent (2013) recommend a gradual transition into running from other low-impact activity (e.g., incline walking) would minimize the risk for musculoskeletal injury. Also, walk-to-run transition speed for obese individuals (have the person walk on a treadmill at increasing speeds until a threshold is reached at which	According to Barton et al. (2016), some barriers for running retraining in the early stages of rehabilitation include: pain and irritability as well as muscle function capacity, joint flexibility, and skeletal structure. In a systematic literature review of gait retraining with augmented feedback, Agresta and Brown (2015) present other barriers with some potential strategies to overcome these barriers for the implementation and evaluation of gait retraining strategies. For example, there are high associated costs of long-term gradual running retraining, depending on the individual runner. Undertaking running retraining on a treadmill is easier than on ground. 3D motion analysis systems are expensive, but 2D video cameras and mirror-based systems seem feasible for clinical environments	

meniscal injuries, and tibial stress syndrome **Novice Runners** A systematic review and meta-analysis from Videbaek, Bueno, Nielsen, and Rasmussen (2015) demonstrated that novice runners are at the highest risk of injury with 17.8 injuries per 1,000 hours of running [95% CI: 16.7, 19.1]. In a different systematic review and meta-analysis, Kluitenberg, van Middelkoop, Diercks, & van der Worp (2015) presented injury rates and anatomical locations for different types of runners. For novice runners, the pooled injury proportion (% [95% CI]) for a short follow-up period (6-15 weeks) is 26.4% [14.2, 43.7], during a one-year follow up is 27.3% [24.5, 30.3], and long-term follow-up (greater than 1 year) is 84.9% [74.8,91.5]. The most common injury site for novice runners is the lower leg (34.7% of injuries), followed by the knee (30.6%), hip/pelvis (10.2%), ankle (8.2%), upper leg	significant risk factor for running-related injuries. In a systematic review by van Der Worp et al. (2015), some of the main, consistent risk factors included: advanced age, navicular drop (>10mm), and leg length difference. In a different systematic review exploring the risk factors for lower-extremity running injuries, Gijon-nogueron & Fernandez-villarejo (2015) found a number of risk factors, including: genu varum alignment, male height >1.70m, alcohol intake, increasing weekly distance >10%, shoe inserts and orthotics, running >= 6 times a week, increased pronation excursion, increased reinversion velocity, inadequate muscle stabilization, wide internal rotation range and peak tibial acceleration, muscle fatigue, and running on a Hard surface. When exploring foot function as a risk factor for lower limb overuse injury, a systematic review by Dowling et al. (2014) found greater lateral and medial directed centre of pressure during running as well as increased or decreased pressure-related outcomes in the 5th metatarsal region to significant risk factors. A prospective randomized clinical trial by Ryan, Elashi, Newsham-West, and Taunton (2014) found more injuries in two minimalist groups (partial and	running is more comfortable; 30-60 mins 3X/week with 1 day rest in between). Avoid rapid increases in running intensity or mileage. General runner stepwise increase of ~10%; and 5-10% stepwise increased for obese individual. This permits the bone tissues to rest and avoid mechanical failure. Runners can use the onset of pain or symptoms as guides for participation in running. Muscle soreness is expected with a big change in running duration or decline grade. Pain that increases during running or walking sessions should be avoided, and if pain increases, the activity should be reduced or stopped. Joint pain should not persist or increased 24 hours after exercise, which indicates that the MSK system is not prepared for that running volume. In the initial phase of a running program, exercising on non-consecutive days permits the individual a self-assessment of his or her exercise response. According to a 22-week prospective research study by Malisoux et al. (2015), runners using different pairs of running shoes concomitantly have a 39% lower risk of running-	In the review by Napier et al. (2015), the authors recommend future studies should include longer follow-up measurements to assess the long-term retention of biomechanical changes due to running re-training, and see whether they have an effect on the reduction of injury.	

(5.5%) and foot (3.5%) (Kluitenberg et al., 2015). **Cross-Country Runners** In the meta-analysis by Videbaek et al. (2015), cross-country runners had a risk of injury at 16.3 injuries per 1,000 hours of running [12.2, 31.3]. Kluitenberg et al. (2015) demonstrated that 19.7% [10.9, 33.1] of cross-country runners (i.e., runners competing in cross-country races) experienced a time-loss injury within a short follow-up period, and 77.4% [60.6, 88.4] of these runners experienced a time-loss injury within a long follow-up period. The most common injury site for cross-country runners was the lower leg (30.3% of injuries), knee (22.5%), ankle (16.2%), upper leg (9.0%), foot (8.1%), and hip/pelvis (5.7%). **Recreational Runners** The Videbaek et al. (2015) study also revealed recreational runners experience 7.7 injuries per 1,000 hours of running [6.9, 8.7], and Kluitenberg et al.	full) than the neutral group contributing to a 160% and 310% relative risk of injury in the full minimalist and partial minimalist group, respectively. A clinical review by Ferber, Hreljac, and Kendall (2009) found that a large, gorwing body of literature suggests inadequate hip stabilization from hip muscle weakness leads to atypical lower extremity mechanics and increased forces while running, which are considered risk factors for running-related injuries. **Protective Factors** A systematic review by Nielsen, Buist, Sørensen, Lind, and Rasmussen (2012) found increased running experience to be a protective factor against overuse running-related injuries. A systematic review by Gijon-nogueron and Fernandez-villarejo (2015) found the following protective factors for running-related injuries: (i) strengthening of gluteus medius and maximus muscles; (ii) maintenance of stress level in running; (iii) shoe sole modification to improve ankle internal plantarflexion moment; (iv) muscle tuning; (v) eccentric training program; and (vi) elastic running surface. A prospective 22-week follow-up study by Malisoux et al. (2015) found that the parralel use of different running shoes was a protective factor [hazard ratio (HR) = 0.614; 95% con-	related injuries compared to runners using only one pair of shoes during their training period. **Strength Training** According to multiple studies, hip and knee exercises related to strength and flexibility may be used as a preventative measure for running-related injuries since these exercises have been shown to reduce pain for those with patellofemoral pain (Ferber, Bolgla, Earl-Boehm, Emery, & Hamstra-Wright, 2015; Neal et al., 2016; van der Heijden, Lankhorst, van Linschoten, Bierma-Zeinstra, & van Middelkoop, 2015) **Running Re-Training** Limited evidence suggests transitioning from a rearfoot to forefoot or midfoot strike pattern, combined with increasing step rate or altering proximal mechanics to facilitate hip flexion can help manage anterior exertional lower leg pain (Barton et al., 2016). Nevertheless, there is substantial evidence for the immediate biomechanical effects of running retraining interventions in uninjured populations. For example,		

(2015) demonstrated that 28% [23.1, 33.5] of runners experience time-loss injuries with a short follow-up (6-15 weeks), then increase to 55% [48.1, 61.8] at a one year follow up. The most common injury site for recreational runners is the knee (26.3% of injuries), followed by the lower leg (22.4%), foot (10.1%), hip/pelvis (8.4%), ankle (7.8%), and upper leg (7.3%). **Ultramarathon Runners** Ultramarathon runners experience 7.2 injuries per 1,000 hours of running [5.5, 8.8] (Videbaek et al., 2015). Kluitenberg et al. (2015) indicated that 64.6% [61.9, 67.2] of ultramarathon runners experience a time-loss running injury within one year. Site-specific injuries have rarely been reported in ultramarathon runners; therefore, pooled statistics were not further analyzed for this running subgroup in the Kluitenberg et al. (2015) meta-analysis.	fidence interval (CI) = 0.389–0.969] for running-related injuries. **Specific Injuries:** **Iliotibial Band Syndrome** *<u>Risk Factors:</u>* According to a systematic review by Mucha, Caldwell, Schlueter, Walters, and Hassen (2016), hip abductor weakness is may be considered a risk factor for iliotibial band syndrome in long distance runners. In a systematic review by van der Worp, van der Horst, de Wijer, Backx, & Nijhuis-van der Sanden (2012), the following factors are associated with an increased risk of ITBS: (i) excessive mileage; (ii) sudden increase in mileage; (iii) little running experience; (iv) leg length discrepancy; (v) genu varum; (vi) high arches; (vii) hip inflexibility. *Female Specific Running Biomechanics:* A cross-sectional experimental study by Ferber, Noehren, Hamill, and Davis (2010) found females with a previous history of ITBS to have greater peak rearfoot invertor moment, peak knee internal rotation angle, and peak hip adduction angle compared to healthy controls, which are considered biomechanical risk factors for ITBS and is consistent with other prospective research.	addressing the presence of overstriding was considered one of the most beneficial running retraining strategies, with the importance of the foot landing closer to the centre of mass. Increasing step rate will move the foot strike closer to the centre of mass. Increasing step rate should be graduate (5-10%) to ensure manageable changes and avoid excessive fatigue. Concurrently addressing muscle function and flexibility deficits is also important. For injury prevention, running retraining may play a role but a lack of evidence to guide implementation exists. Increasing step rate, reducing overstriding, increasing step width, and altering proximal kinematics seem to be the most common, effective prevention strategies in running retraining (Barton et al., 2016). The systematic review by Barton et al. (2016) also addresses gait retraining strategies for site-specific injuries. *Exertional Leg Pain:* Limited evidence indicates a transition from rearfoot to		

