International Journal of Sports Science 2014, 4(5): 181-187
DOI: 10.5923/j.sports.20140405.05

Gait Retraining with Foot Strike Patterns as Management for Patellofemoral Pain Syndrome: A Brief Review

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Abstract Running popularity has increased significantly since the 1990's due to the well-known health benefits. While the number of participants has increased, there has also been a concomitant increase in running-related injuries. One of the most common running-related injuries is patellofemoral pain syndrome. Although the cause appears to be multifactorial, several different strategies have been researched and implemented as treatment. Gait retraining is relatively new and research has shown it reduces pain and improves function in runners affected by patellofemoral pain. Due to the many suggested biomechanical benefits associated with a forefoot strike pattern, it is possible to change foot strike patterns through a gait-retraining program and reduce pain and improve function in affected runners. Because of the increased load at the ankle during forefoot striking, future research should address whether changing foot strike patterns negatively affects ankle function.

Keywords Injury, Knee, Lower extremity, Running

1. Introduction

Running popularity has increased dramatically since the 1990's [1]. More than 15 million people participated in running events in 2012 compared to 4.6 million participants in the 1990's [2]. Much of this increase has been due to the numerous reports about the health benefits associated with cardiovascular exercise [3-5]. However, as the number of participants increase, so does the incidence of running-related injuries.

It has been reported that 19.4% to 79.3% of runners sustain running-related injuries [6-7], with recreational and novice runners showing a higher incidence compared to competitive endurance runners [8-9]. There are many risk factors associated with running and the most common risk factors are reported to be age, running experience, and injury history [6, 8-11]. One of the most commonly reported injuries with a high incidence among runners is patellofemoral pain [7, 11]. Because the cause of patellofemoral pain is largely unknown [12], it is difficult for clinicians to provide preventative strategies to runners that will help decrease the incidence and severity of this condition. This review will briefly examine patellofemoral pain and introduce a strategy that runners may employ to decrease their risk of developing this condition and other running related injuries.

2. Gait Cycle

Running has a distinct gait cycle, which is different than that of walking. Commonly, running is described as having two phases termed stance and swing. These events have been further separated into four sub-phases: stance phase, early float, swing phase, and late float [13]. Stance phase begins with foot contact and ends with toe off. One complete cycle begins at initial contact of one foot and ends with contact of the same foot; therefore, as running speed increases, the gait cycle occurs faster.

When analyzing running, stance phase is of particular interest as this is the phase where most injuries are thought to occur. Stance phase can be broken down further into initial contact, loading response, midstance, and terminal stance / preswing [13]. Initial contact is when a portion of the foot (*i.e.* rear, mid- or forefoot) initially hits the ground. The loading response occurs as the muscles of the thigh and leg contract [14] and the knee flexes to absorb the forces produced from contact with the ground. The center of mass velocity decreases in the horizontal direction and the kinetic and potential energy increases [14]. As the runner transitions to midstance, peak knee flexion occurs. The horizontal velocity of the center or mass increases to prepare the runner for terminal stance/preswing and the transition into swing phase.

Typically, musculoskeletal injuries occur at initial contact due to the transient, passive impact peak. The passive impact peak results from the vertical ground reaction force that is applied to the lower extremity while the lower extremity is

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not considered under muscular control [15]. Therefore, the force is thought to be distributed among the non-contractile properties of the lower extremity during this phase and may cause structures such as ligaments to absorb a large percentage of the collision forces produced at initial contact; however, additional research is needed to confirm this idea.

3. Patellofemoral Pain

Patellofemoral pain (PFP) is one of the most commonly reported running injuries [7, 11], particularly as running distance increases [16]. PFP diagnoses are not made with any specific testing, and therefore, definitive diagnosis can be elusive due to the variation in interpretation of knee pain by individuals reporting to clinicians. However, for the purpose of this review, PFP is defined as pain originating from contact between the posterior surface of the patella and the femur. There are other symptoms that are associated with PFP, including crepitus, catching and giving way, swelling and stiffness [12, 17]; however, the most common complaint is pain during and/or after running. PFP is commonly diagnosed in runners yet the etiology is relatively unclear [12], but several factors have been investigated. Readers are directed to previous reviews [12, 17-19] for an in-depth analysis of PFP as this review will give just a brief description of the pathophysiology of PFP.