Marathon Runners Kluitenberg et al. (2015) reported that 64.7% [24.6, 91.2] will experience a running-related time-loss injury within a short follow-up period. With longer follow-up periods, the rate decreased to 31.3% [28.8, 33.9]. The most common injury site for marathon runners was the lower leg (not including the knee or ankle joints) (29.9% of injuries), followed by the knee (26.6%), foot (13.1%), hip/pelvis (9.4%), upper leg (i.e., the thigh) (8.7%) and ankle (7.9%). **Track & Field Athletes** According to Kluitenberg et al. (2015), within a one-year follow-up period, 63.8% [56.0, 70.5], 63.9% [41.4, 81.6], and 31.7% [25.8, 38.2] of sprinters, middle-distance, and long-distance runners, respectively, experience a time-loss running-related injury. Injury sites were only been reported for sprinters, and sprinters experienced the highest proportion of injuries in the upper leg (32.9%), followed by the	Both Sexes Running Biomechanics: **Patellofemoral Pain Syndrome** *Risk Factors:* A systematic review by Barton, Lack, Malliaras, and Morrissey (2013) found moderate-to-strong evidence that gluteus medias activity is delayed and of shorter duration during running, which may be a risk factor for PFPS. Dutton, Khadavi, and Fredericson (2016) found a number of risk factors for patellofemoral pain in their systematic review. These risk factors include: (i) increase in weekly running distance > 30% over 2 week period; (ii) quadriceps weakness; (iii) delayed Vasti muscle activation; (iv) inflexibility in quadriceps and hamstring muscles; (v) lower hip adduction strength; and (vi) lower hip external rotation strength. In a systematic review and meta-analysis by Cronstrom, Creaby, Nae, and Ageberg (2016), women with patellofemoral pain had greater peak knee abduction compared to men in weight-bearing activities, such as running, which may further increase the risk of overuse running-related injuries. Neal, Barton, Gallie, O'Halloran, and Morrissey (2016) found in their systematic review and meta-analysis	fore- or midfoot strike pattern along with increased step rate can help manage exertional leg pain. Reducing overstriding is also suggested to help anterior exertional leg pain. *Patellofemoral Pain:* Limited evidence suggests visual and verbal feedback to reduce peak hip adduction during stance for runners with patellofemoral pain. Reducing overstriding with increased step rate is also suggested to be an important treatment for patellofemoral pain. *Achilles Tendinopathy:* Very limited to limited evidence suggests transitioning individuals with a pronounced forefoot strike to a rearfoot or midfoot strike is a proposed strategy for Achilles tendinopathy and calf strain. *Iliotibial Band Syndrome:* Very limited to limited evidence suggests increasing step width helps with cross-over gait (hip adduction at foot strike) and reduces iliotibial band strain. For hamstring injuries, *Hamstring Injuries:*		

knee (30.6%), hip/pelvis (10.5%), foot (4.0%), and lower leg (3.4%). **Children & Adolescents** Based on Nelson, Alhajj, Yard, Comstock, and McKenzie (2009) as cited in a clinical review by Krabak, Snitily, and Milani (2016), 25.1% of sport-related injuries in children are due to running. A prospective study by Rauh, Koepsell, Rivara, Margherita, and Rice (2006) of 421 adolescent cross-country runners over one season found that 38.5% sustained at least one injury. Girls sustained a significantly higher overall injury rate (19.6 RRI / 1,000 athletic events) than boys (15.0 RRI / 1,000 athletic events).	that runners with patellofemoral pain have lower extremity malalignment and increased peak hip internal rotation and contralateral drop, which targeted interventions can modify. **Lower Leg Injuries (e.g., MTSS)** A systematic review and meta-analysis by Hamstra-Wright, Bliven, and Bay (2015) found consistent evidence for individuals with MTSS having a significantly greater BMI, navicular drop, ankle plantarflexion range of motion, and hip external rotation range of motion than healthy controls. **Bone Stress Injuries** In a clinical review by Warden, Burr, and Brukner (2006), female sex and intense changes in physical activity were considered risk factors with bone stress fractures. A clinical review by Tenforde, Kraus, & Fredericson (2016) identified the following risk factors for bone stress injuries: (i) running volumes > 32km; (ii) genetics; (iii) medications (anticonvulsants, steroids, antidepressants, antacids); (iv) female athlete triad; (v) insufficient calcium and vitamin D; (vi) prior fracture; and (vii) lower bone mass density. **Achilles Tendon Injuries** A cross-sectional experiment by Michael Ryan et al. (2009) found runners exhibiting Achilles tendinopathy to have greater ankle	General support for anterior pelvic tilt, reduce overstriding with increased step rate, and greater hip and knee flexion during swing. According to a systematic literature review from Napier, Cochrane, Taunton, and Hunt (2015), there are a number of kinematic Alterations associated with manipulation of step rate and stride length that may ultimately protect against overuse running related injureis. For example, an increase in step frequency increases knee flexion at initial contact and decreases peak knee flexion during stance. The ankle is more plantarflexed at heel strike with increased step rate. Less peak hip flexion and adduction during loading with increased step rate. An inverse relationship between step rate and horizontal distance between centre of mass and heel at initial contact (overstriding). There is also an inverse relationship between step rate and vertical centre of mass vertical excursion, and a positive relationship between step rate and leg stiffness.		

	eversion displacement during the stance phase of running. In two systematic reviews by Lorimer and Hume (2014, 2016), the following running-related factors were associated with an increased risk of Achilles tendon injury: (i) greater peak breaking force; (ii) neglecting active recovery measures with slower training runs; (iii) more compliant surfaces such as sand and track; (iv) natural forefoot strikers have more plantarflexed foot at contact resulting in higher risk; and (v) older age. Based on the same two reviews, Lorimer and Hume (2014, 2016) also outline some protective factors for Achilles tendon injuries: (i) high peak vertical ground reaction force; (ii) greater arch height; and (iii) running on stiffer surfaces. **Plantar Fasciitis** A systematic review and with a detailed literature review from Beeson (2014) found runners were at an increased risk of plantar fasciitis with increased body weight & BMI (>30 kg/m^2 = an odds ratio of 5.6 [1.9-16.6] compared to a BMI < 25 kg/m^2), reduced dorsiflexion flexibility, hamstring tightness, inappropriate footwear, improper training (rapid increases in training load), and greater peak rearfoot eversion during stance phase of running.	Greater step length and ground contact time has been associated with novice runners and potentially a higher incidence of injury; therefore, reducing these parameters may prevent injury. Peak tibial acceleration and impact attenuation increases with an increased stride length. Napier et al. (2015) also discusses the use of biofeedback in populations of healthy runners and demonstrates the clinical feasibility of this intervention, potentially for prevention purposes. However, there is no evidence to support long-term injury rates in runners receiving feedback/retraining. There is also limited evidence to support hip adduction angle retraining to reduce vertical impact peak. Augmented feedback is effective in reducing the magnitude of GRFS, vertical instantaneous rate, vertical average loading rage, and vertical impact peak, which have been associated with tibial stress fractures, plantar fasciitis, and MTSS. A systematic review by Schubert, Kempf, and Heiderscheit (2014)		

		demonstrated the minimum change in step frequency to observe biomechanical changes was 10% in most cases, but some changes were noted at 5% increased. None of the studies above addressed injury prevention or recovery. (Schubert et al., 2014).		
Works Cited: Kluitenberg, B., van Middelkoop, M., Diercks, R., & van der Worp, H. (2015). What are the differences in injury proportions between different populations of runners? A systematic review and meta-analysis. *Sports Medicine*, *45*(8), 1143-1161. Krabak, B. J., Snitily, B., & Milani, C. J. (2016). Running injuries during adolescence and childhood. *Physical Medicine and Rehabilitation Clinics*, *27*(1), 179-202. Nelson, N. G., Alhajj, M., Yard, E., Comstock, D., & McKenzie, L. B. (2009). Physical education class injuries treated in emergency departments in the US in	**Works Cited:** Barton, C. J., Lack, S., Malliaras, P., & Morrissey, D. (2012). Gluteal muscle activity and patellofemoral pain syndrome: A systematic review. *British Journal of Sports Medicine*, bjsports-2012. Beeson, P. (2014). Plantar fasciopathy: Revisiting the risk factors. *Foot and Ankle Surgery*, *20*(3), 160-165. Buist, I., Bredeweg, S. W., Lemmink, K. A., Van Mechelen, W., & Diercks, R. L. (2010). Predictors of running-related injuries in novice runners enrolled in a systematic training program: A prospective cohort study. *American Journal of Sports Medicine*, *38*(2), 273-280. Cronström, A., Creaby, M. W., Nae, J., & Ageberg, E. (2016). Gender differences in knee abduction during	**Works Cited:** Barton, C. J., Bonanno, D. R., Carr, J., Neal, B. S., Malliaras, P., Franklyn-Miller, A., & Menz, H. B. (2016). Running retraining to treat lower limb injuries: a mixed-methods study of current evidence synthesised with expert opinion. *British Journal of Sports Medicine*, *50*(9), 513-526. Ferber, R., Bolgla, L., Earl-Boehm, J. E., Emery, C., & Hamstra-Wright, K. (2015). Strengthening of the hip and core versus knee muscles for the treatment of patellofemoral pain: a multicenter randomized controlled trial. *Journal of*	**Works Cited:** Agresta, C., & Brown, A. (2015). Gait retraining for injured and healthy runners using augmented feedback: A systematic literature review. *Journal of Orthopaedic & Sports Physical Therapy*, *45*(8), 576-584. Barton, C. J., Bonanno, D. R., Carr, J., Neal, B. S., Malliaras, P., Franklyn-Miller, A., & Menz, H. B. (2016). Running retraining to treat lower limb injuries: a mixed-methods study of current evidence synthesised with expert opinion. *British Journal of Sports Medicine*, *50*(9), 513-526.	

1997–2007. *Pediatrics*, *124*(3), 918-925. Rauh, M. J., Koepsell, T. D., Rivara, F. P., Margherita, A. J., & Rice, S. G. (2005). Epidemiology of musculoskeletal injuries among high school cross-country runners. *American Journal of Epidemiology*, *163*(2), 151-159. Taunton, J. E., Ryan, M. B., Clement, D. B., McKenzie, D. C., Lloyd-Smith, D. R., & Zumbo, B. D. (2002). A retrospective case-control analysis of 2002 running injuries. *British Journal of Sports Medicine*, *36*(2), 95-101.	weight-bearing activities: A systematic review and meta-analysis. *Gait & Posture*, *49*, 315-328. Dowling, G. J., Murley, G. S., Munteanu, S. E., Smith, M. M. F., Neal, B. S., Griffiths, I. B., ... & Collins, N. J. (2014). Dynamic foot function as a risk factor for lower limb overuse injury: A systematic review. *Journal of Foot and Ankle Research*, *7*(1), 53. Dutton, R. A., Khadavi, M. J., & Fredericson, M. (2016). Patellofemoral pain. *Physical Medicine and Rehabilitation Clinics of North America, 27(*1), 31–52. Ferber, R., Hreljac, A., & Kendall, K. D. (2009). Suspected mechanisms in the cause of overuse running injuries: A clinical review. *Sports Health*, *1*(3), 242-246. Ferber, R., Noehren, B., Hamill, J., & Davis, I. (2010). Competitive female runners with a history of iliotibial band syndrome demonstrate atypical hip and knee kinematics. *Journal of Orthopaedic & Sports Physical Therapy*, *40*(2), 52-58. Gijon-Nogueron, G., & Fernandez-Villarejo, M. (2015). Risk factors and protective factors for lower-extremity running injuries: A systematic review. *Journal of the American Podiatric Medical Association*, *105*(6), 532-540.	*Athletic Training*, *50*(4), 366-377. Malisoux, L., Ramesh, J., Mann, R., Seil, R., Urhausen, A., & Theisen, D. (2015). Can parallel use of different running shoes decrease running-related injury risk? *Scandinavian Journal of Medicine & Science in Sports*, *25*(1), 110-115. Napier, C., Cochrane, C. K., Taunton, J. E., & Hunt, M. A. (2015). Gait modifications to change lower extremity gait biomechanics in runners: a systematic review *British Journal of Sports Medicine*, *49*(21), 1382-1388. Neal, B. S., Barton, C. J., Gallie, R., O'Halloran, P., & Morrissey, D. (2016). Runners with patellofemoral pain have altered biomechanics which targeted interventions can modify: a systematic review and meta-analysis. *Gait & Posture*, *45*, 69-82. Schubert, A. G., Kempf, J., & Heiderscheit, B. C. (2014). Influence of stride frequency and length on running mechanics: A systematic review. *Sports Health*, *6*(3), 210-217.	Napier, C., Cochrane, C. K., Taunton, J. E., & Hunt, M. A. (2015). Gait modifications to change lower extremity gait biomechanics in runners: a systematic review. *British Journal of Sports Medicine, 49*(21), 1382-1388.	

	Hamstra-Wright, K. L., Bliven, K. C. H., & Bay, C. (2015). Risk factors for medial tibial stress syndrome in physically active individuals such as runners and military personnel: A systematic review and meta-analysis. *British Journal of Sports Medicine*, *49*(6), 362-369. Lorimer, A. V., & Hume, P. A. (2014). Achilles tendon injury risk factors associated with running. *Sports Medicine*, *44*(10), 1459-1472. Lorimer, A. V., & Hume, P. A. (2016). Stiffness as a risk factor for Achilles tendon injury in running athletes. *Sports Medicine*, *46*(12), 1921-1938. Malisoux, L., Ramesh, J., Mann, R., Seil, R., Urhausen, A., & Theisen, D. (2015). Can parallel use of different running shoes decrease running-related injury risk? *Scandinavian Journal of Medicine & Science in Sports*, *25*(1), 110-115. Mucha, M. D., Caldwell, W., Schlueter, E. L., Walters, C., & Hassen, A. (2017). Hip abductor strength and lower extremity running related injury in distance runners: A systematic review. *Journal of Science and Medicine in Sport*, *20*(4), 349-355. Neal, B. S., Barton, C. J., Gallie, R., O'Halloran, P., & Morrissey, D. (2016). Runners with patellofemoral pain have altered biomechanics which	van der Heijden, R. A., Lankhorst, N., Van Linschoten, R., Bierma-Zeinstra, S. M., & van Middelkoop, M. (2013). Exercise for treating patellofemoral pain syndrome. *Cochrane Database of Systematic Reviews*, *2*. Vincent, H. K., & Vincent, K. R. (2013). Considerations for initiating and progressing running programs in obese individuals. *Journal of the American Academy of Physical Medicine and Rehabilitation*, *5*(6), 513-519.		

	targeted interventions can modify: A systematic review and meta-analysis. *Gait & Posture*, *45*, 69-82. Nielsen, R. O., Buist, I., Sørensen, H., Lind, M., & Rasmussen, S. (2012). Training errors and running related injuries: a systematic review. *International Journal of Sports Physical Therapy*, *7*(1), 58. Ryan, M., Elashi, M., Newsham-West, R., & Taunton, J. (2013). Examining injury risk and pain perception in runners using minimalist footwear. *British Journal of Sports Medicine*, bjsports-2012. Ryan, M., Elashi, M., Taunton, J., & Koehl, M. (2014). Is gender a risk factor for injury in runners? The first of a three part series to develop a gender targeted injury prevention strategy. *Journal of Science and Medicine in Sport*, *18*, e72-e73. Ryan, M., Grau, S., Krauss, I., Maiwald, C., Taunton, J., & Horstmann, T. (2009). Kinematic analysis of runners with achilles mid-portion tendinopathy. *Foot & Ankle International*, *30*(12), 1190-1195. Tenforde, A. S., Kraus, E., & Fredericson, M. (2016). Bone stress injuries in runners. *Physical Medicine and Rehabilitation Clinics*, *27*(1), 139-149. van der Worp, M. P., Ten Haaf, D. S., van Cingel, R., de Wijer, A., Nijhuis-van			

	der Sanden, M. W., & Staal, J. B. (2015). Injuries in runners: A systematic review on risk factors and sex differences. *PLoS One*, *10*(2), e0114937. Van der Worp, M. P., van der Horst, N., de Wijer, A., Backx, F. J., & Nijhuis-van der Sanden, M. W. (2012). Iliotibial band syndrome in runners. *Sports Medicine*, *42*(11), 969-992. Vincent, H. K., & Vincent, K. R. (2013). Considerations for initiating and progressing running programs in obese individuals. *PM&R*, *5*(6), 513-519. Warden, S. J., Burr, D. B., & Brukner, P. D. (2006). Stress fractures: pathophysiology, epidemiology, and risk factors. *Current Osteoporosis Reports*, *4*(3), 103-109.			

Review of Sport Injury Burden, Risk Factors and Prevention

Running

Incidence and Prevalence

The incidence of lower extremity running-related injuries has been reported to be between 19.4 and 79.3% of all runners (van Gent et al., 2007), and the most common site of running-related injuries are the knee (42.1% of all injuries), foot/ankle (16.9%), lower leg (12.8%), hip/pelvis (10.9%), achilles/calf (6.4%), upper leg (5.2%), and lower back (3.4%) (Taunton et al., 2002). More specifically, the top five most common overuse running-related injuries are patellofemoral pain syndrome, iliotibial band syndrome, plantar fasciitis, meniscal injuries, and tibial stress syndrome (Taunton et al., 2002). The aforementioned large range of incidence for running-related injuries in the general running population likely depends on how a running-related injury is defined and which population of runners is explored.