The pathophysiology of PFP appears to be multifactorial in nature with several dynamic abnormalities of the lower extremity involved [12, 17-18, 20]. Although many mechanisms have been associated with PFP, it is well established that several factors have been consistently linked with PFP. Specifically, thigh muscle imbalances [12, 18, 20], patellar maltracking due to functional malalignment or dynamic knee valgus [12, 17], and overuse [12] appear to have the strongest evidence as elements of the multifactorial cause of PFP.

There have been several interventions suggested for the treatment and prevention of PFP [12, 17-18], including gait retraining [20-21]. Gait retraining, in its simplest form, is learning how to ambulate again after injury. This concept can be applied to runners with PFP to teach them how to run in such a way that they decrease their risk for exacerbating PFP.

4. Gait Retraining

Gait retraining is a relatively new technique that has been used to correct gait perturbations that lead to injuries in runners. To our knowledge, the literature is limited on the effects of gait retraining on PFP in runners, however several recent studies have been published.

Noehren and Davis [22] conducted one of the initial gait retraining investigations. Researchers performed a case study on two female runners who presented with a history of PFP. Following gait retraining sessions, they determined that the subjects reduced hip adduction and knee pain. They subsequently followed up with a similar gait retraining study that involved real-time feedback on dynamic knee alignment [23]. Eight subjects with clinical malalignment (tibial mechanical axis ≥ 11°) performed eight gait-retraining sessions while walking on a treadmill at a self-selected pace. Subjects received real-time visual feedback on knee alignment in a fading feedback design. Over-ground gait analysis was performed pre- and immediately post-retraining with a one-month follow-up analysis. Barrios and colleagues reported a 20% average reduction in the knee external adductor moment and an increase of hip internal rotation by an average of eight degrees immediately post- and one-month post-retraining compared to baseline [23]. Their results indicate that gait retraining improved the dynamic knee alignment while walking and that the modified gait was internalized through the retraining sessions. These data are similar to the results of Noehren et al. [24], who determined that gait retraining in individuals with PFP using real-time feedback on hip alignment decreased hip adduction immediately post- and one-month after gait retraining using a similar retraining protocol. They also found that pain was significantly decreased immediately post- and one-month post retraining (86% mean decrease). Hunt et al. [25] achieved similar results when they utilized gait retraining with an increased trunk lean. They determined that there was a significant reduction in the peak knee adductor moment and the peak external hip adduction moments. However, subjects reported difficulty in learning the new gait pattern and complained of joint discomfort as a result. Therefore, this protocol, although shown to decrease frontal plane joint moments, may not be an appropriate recommendation for some individuals.

Crowell & Davis [26] implemented gait retraining with a protocol similar to those previously described [23-24] using subjects with high peak tibial acceleration values. Real-time feedback was provided to the subject through the usage of an accelerometer attached to the distal tibia. Researchers demonstrated that subjects were able to significantly reduce tibial acceleration and vertical force loading with the modified gait immediately post- and one-month post retraining, also concluding that learning occurred through internalization.

Since real-time feedback requires the usage of a motion analysis system and other expensive equipment, a simpler method was tested to determine its effect on gait retraining in runners with PFP. Willy and colleagues [27] had subjects perform eight gait-retraining sessions with mirror and verbal feedback during treadmill running with a fading feedback design. Researchers determined that there was a significant reduction in peak hip adduction, contralateral pelvic drop, and hip abduction moment during running post-retraining. Additionally, subjects maintained these changes at the one-month and three-month follow-up analyses with reported improvements in pain and function.

Most recently, gait retraining was investigated for its effect on the knee adduction moment and pain [28]. Individuals with medial-compartment knee osteoarthritis were subjected to six weeks of gait retraining using real-time feedback. Researchers determined that at the end of the retraining sessions, subjects decreased the knee adduction moment and maintained this decrease one-month post retraining. Subjects also reported improvements in pain reduction and function. However, this study was conducted with subjects walking and therefore, caution should be used when interpreting these data and applying the results to runners.