When comparing the number of running-related injuries between different types of runners, it is important to standardize the amount of time spent running. Specifically, running-related injuries per 1,000 hours of running is a common way to standardize the risk of injury for different types of runners. Based on this measurement, novice runners are at the highest risk of injury with 17.8 injuries per 1,000 hours of running [95% CI: 16.7, 19.1], followed by cross-country runners at 16.3 injuries per 1,000 hours of running [12.2, 31.3], recreational runners with 7.7 injuries per 1,000 hours of running [6.9, 8.7], and ultramarathon runners with 7.2 injuries per 1,000 hours of running [5.5, 8.8] (Videbaek, Bueno, Nielsen, & Rasmussen, 2015).

Although a consensus definition for running-related injuries has only been recently developed by Yamato, Saragiotto, and Lopes (2015) to help increase the consistency in running injury research, pooled injury proportions from previous studies have also been found for different, homogeneous populations of runners with different lengths of follow-up.

For novice runners (i.e., runners with no regular running experience within the previous year), the pooled injury proportion (% [95% CI]) for a short follow-up period (6-15 weeks) is 26.4% [14.2, 43.7], during a one-year follow up is 27.3% [24.5, 30.3], and long-term follow-up (greater than 1 year) is 84.9% [74.8,91.5]. The most common injury site for novice runners is the lower leg (34.7% of injuries), followed by the knee (30.6%), hip/pelvis (10.2%), ankle (8.2%), upper leg (5.5%) and foot (3.5%) (Kluitenberg et al., 2015).

For recreational runners (i.e., non-competitive runners or runners participating in road races shorter than 10km), a similar trend shows that 28% [23.1, 33.5] of runners will experience time-loss injuries (i.e., injury that hampered training for at least one day) with a short follow-up (6-15 weeks), then increase to 55% [48.1, 61.8] at a one year follow up. The most common injury site for recreational runners is the knee (26.3% of injuries), followed by the lower leg (22.4%), foot (10.1%), hip/pelvis (8.4%), ankle (7.8%), and upper leg (7.3%) (Kluitenberg et al., 2015)

A reported 19.7% [10.9, 33.1] of cross-country runners (i.e., runners competing in cross-country races) will experience a time-loss injury within a short follow-up period, and 77.4% [60.6, 88.4] of these runners will experience a time-loss injury within a long follow-up period. The most common injury site for cross-country runners is the lower leg (30.3% of injuries), knee (22.5%), ankle (16.2%), upper leg (9.0%), foot (8.1%), and hip/pelvis (5.7%) (Kluitenberg et al., 2015).

For marathon runners (i.e., runners competing in a marathon), it is reported that 64.7% [24.6, 91.2] will experience a running-related time-loss injury within a short follow-up period. With longer follow-up periods, the rate decreases to 31.3% [28.8, 33.9]. The most common injury site for marathon runners is the lower leg (not including the knee or ankle joints) (29.9% of injuries), followed by the knee (26.6%), foot (13.1%), hip/pelvis (9.4%), upper leg (i.e., the thigh) (8.7%) and ankle (7.9%) (Kluitenberg et al., 2015).

When exploring specific types of track athletes with a one-year follow-up period, 63.8% [56.0, 70.5], 63.9% [41.4, 81.6], and 31.7% [25.8, 38.2] of sprinters, middle-distance, and long-distance runners, respectively, will experience a time-loss running-related injury. Injury sites have only been reported for sprinters, and the data suggest sprinters experience the highest proportion of injuries in the upper leg (32.9%), followed by the knee (30.6%), hip/pelvis (10.5%), foot (4.0%), and lower leg (3.4%) (Kluitenberg et al., 2015).

Finally, 64.6% [61.9, 67.2] of ultramarathon runners (i.e., runners competing in races longer than a marathon) will experience a time-loss running injury within one year (Kluitenberg et al., 2015). Site-specific injuries have rarely been reported in ultramarathon runners; therefore, pooled statistics were not further analyzed for this running subgroup.

Risk and Protective Factors

The etiology of running-related injuries is multifactorial, with both modifiable and non-modifiable risk and protective factors that may increase or decrease the risk of running-related injuries. These risk and protective factors can be clustered into four main domains: (1) personal factors, (2) running biomechanics, (3) training factors, and (4) health and lifestyle related factors, which can be understood for running-related injuries in general or site-specific injuries (Gijon-nogueron & Fernandez-villarejo, 2015; van Der Worp et al., 2015).

General Running-Related Injuries

Personal Factors. Personal risk factors are considered non-modifiable, and for general running-related injuries, the personal risk factors include: advanced age, leg length difference, male height greater than 1.70m, and a genu varum alignment (Gijon-nogueron & Fernandez-villarejo, 2015; van Der Worp et al., 2015). Although the incidence rate between males and females for running-related injuries (RRIs) is not significantly different, prospective research has shown that females have a lower injury rate than males (4.46 vs 6.86 RRIs/1000 training session, respectively), resulting in a relative risk ratio of 0.67 [95% CI: 0.32-1.40] (M Ryan et al., 2014).

Running Biomechanics. Modifiable risk factors associated with running biomechanics include: a navicular drop greater than 10mm during the stance phase of running, increased pronation excursion, increased reinversion velocity, wide internal rotation range and peak tibial acceleration, greater lateral or medial directed centre of pressure during running, and increased or decreased pressure-related outcomes in the fifth metatarsal region (Dowling et al., 2014; Gijon-nogueron & Fernandez-villarejo, 2015; van Der Worp et al., 2015). Since gait modification for running retraining has demonstrated positive outcomes for biomechanical risk factors associated with running-related injuries (Barton et al., 2016), all running biomechanics-related risk factors can be considered modifiable.

Training Factors. With respect to training factors, runners are generally at an increased risk of injury with a progressive increase in weekly running mileage greater than 10% per week, running six or more times per week, consistently running on a hard surface, experiencing high levels of muscle fatigue and improper recovery regimens, and wearing shoe inserts or orthotics (van Der Worp et al., 2015). Also, the use of minimalist footwear may increase the risk of experiencing a running-related injury, as compared with more neutral footwear (Ryan, Elashi, Newsham-West, & Taunton, 2014). Finally, hip muscle weakness can lead to significantly lower hip stabilization during running, which can increase the likelihood of overuse running-related injuries (Ferber, Hreljac, & Kendall, 2009)

Health and Lifestyle. Previous lower limb injury has been suggested to be a strong non-modifiable risk factor for lower-limb running-related injuries (Hulme, Nielsen, Timpka, Verhagen, & Finch, 2017; Saragiotto et al., 2014b; Taunton et al., 2003; van Der Worp et al., 2015), where research demonstrates half of runners reporting a running-related injury had previously sustained an injury to the same anatomical area (Taunton et al., 2003). Modifiable health and lifestyle related factors associated with running-related injuries include: incomplete rehabilitation from a prior injury (42% of runners who had a previous injury and sustained another injury declared themselves as not 100% rehabilitated) (Taunton et al., 2003), higher body mass index, tobacco use, and increased alcohol intake (Hulme et al., 2017; Saragiotto et al., 2014b; Taunton et al., 2003; van Der Worp et al., 2015).

Protective Factors. The alternatives to the aforementioned modifiable risk factors may be considered protective factors within their respective domain. Nevertheless, research suggests some specific protective factors that a runner may consider during their training. These include increasing and improving experience level in running, improvements in strength (concentric and eccentric) and muscle tuning of the gluteal and quadriceps muscles, modifying the sole of the shoe to improve ankle internal plantarflexion moment, and running on a more elastic running surface (Gijon-nogueron & Fernandez-villarejo, 2015). Furthermore, it has been suggested that the concomitant use of multiple pairs of running shoes during a training program can help protect against running-related injuries (Malisoux et al., 2015).

Site-Specific Injuries

Considering site-specific time-loss injuries vary between different types of runners based on training history, running experience, and distance, it is important to understand modifiable and non-modifiable risk and protective factors for site-specific injuries to educate those more prone to specific running-related injuries.

Patellofemoral Pain Syndrome

Patellofemoral pain syndrome is the most common running-related injury at the knee joint, especially in recreational runners. There are various modifiable risk factors associated with patellofemoral pain syndrome for running biomechanics and training.

Training Factors. Modifiable risk factors associated with training include an increase in weekly running distance greater than 30% over a two-week period, quadriceps weakness, delayed quadriceps and gluteus medius muscle activation, inflexibility in the quadriceps and hamstring muscles, hip abduction weakness, and lower hip external rotation weakness (Barton, Lack, Malliaras, & Morrissey, 2013; Dutton, Khadavi, & Fredericson, 2016; Lankhorst, A Bierma-Zeinstra, & Middelkoop, 2013; Oser, Oser, & Silvis, 2013).

Running Biomechanics. With respect to running biomechanics, studies suggest greater knee abduction in women and greater peak force in the second and third metatarsal region during the stance phase of running to be modifiable risk factors (Cronstrom et al., 2016; Dowling et al., 2014).

Iliotibial Band Syndrome

Personal Factors. For iliotibial band syndrome, non-modifiable personal risk factors include leg length discrepancy, genu varum, and high arched feet (van der Worp et al., 2012).

Training Factors. Other modifiable risk factors associated with iliotibial band syndrome include hip abductor weakness, excessive running mileage, a sudden increase in running mileage, minimal running experience, and hip inflexibility (Mucha et al., 2016; Oser et al., 2013; van der Worp et al., 2012). Consequently, some modifiable protective factors would include improved hip abductor strength, proper training, and greater hip flexibility (van der Worp et al., 2012).

Running Biomechanics. Some modifiable risk factors associated with running biomechanics may include an increased peak knee internal rotation during stance (mean difference range of 0.70-3.88 degrees greater than control), increased peak trunk ipsilateral flexion during stance (mean difference range of 0.3-2.30 degrees greater than control), increased peak hip adduction during stance (mean difference range of 2.47-3.50 degrees greater than control), and increased peak knee internal rotation during stance (mean difference range of 2.89-3.88 degrees greater than control) (Aderem & Louw, 2015; Ferber, Cat, Noehren, Hamill, & Davis, 2010). To prevent iliotibial band syndrome, one protective factor includes a mid- to fore-foot strike pattern during running to improve form and running biomechanics. This will result in greater knee flexion at contact and shorter stride lengths, which reduces the load at the hip and knee (Almeida et al., 2015; Hall et al., 2013).

Lower Leg Injuries (e.g., Medial Tibial Stress Syndrome):

Personal Factors. A greater Q-angle and previous injury is a non-modifiable personal risk factor that has been related to lower leg injuries in running (Hamstra-Wright et al., 2015; Oser et al., 2013; Reinking, Austin, Richter, & Krieger, 2016).

Training Factors. Modifiable risk factors associated with training can include running greater than 40-64 km per week, running barefoot, and running on uneven surfaces (Hamstra-Wright et al., 2015; Reinking et al., 2016).

Running Biomechanics. Modifiable factors associated with running biomechanics include an imbalance of foot pressure, excessive foot pronation, a significantly greater navicular drop by 1.19 degrees [95% CI 0.54 to 1.84], greater plantarflexion range of motion by 5.94 degrees [95% CI 3.65 to 8.24], and greater hip external rotation range of motion of 3.95 degrees [95% CI 1.78 to 6.13]) compared to healthy controls (Hamstra-Wright et al., 2015)

Health and Lifestyle Factors. Modifiable health and lifestyle factors for lower leg injuries can include a significantly greater body mass index (Oser et al., 2013).

Achilles Tendon Injuries

Personal Factors. Older age is a non-modifiable personal risk factor associated with Achilles tendinopathy (van Der Worp et al., 2015).

Training Factors. Finally, more compliant surfaces – sand or track – are considered modifiable risk factors for Achilles tendinopathy, which means running on stiffer surfaces is considered a protective risk factor (Lorimer & Hume, 2014, 2016; Tenforde & Hunt, 2016).

Running Biomechanics. Some biomechanical modifiable risk factors include greater ankle eversion displacement during stance, a greater peak breaking force in running and a more plantarflexed foot at initial contact (Lorimer & Hume, 2014, 2016; Ryan et al., 2009).

Plantar Fasciitis

Plantar fasciitis is also a very common running-related injury, and some of the most common modifiable risk factors reported in the literature are an increased BMI (>30 kg/m^2 = an odds ratio of 5.6 [1.9-16.6] compared to a BMI < 25 kg/m^2), limited dorsiflexion flexibility, hamstring tightness, inappropriate footwear, and rapid increases in training load (Beeson, 2014). These risk factors, combined with poor running biomechanics (e.g., greater peak rearfoot eversion during stance), will generate an unhealthy mechanical overload that results in a degenerative process of microtears in the plantar fascia (Beeson, 2014).

Bone Stress Injuries

Personal Factors. For bone stress injuries, non-modifiable personal risk factors include being of the female sex, genetics, female athlete triad, and leg length discrepancy (Tenforde et al., 2016).

Training Factors. The modifiable risk factors for training include weekly running in excess of 32km and using the same running shoes for more than 6 months (Tenforde et al., 2016).

Running Biomechanics. Modifiable running biomechanics risk factors associated with bone stress injuries include higher peak hip adduction, greater knee internal rotation, greater knee abduction, greater tibial rotation, and greater rearfoot eversion (Warden, Davis, & Fredericson, 2014).

Health and Lifestyle Factors. Finally, the modifiable health and lifestyle related factors include using certain medications (i.e., anticonvulsants, steroids, antidepressants, and antacids), insufficient calcium and vitamin D intake, prior fracture, and low bone mass density (Oser et al., 2013; Tenforde et al., 2016).

Although there has been extensive research on the risk and protective factors of running-related injuries, these studies have often been cross-sectional in nature. Specifically, the majority of these studies have studied runners who have already experienced a running-related injury, and researchers have made evidence informed decisions about which characteristics these individuals may have or have had that increased their likelihood of injury. Studies are beginning to explore running-related injuries in prospective longitudinal studies to fully understand the risk factors leading up to certain types of injuries as well as protective factors that may prevent running-related injuries.

Opportunities for Prevention: Effective Interventions, Cost-Effectiveness, Implementation and Evaluation

Despite extensive research in understanding the incidence, prevalence, and risk factors with running-related injuries, there is a lack of effective long-term prevention strategies (Barton et al., 2016).

Nevertheless, based on the risk factors associated with running-related injuries, researchers and clinicians have developed some evidence-informed strategies to prevent or minimize the risk of running injuries, particularly for new or novice runners. Considering novice runners are at an increased risk of injury compared with other running subgroups, this is likely due to inappropriate preparation and training for a new running program. Novice runners need appropriate strategies for start-to-run programs, and this has been discussed in the literature. Training is a modifiable factor, so implementing evidence-informed training methods at the beginning of the running program is not only important to prevent running-related injuries at the beginning of a program, but early implementation will help the novice runner get in a healthy routine as they progressively continue their training over longer periods of time. There are various ways in which a running program can be developed, and it should very much be individualized for the runner. There are some general guidelines, however, to help novice runners begin their program and avoid injury.

'Start to Run' Training Program

First, a gradual transition into running from other low-impact activity would minimize the risk for musculoskeletal injury (Vincent & Vincent, 2013). For example, a new runner can gradually transition from incline walking to a slow jog, or gradually increase the walking speed for each training session (treadmill or overground) until a threshold is reached at which running is more comfortable (Vincent & Vincent, 2013). Also, strength and flexibility exercises are important for the musculoskeletal system to positively adapt to the increased physical load of running. Specifically, hip and knee exercises related to strength and flexibility may be used as a preventative measure for running-related injuries since these exercises have been shown to reduce pain for those with patellofemoral pain (Bolgla, Earl-Boehm, Emery, Hamstra-Wright, & Ferber, 2016; Reed Ferber et al., 2015; Neal et al., 2016; van der Heijden et al., 2015).

Secondly, rapid increases in running intensity and/or mileage is considered a significant risk factor for running-related injuries (Gijon-nogueron & Fernandez-villarejo, 2015; van Der Worp et al., 2015). Therefore, regardless of running experience, a runner should increase the mileage or intensity in a stepwise fashion between 5-10% at each training session (Vincent & Vincent, 2013). This relative increase will permit the musculoskeletal tissues to rest and avoid mechanical failure while still allowing the runner to improve their health status with increased intensity and volume.

Thirdly, it has been suggested that runners using more than one pair of running shoes concomitantly during their training programs have a significantly lower risk of running-related injuries (Malisoux et al., 2015). Wearing more than one pair of running shoes will increase the amount of variability in physical load on the musculoskeletal system and minimizes excessive force to one anatomical landmark, thus reducing the likelihood of injury (Malisoux et al., 2015). There is not enough evidence to make clinically relevant conclusions for barefoot vs. shod running. However, certain biomechanical differences are observed with running barefoot, such as less vertical ground reaction forces, less knee extension moment, less dorsiflexion at ground contact, less ground contact time, shorter stride length, increased stride frequency, and increased knee flexion at contact (Perkins et al., 2014), which have been considered protective factors for running-related injuries. These biomechanical adaptations may also indicate that that certain injury patterns (iliotibial band syndrome, patellofemoral pain, gluteal/hamstring strain and tendinitis, and plantar fasciitis) may benefit from barefoot running, whereas Achilles tendinitis and calf injuries may benefit from shod running (Hollander et al., 2016). In sum, it appears that runners should alternate between different types of running shoes during their running program.