Collectively, these outcomes demonstrate that gait retraining has been successful in internalizing a modified gait pattern and maintaining changes in measured variables, reported decreases in pain and improvements in function. However, these studies have focused on gluteal and hip mechanics (tibial acceleration for those prone to stress fractures) and have not examined the effects of changing footstrike patterns on pain and function in runners with PFP. Different foot-strike patterns may cause various gait perturbations and may put the runners at risk for other running-related injuries. In a case series, Cheung et al. [29] reported that switching from RFS to FFS reduced vertical impact peak and rates of loading in addition to reduced knee pain, providing preliminary data to warrant further investigation into gait retraining with foot strike patterns.

5. Forefoot Strike vs. Rearfoot Strike

Rearfoot strike (RFS) during running is the most common foot strike pattern among runners. It has been reported that upwards of 75% of runners tend to RFS, with approximately 24% using a midfoot strike (MFS) and 1% using a forefoot strike (FFS) gait pattern [30-32]. Typically, researchers either combine MFS and FFS or negate MFS during experimental procedures due to the minor biomechanical differences between MFS and FFS, which can affect interpretation of results. There are many kinematic and kinetic differences between RFS and FFS patterns during running that result in different injury risks [33]. This review identifies salient variables that are distinctly different between foot strike patterns.

5.1. Kinematics

Many studies have investigated the kinematic differences between FFS and RFS. Most of the differences observed are at initial contact, although there is some different stance phase characteristics possibly resulting from differences in foot contact time [34] or in the methodological definition(s) of foot strike pattern.

Classically, foot strike has been determined using a strike index (SI) with the use of a force platform and location of the center of pressure (COP) within the foot at initial contact [35]. RFS was measured as initial contact with 0%-33% of the foot or the posterior third of the foot. MFS was measured as initial contact with 34%-67% of the foot or the middle third of the foot. FFS was measured as initial contact with 68%-100% of the foot or the anterior third of the foot. However, more contemporary methods have been developed and validated to identify foot strike patterns. Altman and Davis [36] determined that calculating the foot strike angle (FSA) was significantly correlated ($r = 0.92$, $p < 0.01$) with the strike index. Researchers reported that the FSA was calculated by subtracting the angle of the foot while standing from the angle of the foot at foot strike. The results were that RFS = FSA > 8°, MFS = $-1.6° < \text{FSA} < 8°$, and FFS = FSA < $-1.6°$. Therefore, use of FSA may be acceptable when there is limited access to a force platform to measure COP. More recently, it was determined that identifying foot strike patterns through measurement of heel and metatarsal accelerations was highly correlated ($r = 0.916$, $p < 0.0001$) with the FSA in the sagittal plane [37]. Giandolini et al. positioned two uniaxial accelerometers on the foot and measured the time between the heel and metatarsal acceleration peaks. Foot strike classification was: FFS < -5.49 ms< MFS < 15.2 ms< RFS. Each of these methods arevalid in identifying foot strike patterns and researchers should choose which method to use based on available equipment in the study location (i.e. laboratory setting versus outdoor running track).

There is a significant difference in ankle angle at initial foot contact with the ground between FFS and RFS [34, 38-40]. It has been shown that RFS resulted in ankle dorsiflexion at initial contact while FFS resulted in ankle plantarflexion while running along a 20-m runway at a fixed running speed [40], which is similar to results from Shih et al. [39] who determined that there was increased dorsiflexion in RFS, both barefoot and shod, compared to FFS.

Currently, the results shown in the research are equivocal as to whether there is a significant difference in knee and hip angles at initial contact between FFS and RFS patterns [40]. While running along a runway at a fixed running speed, several researchers determined that there were no significant differences in knee and hip angles at initial contact [34, 38, 40]. Conversely, others [39, 41-42] have determined that there was a greater degree of knee flexion at initial contact with FFS, while there was a greater amount of hip extension at initial contact with FFS compared to RFS.