Finally, listening to the body with biofeedback is important for runners to understand their body's reaction to the running programs. Runners can use the onset of pain or symptoms as a guide for participating in or restraining from running and engaging in the next training session. Although muscle soreness is expected with a big change in running duration or intensity, pain that increases during running or walking sessions should be avoided. If the pain increases during the activity, then the activity should be reduced or stopped (Vincent & Vincent, 2013). Any joint pain should not persist or increase 24 hours after exercise, and if it does, this indicates that the musculoskeletal system is not prepared for the previous chosen running volume. In the beginning stages of the running program, running on non-consecutive days permits the musculoskeletal system to recover appropriately and allows the runner to complete a self-assessment of his or her exercise response to the current training load (Vincent & Vincent, 2013).

Gait Manipulation and Running Retraining

Evidence exists to support running retraining for the treatment of exertional lower leg pain and patellofemoral pain. Specifically, this running retraining consists of transitioning from a rearfoot to forefoot or midfoot strike pattern, combined with an increased step rate and alterations in proximal mechanics to facilitate hip flexion (Barton et al., 2016). However, there is little prospective research on how gait training/retraining can prevent injuries longitudinally (Barton et al., 2016). Running retraining may play a role in injury prevention, but minimal evidence to guide implementation exists. Nevertheless, there is substantial evidence for the immediate biomechanical effects of running retraining interventions in uninjured populations, and this delivers some evidence to suggest the positive effects of running training and retraining. Running training and retraining are based on evidence-informed decisions to place the body in a better position during running in order to reduce the physical load on the musculoskeletal system. For example, greater step length and ground contact time have been associated with novice runners, and may be associated with the increase in incidence of running-related injuries in this running subgroup (Edwards, Taylor, Rudolphi, Gillette, & Derrick, 2009; Napier et al., 2015). Therefore, addressing these factors may help minimize the risk of injury.

For reducing the risk of general running injuries, addressing the presence of 'overstriding' is considered one of the most beneficial biomechanical strategies for running. The term 'overstriding' refers to the distance between the leading foot at initial contact and the centre of mass. Improving 'overstriding' is important for decreasing the incidence of running-related injuries, as it will decrease peak tibial acceleration and impact attenuation (Schubert et al., 2014), and this can be achieved from a few different strategies. An increase in step rate or cadence will increase knee flexion at initial contact and move the foot strike closer to the centre of mass, thus reducing 'overstriding' (Napier et al., 2015). Similar to any training intervention associated with running, a gradual increase in step rate over time is suggested to ensure manageable changes and avoid excessive fatigue and strain on the musculoskeletal system. A 5-10% gradual stepwise increase in cadence has been suggested to be a healthy intervention strategy to reduce 'overstriding'.

The effects of increased cadence also impact the biomechanics of other areas of the body, which can minimize physical load in certain areas. For example, an increased step frequency increases peak knee flexion during stance, which increases leg stiffness and reduces the risk of overuse running-related injuries (Napier et al., 2015). Additionally, an increased step rate can increase gluteus maximus and gluteus medius activity, which may help anterior knee pain (Hall et al., 2013). Also, less peak hip flexion and adduction during loading has been associated with an increase in step rate (Napier et al., 2015). Step rate is also associated with a decrease in ground contact time, leg length compression, braking impulse, and vertical centre of mass excursion, or vertical oscillation (Heiderscheit, Chumanov, Michalski, Wille, & Ryan, 2012; Lieberman, Warrener, Wang, & Castillo, 2015; Morin, Samozino, Zameziati, & Belli, 2007), and can lead to a "smoother" and "safer" running style during prolonged running(Morin, Samozino, & Millet, 2011).

The use of augmented feedback for healthy populations demonstrates the clinical feasibility of gait training and retraining. With step rate manipulation, the runner can monitor their changes using commercial-based wearable technology. Other strategies and tools that may be important for gait manipulation to help reduce the risk of injury are more feasible in the clinic. For example, 2D video analysis, 3D motion capture, and mirror-based systems with augmented feedback enable the runner to position their body in a more correct position in real-time to reduce the physical load during running (Agresta & Brown, 2015). Although there are many biomechanical risk factors associated with various running-related injuries, increased hip adduction seems to be a common risk factor for multiple running-related injuries. Therefore, researchers and clinicians have suggested that direct manipulation of the hip adduction angle or an increase in step width with augmented feedback is an effective intervention to re-position the thigh and hip angle during running. Specifically, there is evidence to support a decrease in hip adduction angle with gait retraining reduces the vertical impact peak while running, which may reduce the risk of running-related injuries (Agresta & Brown, 2015; Napier et al., 2015). Although there is no evidence to support long-term injury rates in runners that have changed their running patterns to alter their running biomechanics, studies indicate augmented feedback is effective in reducing the magnitude of ground reaction forces, vertical instantaneous rate, vertical average loading rate, and vertical impact peak (Napier et al., 2015) – all of which have been associated with injuries including tibial stress fractures, plantar fasciitis, and medial tibial stress syndrome.

Since there are risk and protective factors for site-specific injuries, researchers have also suggested certain strategies for gait manipulation (i.e., running gait training and retraining) to reduce the risk of specific running-related injuries. For example, limited evidence suggests visual and verbal feedback to reduce peak hip adduction angle during stance is an effective strategy to minimize patellofemoral pain (Neal et al., 2016). Reducing 'overstriding' with an increase in step rate is also suggested help with patellofemoral pain syndrome (Neal et al., 2016). Very limited to limited evidence suggests an increase in step width helps with cross-over gait (i.e., increased hip adduction at foot strike), which also reduces the strain and strain rate on the iliotibial bad and helps reduce the risk of iliotibial band syndrome. There is general support in the research community that hamstring injuries can be reduced or possibly prevented with a greater anterior pelvic tilt, greater hip and knee flexion during swing, and, once again, increase in step rate and reduced ‘overstriding’.

Limited evidence suggests a mid- to fore-foot strike pattern along with an increase in step rate can help manage anterior exertional lower leg pain (Almeida et al., 2015; Hall et al., 2013). Therefore, these same biomechanical strategies can potentially decrease the risk or prevent anterior exertional leg pain. On the contrary, a more mid- to fore-foot strike pattern is considered a risk factor for Achilles tendinopathy and calf strains. Therefore, transitioning into a different foot strike may alleviate pain for one area, but increase the risk of running-related injuries in another anatomical location. Perhaps a mid-foot strike, as opposed to extreme rear- and fore-foot strike patterns, may help decrease the risk of general injuries. However, the literature suggests that changing foot strike patterns does not eliminate impact at the foot-ground contact and does not reduce the risk of running-related injuries (Hamill & Gruber, 2017). More prospective, longitudinal research is evidently needed to study the effects of different foot strikes on site-specific running-related injuries.

Gait training- and retraining appears to be a positive intervention for running injury prevention, but there are some barriers that may limit the runner’s investment in the intervention. For example, in the early stages of gait retraining, runners may experience some pain and irritability with the changes. Depending on the individual, the runner’s muscle function capacity, joint flexibility, and skeletal structure may limit the amount of change he or she can do. Consequently, the more barriers to overcome for running gait training, the higher the associated costs of long-term, gradual gait retraining. Undertaking gait retraining on a treadmill is practically easier than overground running since the set-up is more controlled and the runner can take significantly more steps in a small space with an observer helping with augmented feedback. However, applying the new gait strategies to overground running surfaces may be an additional barrier if all the training was done on a treadmill. Also, treadmills can be quite expensive, which are often bound to a gym, clinic, or laboratory.

For augmented feedback using 3D motion capture systems, the cost of equipment is also very expensive. Nevertheless, 2D video camera systems and mirror-based equipment set-up are feasible for clinical environments to implement augmented feedback in running gait training and retraining. Also, wearable technology is relatively inexpensive, and provides the runner with feedback on certain metrics (e.g., step rate and vertical oscillation) that may help the runner monitor their changes in running patterns over time. For example, the Lumo Run® is a thumb-sized sensor that clips onto the lower body garments and measures movement near the centre of mass. The device provides metrics related to running form – cadence, bounce (vertical oscillation), braking, pelvic drop, and pelvic rotation – based on scientific literature to better quantify a runner’s gait pattern that may help with performance and injury (Heiderscheit et al., 2012; Moore, 2016; Morin et al., 2007; Schache, Bennell, Blanch, & Wrigley, 1999; Willy, Scholz, & Davis, 2012). The Lumo Run® app also delivers a coaching process that recommends pre- and post-run exercises based on the output to help improve running form.

There is a lack of evidence-based, longitudinal and prospective evidence to support the implementation of these intervention strategies to actually prevent running-related injuries. Future studies should include longer follow-up measurements to assess the long-term retention of biomechanical changes associated with running gait training and retraining, and see whether this has an effect on the reduction and/or prevention of injury (Napier et al., 2015). Until a high quality randomized controlled trial is done to quantify the outcomes of these interventions on injury risk, these guides for implementation are all evidence-informed strategies. Therefore, future studies need to explore how these intervention strategies affect injury risk, as well as determine the proper prescription for these intervention strategies in the clinic (i.e., number and duration of intervention sessions) and/or at home for the runner with proper equipment (Agresta & Brown, 2015).