Delgado and colleagues [43] determined that changing runners from RFS to FFS decreased range of motion (ROM) in the lumbar spine, but did not change sagittal plane spine position during running. Similarly, it was determined that knee and ankle ROM was not significantly different between foot strike patterns, although hip ROM was significantly different between the foot strike patterns [39]. Conversely, it has been demonstrated that knee ROM was significantly different between RFS and FFS [38]. Very few studies have measured these variables and thus, results remain equivocal.

5.2. Kinetics

Loading rate (LR) is the rate at which forces are applied to the body. More specifically, it is the slope of the vertical ground reaction force (vGRF) typically defined from initial contact to the first impact peak maximum [39, 44]. However, there are other methods employed to compute LR, specifically with and without the presence of an impact peak that occurs during RFS and FFS, respectively. Although LR is typically defined from initial contact to impact peak during RFS running, some researchers use only 20% to 80% of the ground contact time leading to the impact peak to compute LR [34, 44], while others have used a threshold value of 200 N to 90% of the impact peak [42]. During FFS running, due to the absence of the impact peak, researchers typically use a percentage of stance phase with some using 3% - 12% of stance phase [44] and others using a threshold value of 200 N to 6.2 ± 3.7% of stance phase [42]. It is not common that that the same calculation is used to determine LR in RFS and FFS, although it has been done successfully with significant differences between results [39]. However, the different methods of calculating LR can influence the results when comparing RFS to FFS due to the varying amount of data that is included. Comparing the differing methodologies for calculating LR is an area of future research that needs to be addressed.

Nevertheless, it appears that a lesser LR is more favorable in terms of injury prevention [45-46]. Shih et al. [39] determined that in both barefoot and shod conditions, FFS pattern resulted in a lesser average and peak LR compared to RFS. Similarly, it was established that FFS was associated with a lesser LR compared to RFS while running at a fixed speed [34, 42, 44].

Shock attenuation during running is the act of absorbing energy due to foot impact with the ground (or contact surface), which reduces the shock wave magnitude between the head and the foot [47] and varies with running speed [48], knee flexion angles and different foot contact patterns [49]. It has been shown that RFS had greater shock attenuation compared to FFS [43]. This is likely due to the lesser peak leg impact at contact with FFS, suggesting that use of a FFS decreases shock while running [20, 42-43, 50-53]. This is a feasible conclusion as it has been shown that vGRF and vertical loading rate are both significantly smaller in FFS compared to RFS [34], and RFS would have increased shock absorption due to the greater stride length [47, 52]. Stride length may be greater during RFS because there is more cushioning in the shoe underneath the heel, which absorbs some of the impact force experienced with running. There is less cushioning underneath the forefoot, suggesting that the impact forces associated with FFS would not be absorbed by the shoe to the same extent as with RFS. Runners using FFS would then adjust stride length to limit the impact forces experienced during running [52].

Knee moments during running with FFS compared to RFS have been found to be significantly different [34]. Specifically, it has been shown that the patellofemoral contact force and patellofemoral stress were significantly less during FFS compared to RFS [34]. Additionally, the knee abduction moment was significantly less during FFS compared to RFS, possibly due to the decreased stride length and subsequent shock absorption associated with FFS [47, 52].

However, recent research has shown that while running at a self-selected speed, runners exhibited greater peak contact forces at the ankle during FFS, but similar peak contact forces at the knee and hip [54]. It was also determined that habitual use of FFS resulted in increased contact forces at each joint compared to habitual use of RFS and those increased contact forces occurred in the first 40% of the stance phase [54]. Similar results were found when several research groups determined that FFS was associated with an increased Achilles tendon force [34, 55] and plantarflexion moment [34, 56]. Together, these results suggest that usage of a FFS pattern during running may increase the risk of developing injuries at the ankle due to the increased force and loading rate. The anteroposterior component of the GRF during FFS has two impact peaks during the first 40% of stance phase, with the first peak being a transient, increase in force in the negative direction (braking). This peak is similar to the first impact peak in the vGRF component that is evident with RFS and could result in injury. During running with a FFS, an excessive braking impulse may be present which results in increased repetitive tensile forces on the muscles of the posterior lower extremity [13, 53] and may partially explain why an increased Achilles tendon force and plantarflexion moment may increase ankle injury risk [34, 55-56].