References

Aderem, J., & Louw, Q. A. (2015). Biomechanical risk factors associated with iliotibial band syndrome in runners: a systematic review. *BMC Musculoskeletal Disorders*, *16*, 356. https://doi.org/10.1186/s12891-015-0808-7

Agresta, C., & Brown, A. (2015). Gait retraining for injured and healthy runners using augmented feedback: A systematic literature review. *Journal of Orthopaedic & Sports Physical Therapy*, *45*(8), 576–584. https://doi.org/10.2519/jospt.2015.5823

Almeida, M. O., Davis, I. S., & Lopes, A. D. (2015). Biomechanical differences of foot strike patterns during running: A systematic review with meta-analysis. *The Journal of Orthopaedic and Sports Physical Therapy*, *45*(10), 1–40. https://doi.org/10.2519/jospt.2015.6019

Barton, C., Bonanno, D., Carr, J., Neal, B. S., Malliaras, P., Franklyn-Miller, A., & Menz, H. B. (2016). Running retraining to treat lower limb injuries: A mixed-methods study of current evidence synthesised with expert opinion. *British Journal of Sports Medicine*, *50*(9), 513–526. https://doi.org/10.1136/bjsports-2015-095278

Barton, C. J., Lack, S., Malliaras, P., & Morrissey, D. (2013). Gluteal muscle activity and patellofemoral pain syndrome: A systematic review. *British Journal of Sports Medicine*, *47*(4), 207–214. https://doi.org/10.1136/bjsports-2012-090953

Beeson, P. (2014). Plantar fasciopathy: Revisiting the risk factors. *Foot and Ankle Surgery*, *20*(3), 160–165. https://doi.org/10.1016/j.fas.2014.03.003

Bolgla, L. A., Earl-Boehm, J., Emery, C., Hamstra-Wright, K., & Ferber, R. (2016). Pain, function, and strength outcomes for males and females with patellofemoral pain who participate in either a hip/core- or knee-based rehabilitation program. *International Journal of Sports Physical Therapy*, *11*(6), 926–935. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/27904794%5Cnhttp://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC5095944

Buist, I., Bredeweg, S. W., Lemmink, K. A. P. M., van Mechelen, W., & Diercks, R. L. (2010). Predictors of Running-Related Injuries in Novice Runners Enrolled in a Systematic Training Program: A Prospective Cohort Study. *The American Journal of Sports Medicine*, *38*(2), 273–280. https://doi.org/10.1177/0363546509347985

Cronstrom, A., Creaby, M. W., Nae, J., & Ageberg, E. (2016). Gender differences in knee abduction during weight-bearing activities: A systematic review and meta-analysis. *Gait and Posture*, *49*, 315–328. https://doi.org/10.1016/j.gaitpost.2016.07.107

Dowling, G., Murley, G. S., Munteanu, S. E., Franettovich Smith, M. M., Neal, B. S., Griffiths, I. B., … Collins, N. J. (2014). Dynamic foot function as a risk factor for lower limb overuse injury: A systematic review. *Journal of Foot and Ankle Research*, *7*(1), 1–13. https://doi.org/10.1186/s13047-014-0053-6

Dutton, R. A., Khadavi, M. J., & Fredericson, M. (2016). Patellofemoral Pain. *Physical Medicine* *and Rehabilitation Clinics of North America*, *27*(1), 31–52. https://doi.org/10.1016/j.pmr.2015.08.002

Edwards, B. W., Taylor, D., Rudolphi, T. J., Gillette, J. C., & Derrick, T. R. (2009). Effects of stride Length and Running Mileage on a Probabilistic Stress Fracture Model. *Medicine and Science in Sports and Exercise*, *41*(12), 2177–2184. https://doi.org/10.1016/j.clinbiomech.2010.01.001

Ferber, R., Bolgla, L., Earl-Boehm, J. E., Emery, C., & Hamstra-Wright, K. (2015). Strengthening of the hip and core versus knee muscles for the treatment of patellofemoral pain: A multicenter randomized controlled trial. *Journal of Athletic Training*, *50*(4), 366–377. https://doi.org/10.4085/1062-6050-49.3.70

Ferber, R., Hreljac, a., & Kendall, K. D. (2009). Suspected mechanisms in the cause of overuse running injuries: A clinical review. *Sports Health: A Multidisciplinary Approach*, *1*(3), 242–246. https://doi.org/10.1177/1941738109334272

Ferber, R., Noehren, A. T. C. B., Hamill, J., & Davis, P. I. (2010). Competitive female runners with a history of iliotibial band syndrome demonstrate atypical hip and knee kinematics, *40*(2). https://doi.org/10.2519/jospt.2010.3028

Gijon-nogueron, G., & Fernandez-villarejo, M. (2015). Risk factors and protective factors for lower-extremity running injuries: A systematic review. *Journal of the American Podiatric Medical Association*, *105*(6), 532–540.

Hall, J. P. L., Barton, C., Jones, P. R., & Morrissey, D. (2013). The biomechanical differences between barefoot and shod distance running: A systematic review and preliminary meta-analysis. *Sports Medicine*, *43*(12), 1335–1353. https://doi.org/10.1007/s40279-013-0084-3

Hamill, J., & Gruber, A. H. (2017). Is changing footstrike pattern beneficial to runners? *Journal of Sport and Health Science*, (May). https://doi.org/10.1016/j.jshs.2017.02.004

Hamstra-Wright, K. L., Bliven, K. C. H., & Bay, C. (2015). Risk factors for medial tibial stress syndrome in physically active individuals such as runners and military personnel: A systematic review and meta-analysis. *British Journal of Sports Medicine*, *49*, 362–369. https://doi.org/10.1136/bjsports-2014-093462

Heiderscheit, B. C., Chumanov, E. S., Michalski, M. P., Wille, C. M., & Ryan, M. B. (2012). Effects of step rate manipulation on joint mechanics during running. *Medicine & Science in Sports & Exercise*, *43*(2), 296–302. https://doi.org/10.1249/MSS.0b013e3181ebedf4.Effects

Hollander, K., Heidt, C., van der Zwaard, B., Braumann, K. M., & Zech, A. (2016). Long-term effects of habitual barefoot running and walking: A systematic review. *Medicine and Science in Sports and Exercise*. https://doi.org/10.1249/MSS.0000000000001141

Hulme, A., Nielsen, R. O., Timpka, T., Verhagen, E., & Finch, C. (2017). Risk and protective factors for middle- and long-distance running-related injury. *Sports Medicine*, *47*(5), 869–886. https://doi.org/10.1007/s40279-016-0636-4

Kluitenberg, B., van Middelkoop, M., Diercks, R., & van der Worp, H. (2015). What are the differences in injury proportions between different populations of runners? A systematic review and meta-analysis. *Sports Medicine*, 1143–1161. https://doi.org/10.1007/s40279-015-0331-x

Krabak, B. J., Snitily, B., & Milani, C. J. E. (2016). Running injuries during adolescence and childhood. *Physical Medicine and Rehabilitation Clinics of North America*, *27*(1), 179–202. https://doi.org/10.1016/j.pmr.2015.08.010

Lankhorst, N. E., A Bierma-Zeinstra, S. M., & Middelkoop, M. van. (2013). Factors associated with patellofemoral pain syndrome: a systematic review. *Br J Sports Med*, *47*, 193–206. https://doi.org/10.1136/bjsports-2011-090369

Lieberman, D. E., Warrener, A. G., Wang, J., & Castillo, E. R. (2015). Effects of stride frequency and foot position at landing on braking force, hip torque, impact peak force and the metabolic cost of running in humans. *The Journal of Experimental Biology*, *218*, 3406–14. https://doi.org/10.1242/jeb.125500

Lorimer, A. V., & Hume, P. A. (2014). Achilles tendon injury risk factors associated with running. *Sports Medicine*, *44*(10), 1459–1472. https://doi.org/10.1007/s40279-014-0209-3

Lorimer, A. V., & Hume, P. A. (2016). Stiffness as a risk factor for Achilles tendon injury in running athletes. *Sports Medicine*, *46*(12), 1921–1938. https://doi.org/10.1007/s40279-016-0526-9

Malisoux, L., Ramesh, J., Mann, R., Seil, R., Urhausen, A., & Theisen, D. (2015). Can parallel use of different running shoes decrease running-related injury risk? *Scandinavian Journal of Medicine and Science in Sports*, *25*(1), 110–115. https://doi.org/10.1111/sms.12154

Moore, I. S. (2016). Is there an economical running technique? A review of modifiable biomechanical factors affecting running economy. *Sports Medicine*, *46*(6), 793–807. https://doi.org/10.1007/s40279-016-0474-4

Morin, J. B., Samozino, P., & Millet, G. Y. (2011). Changes in running kinematics, kinetics, and spring-mass behavior over a 24-h run. *Medicine and Science in Sports and Exercise*, *43*(5), 829–836. https://doi.org/10.1249/MSS.0b013e3181fec518