5.3. Muscle Activity

Muscle activity has not been well researched regarding differences between foot strike patterns. However, recently Rooney & Derrick [54] determined that there were increased gastrocnemius, soleus, and peroneal forces with a FFS during the first half of stance phase, which contributed to the increased contact forces at the ankle. Similar results were found when researchers evaluated the muscle activity of runners using a FFS and RFS while barefoot [39, 55] and shod [39].

5.4. Running Economy and Performance

Running economy is a measure of how efficiently a person uses oxygen at a given running speed. Therefore, typically, the lower the oxygen consumption (VO_2) at a given running pace, the more economical the individual. Limited research exists on the variability in running economy between FFS and RFS, however a few studies will be reviewed on the economy differences between the foot strike patterns.

Gruber and colleagues [57] investigated the difference in economy while running at three different fixed speeds using FFS and RFS patterns. They determined that runners using their habitual foot strike pattern showed no difference in VO_2 between groups, which is similar to the results of a subsequent study [58]. However, when running at a fast speed (4.0 m/s), FFS pattern resulted in higher VO_2 compared to the RFS pattern. This happened specifically when RFS runners were switched to FFS, suggesting that FFS is not more economical than the RFS when runners switch to a non-habitual foot strike pattern [57]. Similarly, Ogueta-Alday et al. [59] determined that RFS runners were more economical at various fixed running speeds compared to midfoot strikers. The differences observed in running economy in these studies may be due to the increased muscle activity associated with FFS [54], which will increase oxygen consumption. To our knowledge, no evidence exists on whether running economy will return to pre-training levels after implementation of a gait retraining protocol switching from RFS to a FFS during running, and remains to be an area of future research.

Cost of transport (CoT) is the energetic cost to travel a given distance and has also been measured for its differences between foot strike patterns. Perl et al. [60] determined that there was no significant difference in the CoT between RFS and FFS. This suggests that the energy expenditure for a given distance will be the same for a runner using either foot strike pattern, signifying that switching foot strike patterns will not change energy expenditure over a given distance.

Kasmer and colleagues [30] examined whether there was a difference in performance between footstrike patterns in subelite runners during a marathon. Among the 1991 runners that were evaluated, they determined that the more elite runners were more likely to use a FFS or midfoot strike and have a better finishing position in the race, likely due to the decreased ground contact time and increased stride frequency associated with FFS [32, 38, 52-53, 58, 61]. Similarly, it was determined that as running speed increased, the likelihood of FFS or midfoot strike pattern during running increased as well [32, 50, 61]. However, other work has shown that there was no significant difference between footstrike patterns and race times [31]. This discrepancy in findings may be due to the specific type of race, as one was a qualifier for the Boston marathon [30] and the other was not as competitive.

5.5. Injury Rates

Before making recommendations regarding usage of foot strike patterns, it is necessary to evaluate the injury rates associated with each. Daoud and colleagues [62] determined that RFS runners have significantly higher rates of injury from repetitive stress compared to FFS runners. Similarly, it was determined that RFS runners were 3.41 times more likely to report injuries compared to FFS runners [33]. Collectively, these studies suggest that FFS reduces the likelihood of injury in runners, and its usage during running is a clinical recommendation that can be made to individuals [63].

6. Conclusions

Many runners are affected by PFP and the cause appears to be multifaceted. There have been a number of strategies utilized to aid in decreasing the occurrence and severity of PFP, including gait retraining. Several studies have addressed gait retraining and collectively, the results suggest that it is a successful strategy to employ. These studies focused on hip and gluteal mechanics; however, usage of footstrike patterns with gait retraining may be an appropriate alternative due to the benefits associated with FFS compared to RFS. Future research should investigate the effects of gait retraining utilizing footstrike patterns and determine the magnitude of internalization of the new footstrike pattern. Additionally, future research should address whether switching from a RFS to a FFS significantly increases pain and/or injuries at the ankle, due to the increased force and loading at the ankle associated with FFS.

REFERENCES

[1] Lynch, S. L. and Hoch, A. Z., The female runner: gender specifics, *Clin. Sports Med.*, 29(3), 477-498, 2010.

[2] Running USA (2013). 2013 state of the sport- part III: US race trends. [Online]. Available: http://www.runningusa.org/state-of-sport-2013-part-III?returnTo=annual-reports

[3] Dangardt, F. J., McKenna, W. J., Lusher, T. F., and Deanfield, J.E., Exercise: friend or foe?, *Nat. Rev. Cardiol.*, 10, 495-507, 2013.

[4] Dhaliwal, S. S., Welborn, T. A., and Howat, P. A., Recreational physical activity as in independent predictor of multivariate cardiovascular disease risk, *PLoS ONE*, 8(12), e83435, doi:10.1371/journal.pone.0083435, 2013.

[5] Kravitz, L., The 25 most significant health benefits of physical activity and exercise, pp. 55-63, Oct. 2007.

[6] Newman, P., Witchalls, J., Waddington, G., and Adams, R., Risk factors associated with medial tibial stress syndrome in runners: a systematic review and meta-analysis, *J. Sports, Med.*, 4, 229-241, 2013.

[7] van Gent, R. N., Siem, D., van Middelkoop, M., van Os, A. G., Bierma-Zeinstra, S. M. A., and Koes, B. W., Incidents and determinants of lower extremity running injuries in long distance runners: a systematic review, *Br. J. Sports. Med., 41, 469-480*, 2007.

[8] Buist, I., Bredeweg, S. W., Bessem, B., van Mechelen, W., Lemmink, K. A. P. M., and Diercks, R. L., Incidence and risk factors of running-related injuries during preparation for a 4-mile recreational running event, *Br. J. Sports. Med., 44, 598-604*, 2010.

[9] Tonoli, C., Cumps, E., Aerts, I., Verhagen, E., Meeusen, R., Incidence, risk factors, and prevention of running related injuries in long distance running: a systematic review, *Sport & Geneeskunde*, 5, 12-18, Dec. 2010.

[10] Van middlekoop, M., Kolkman, J., Van Ochten, J., Bierma-Zeinstra, S. M. A., and Koes, B. W., Risk factors for lower extremity injuries among male marathon runners, *Scand. J. Med. Sci. Sports.*, 18, 691-697, 2008.

[11] Taunton, J. E., Ryan, M. B., Clement, D. B., McKenzie, D. C., Lloyd-Smith, D. R., and Zumbo, B. D., A retrospective case-control analysis of 2002 running injuries, *Br. J. Sports. Med.*, 36, 95-101, 2002.

[12] Thomee, R., Augustsson, J., and Karlsson, J., Patellofemoral pain syndrome: a review of current issues, *Sports. Med.*, 28(4),

245-262, 1999.

[13] Lohman III, E. B., Sackiriyas, K. S. B., and Swen, R. W., A comparison of the spatiotemporal parameters, kinematics, and biomechanics between shod, unshod, and minimally supported running as compared to walking, *Phys. Thera. Sport.*, 12, 151-163, 2011.

[14] Novacheck, T. F., The biomechanics of running, *Gait Posture*, 7, 77-95, 1998.

[15] Hamill, J. and Knutzen, K. M., Biomechanical basis of human movement, 3rd ed., Philadelphia, PA: Lippincott Williams & Wilkins, 2009.

[16] Lopes, A. D., Hespanhol Jr., L. C., Yeung, S. S., and Costa, L. O. P., What are the main running-related musculoskeletal injuries?, *Sports Med.*, 42(10), 891-905, 2012.

[17] Petersen, W., Ellermann, A., Gosele-Koppenburg, A., et al., Patellofemoral pain syndrome, *Knee Surg. Sports Traumatol. Arthrosc.*, published online doi:10.1007/s00167-013-2759-6, 2013.

[18] Lankhorst, N. E., Bierma-Zeinstra, S. M. A., and Van Middlekoop, M., Risk factors for patellofemoral pain syndrome: a systematic review, *J Sports Orthrop. Sports Phys Ther.,*42(2), 81-94, 2012.

[19] Barton, C. J., Levinger, P., Menz, H. B., and Webster, K. E., Kinematic gait characteristics associated with patellofemoral pain syndrome: a systematic review, *Gait Posture*, 30, 405-416, 2009.