Morin, J. B., Samozino, P., Zameziati, K., & Belli, A. (2007). Effects of altered stride frequency and contact time on leg-spring behavior in human running. *Journal of Biomechanics*, *40*(15), 3341–3348. https://doi.org/10.1016/j.jbiomech.2007.05.001

Mucha, M. D., Caldwell, W., Schlueter, E. L., Walters, C., & Hassen, A. (2016). Hip abductor strength and lower extremity running related injury in distance runners: A systematic review. *Journal of Science and Medicine in Sport*, *20*(4), 349–355. https://doi.org/10.1016/j.jsams.2016.09.002

Napier, C., Cochrane, C. K., Taunton, J. E., & Hunt, M. A. (2015). Gait modifications to change lower extremity gait biomechanics in runners: a systematic review. *British Journal of Sports Medicine*, *49*(1), 1382–1388. https://doi.org/10.1136/bjsports-2014-094393

Neal, B. S., Barton, C. J., Gallie, R., O'Halloran, P., & Morrissey, D. (2016). Runners with patellofemoral pain have altered biomechanics which targeted interventions can modify: A systematic review and meta-analysis. *Gait and Posture*, *45*, 69–82. https://doi.org/10.1016/j.gaitpost.2015.11.018

Nelson, N. G., Alhajj, M., Yard, E., Comstock, D., & McKenzie, L. B. (2009). Physical education class injuries treated in emergency departments in the US in 1997-2007. *Pediatrics*, *124*(3), 918–25. https://doi.org/10.1542/peds.2008-3843

Nielsen, R. O., Buist, I., Sørensen, H., Lind, M., & Rasmussen, S. (2012). Training errors and running related injuries: A systematic review. *The International Journal of Sports Physical Therapy*, *7*(1), 58–75.

Oser, S. M., Oser, T. K., & Silvis, M. L. (2013). Evaluation and treatment of biking and running injuries. *Primary Care - Clinics in Office Practice*, *40*(4), 969–986. https://doi.org/10.1016/j.pop.2013.08.011

Perkins, K. P., Hanney, W. J., & Rothschild, C. E. (2014). The risks and benefits of running barefoot or in minimalist shoes: A systematic review. *Sports Health: A Multidisciplinary Approach*, *6*(6), 475–480. https://doi.org/10.1177/1941738114546846

Rauh, M. J., Koepsell, T. D., Rivara, F. P., Margherita, A. J., & Rice, S. G. (2006). Epidemiology of musculoskeletal injuries among high school cross-country runners. *American Journal of Epidemiology*, *163*(2), 151–159. https://doi.org/10.1093/aje/kwj022

Reinking, M. F., Austin, T. M., Richter, R. R., & Krieger, M. M. (2016). Medial tibial stress syndrome in active individuals: A systematic review and meta-analysis of risk factors. *Sports Health: A Multidisciplinary Approach*, *9(3)*, 252-261. https://doi.org/10.1177/1941738116673299

Ryan, M., Elashi, M., Newsham-West, R., & Taunton, J. (2014). Examining injury risk and pain perception in runners using minimalist footwear. *British Journal of Sports Medicine*, *48*(16), 1257–1262. https://doi.org/10.1136/bjsports-2012-092061

Ryan, M., Elashi, M., Taunton, J., & Koehl, M. (2014). Is gender a risk factor for injury in runners? The first of a three part series to develop a gender targeted injury prevention strategy. *Journal of Science and Medicine in Sport*, *18*, e72–e73. https://doi.org/10.1016/j.jsams.2014.11.308

Ryan, M., Grau, S., Krauss, I., Maiwald, C., Taunton, J., & Horstmann, T. (2009). Kinematic analysis of runners with achilles mid-portion tendinopathy. *Foot & Ankle International / American Orthopaedic Foot and Ankle Society [and] Swiss Foot and Ankle Society*, *30*(12), 1190–1195. https://doi.org/10.3113/FAI.2009.1190

Saragiotto, B. T., Yamato, T. P., Hespanhol Junior, L. C., Rainbow, M. J., Davis, I. S., & Lopes, A. D. (2014a). What are the main risk factors for running-related injuries? *Sports Medicine*, *44*(8), 1153–1163. https://doi.org/10.1007/s40279-014-0194-6

Saragiotto, B. T., Yamato, T. P., Hespanhol Junior, L. C., Rainbow, M. J., Davis, I. S., & Lopes, A. D. (2014b). What are the main risk factors for running-related injuries? *Sports Medicine*, *44*(8), 1153–1163. https://doi.org/10.1007/s40279-014-0194-6

Schache, A. G., Bennell, K. L., Blanch, P. D., & Wrigley, T. V. (1999). The coordinated movement of the lumbo – pelvic – hip complex during running : A literature review. *Gait & Posture*, *10*, 30–47.

Schubert, A. G., Kempf, J., & Heiderscheit, B. C. (2014). Influence of stride frequency and length on running mechanics: A systematic review. *Sports Health*, *6*(3), 210–7. https://doi.org/10.1177/1941738113508544

Taunton, J. E., Ryan, M. B., Clement, D. B., McKenzie, D. C., Lloyd-Smith, D. R., & Zumbo, B. D. (2002). A retrospective case-control analysis of 2002 running injuries. *British Journal of Sports Medicine*, *36*, 95–101.

Taunton, J. E., Ryan, M. B., Clement, D. B., McKenzie, D. C., Lloyd-Smith, D. R., & Zumbo, B. D. (2003). A prospective study of running injuries: the Vancouver Sun Run " In Training " clinics. *British Journal of Sports Medicine*, *37*, 239–244. https://doi.org/10.1136/bjsm.37.3.239

Tenforde, A. S., & Hunt, K. J. (2016). Foot and ankle injuries in runners. *Physical Medicine and Rehabilitation Clinics of North America*, *27*(1), 121–137. https://doi.org/10.1016/j.pmr.2015.08.007

Tenforde, A. S., Kraus, E., & Fredericson, M. (2016). Bone stress injuries in runners. *Physical Medicine and Rehabilitation Clinics of North America*, *27*(1), 139–149. https://doi.org/10.1016/j.pmr.2015.08.008

van der Heijden, R., Lankhorst, N., van Linschoten, R., Bierma-Zeinstra, S., & van Middelkoop, M. (2015). Exercise for treating patellofemoral pain syndrome (Protocol). *Cochrane Database of Systematic Reviews*, (1). https://doi.org/10.1002/14651858.CD010387.pub2

van Der Worp, M. P., ten Haaf, D. S. M., van Cingel, R., de Wijer, A., Nijhuis-Van Der Sanden, M. W. G., & Bart Staal, J. (2015). Injuries in runners: A systematic review on risk factors and sex differences. *PLoS ONE*, *10*(2), 1–18. https://doi.org/10.1371/journal.pone.0114937

van der Worp, M. P., van der Horst, N., de Wijer, A., Backx, F. J. G., & Nijhuis-van der Sanden, M. W. G. (2012). Iliotibial band syndrome in runners. *Sports Medicine*, *42*(11), 969–992. https://doi.org/10.2165/11635400-000000000-00000

van Gent, B. R., Siem, D. D., van Middelkoop, M., van Os, T. A., Bierma-zeinstra, S. S. M. A., & Koes, B. B. W. (2007). Incidence and determinants of lower extremity running injuries in long distance runners: A systematic review. *British Journal of Sports Medicine*. https://doi.org/10.1136/bjsm.2006.033548

Videbaek, S., Bueno, A. M., Nielsen, R. O., & Rasmussen, S. (2015). Incidence of running-related injuries per 1000 h of running in different types of runners: A systematic review and meta-analysis. *Sports Medicine*, *45*(7), 1017–1026. https://doi.org/10.1007/s40279-015-0333-8

Vincent, H. K., & Vincent, K. R. (2013). Considerations for initiating and progressing running programs in obese individuals. *Journal of the American Academy of Physical Medicine and Rehabilitation*, *5*(6), 513–519. https://doi.org/10.1016/j.pmrj.2013.03.008

Warden, S. J., Burr, D. B., & Brukner, P. D. (2006). Stress fractures : Pathophysiology, epidemiology, and risk factors. *Current Osteoporosis Reports*, *4*, 103–109. https://doi.org/10.1007/s11914-996-0029-y

Warden, S. J., Davis, I. S., & Fredericson, M. (2014). Management and prevention of bone stress injuries in long-distance runners. *Journal of Orthopaedic & Sports Physical Therapy*, *44*(10), 749–765. https://doi.org/10.2519/jospt.2014.5334

Willy, R. W., Scholz, J. P., & Davis, I. S. (2012). Mirror gait retraining frot he treatment of patellofemoral pain in female runners. *Clinical Biomedical Journal*, *27*(10), 1045–1051. https://doi.org/10.1016/j.clinbiomech.2012.07.011.Mirror

Yamato, T. P., Saragiotto, B. T., & Lopes, A. D. (2015). A consensus definition of running-related injury in recreational runners: A modified Delphi approach. *Journal of Orthopaedic & Sports Physical Therapy*, *45*(5), 375–380. https://doi.org/10.2519/jospt.2015.5741