[20] Davis, I. S. and Powers, C., Patellofemoral pain syndrome: proximal, distal, and local factors, *J. Orthrop. Sports Phys. Ther.,* 40(3), A1-A48, 2009.

[21] Rixe, J. A., Gallo, R. A., and Silvis, M. L., The barefoot debate: can minimialist shoes reduce running-related injuries?, *Curr. Sports Med. Reports*, 11(3), 160-165, 2012.

[22] Noehren, B. and Davis, I., The effect of gait retraining on hip mechanics, pain, and function in runners with patellofemoral pain syndrome, *J. Orthrop. Sports Phys. Ther.*, 40(3), A40-A41, 2009.

[23] Barrios, J. A., Crossley, K. M., and Davis, I. S., Gait retraining to reduce the knee adduction momentthrough real-time visual feedback of dynamic knee alignment, *J. Biomech.*, 43, 2208-2213, 2010.

[24] Noehren, B., Scholz, J., and Davis, I., The effect of real-time gait retaining on hip kinematics, pain and function in subjects with patellofemoral pain syndrome, *Br. J. Sports Med.*, 45, 691-696, 2011.

[25] Hunt, M. A., Simic, M., Hinman, R. S., Bennell, K. L., and Wrigley, T. V., Feasibility of a gait retraining strategy for reducing knee joint loading: Increased trunk lean guided by real-time biofeedback, *J. Biomech.*, 44, 943-947, 2011.

[26] Crowell, H. P., and Davis, I. S., Gait retraining to reduce lower extremity loading in runners, *Clin. Biomech.*, 26, 78-83, 2011.

[27] Willy, R. W., and Davis, I. S., Varied response to mirror gait retraining of gluteus medius control, hip kinematics, pain, and function in 2 female runners with patellofemoral pain, *J. Orthrop. Sports Phys. Ther.*, 43(12), 864-874, 2013.

[28] Shull, P. B., Silder, A., Shultz, R., Dragoo, J. L., Besier, T. F., Delp, S. L., and Cutkosky, M. R., Six-week gait retraining program reduces knee adduction moment, reduces pain, and improves function in individuals with medial compartment knee osteoarthritis, *J. Orthop. Res.*, 31, 1020-1025, 2013.

[29] Cheung, R. T. H., and Davis, I. S., Landing pattern modification to improve patellofemoral pain in runners: a case series, *J. Orthop. Sports Phys. Ther.*, 41(12), 914-919, 2011.

[30] Kasmer, M. E., Liu, X-C., Roberts, K. G., and Valadao, J. M., Foot-strike pattern and performance in marathon, *Int. J. Sports Phys. Perform.*, 8, 286-292, 2013.

[31] Larson, P., Higgins, E., Kaminski, J., et al., Foot-strike patterns of recreational and sub-elite runners in a long-distance road race, *J. Sport Sci.,* 29(15), 1665-1673, 2011.

[32] Hasegawa, H., Yamauchi, T., and Kraemer, W. J., Foot strike patterns of runners at the 15-km point during an elite-level half marathon, *J. Strength Cond. Res.*, 21(3), 888-893, 2007.

[33] Goss, D. L. and Goss, M. T., A review of mechanics and injury trends among various running styles, *Army Med. Dep. J.*, July- September, 62-71, 2012.

[34] Kulmala, J. P., Avela, J., Pasanen, K., and Parkkari, J., Forefoot strikers exhibit lower running-induced knee loading than rearfoot strikers, *Med. Sci. Sports Exerc.,*45(12), 2306-2313, 2013.

[35] Cavanaugh, P. R. and LaFortune, M. A., Ground reaction forces in distance running, *J. Biomech.*, 13, 397-406, 1980.

[36] Altman, A. R. and Davis, I. S., A kinematic method for footstrike pattern detection in barefoot and shod runners, *Gait Posture*, 35(2), 298-300, 2012.

[37] Giandolini, M., Poupard, T., Gimenez, P., et al., A simple field method to identify foot strike pattern during running, *J. Biomech.*, 47, 1588-1593, 2014.

[38] Nunns, M., House, C., Fallowfield, J., Allsopp, A., and Dixon, S., Biomechanical characteristics of barefoot footstrike modalities, *J. Biomech.*, 46, 2603-2610, 2013.

[39] Shih, Y., Lin, K-L., and Shiang, T-Y., Is the footstrike pattern more important than barefoot or shod conditions in running?, *Gait Posture*, 38, 490-494, 2013.

[40] Williams, D. S. B., Green, D. H., and Wurzinger, B., Changes in lower extremity movement and power absorption during forefoot striking and barefoot running, *Int. J. Sports Phys. Ther.*, 7(5), 525-532, 2012.

[41] Hall, J. P. L., Baron, C., Jones, P. R., and Morrissey, D., The biomechanical differences between barefoot and shod distance running: a systematic review and preliminary meta-analysis, *Sports Med.*, 43, 1335-1353, 2013.

[42] Lieberman, D. E., Venkadesan, M., Werbel, W. A., et al., Foot strike patterns and collision forces in habitually barefoot versus shod runners, *Nature*, 463, 531-535, 2010.

[43] Delgado, T. L., Kubera-Shelton, E., Robb, R. R., Hickman, R., Wallmann, H. W., and Dufek, J. S., Effects of foot strike on low back posture, shock attenuation, and comfort in running, *Med. Sci. Sports Exerc.*, 45(3), 490-496, 2013.

[44] Goss, D. L. and Goss, M. T., A comparison of negative joint work and vertical ground reaction force loading rates in chi runners and rearfoot-striking runners, *J. Orthop. Sports Phys. Ther.*, 43(10), 685-692, 2013.

[45] Zadpoor, A. A. and Nikooyan, A. A., The relationship between lower-extremity stress fractures and the ground reaction force: a systematic review, *Clin. Biomech.*, 26(1), 23-28, 2011.

[46] Milner, C. E., Ferber, R., Pollard, C. D., Hamill, J., and Davis, I. S., Biomechanical factors associated withtibial stress fracture in female runners, *Med. Sci. Sports Exerc.*, 38(2), 323-328, 2006.

[47] Mercer, J. A., Bates, B. T., Dufek, J. S., and Hreljac, A., Characteristics of shock attenuation during fatigued running, *J Sport Sci.*, 21, 911-919, 2003.

[48] Shorten, M. R. and Winslow, D. S., Spectral analysis of impact shock during running, *Int. J. Sport Biomech.*, 8, 288-304, 1992.

[49] Frederick, E. C. and Hagy, J., Factors affecting peak vertical ground reaction forces in running, *Int. J. Sport Biomech.*, 2, 41-49, 1986.

[50] Hatala, K. G., Dingwall, H. L., Wunderlich, R. E., and Richmond, B. G., Variation in foot strike patterns during running among habitually barefoot populations, *PLoS ONE*, 8(1), e52548. Doi:10.1371/journal.pone.0052548, 2013.

[51] Hamill, J., Russell, E. M., Gruber, A. H., and Miller, R., Impact characteristics in shod and barefoot running, *Footwear Sci.*, 3(1), 33-40, 2011.

[52] Squadrone, R., and Gallozzi, C., Biomechanical and physiological comparison of barefoot and two shod conditions in experienced barefoot runners, *J. Sports Med. Phys. Fitness*, 49(1), 6-13, 2009.

[53] Divert, C., Mornieux, G., Baur, H., Mayer, F., and Belli, A., Mechanical comparison of barefoot and shod running, *Int. J. Sports Med.*, 26, 593-598, 2005.

[54] Rooney, B. D. and Derrick, T. R., Joint contact loading in forefoot and rearfoot strike patterns during running, *J. Biomech.*, 46, 2201-2206, 2013.

[55] Almonroeder, T., Willson, J. D., and Kernozek, T. W., The effect of foot strike pattern on Achilles tendon load during running, *Annals Biomed. Engin.,* 41(8), 1758-1766, 2013.

[56] Paquette, M. R., Zhang, S., and Baumgartner, L. D., Acute effects of barefoot, minimal shoes and running shoes onlower limb mechanics in rear and forefoot strike runners, *Footwear Sci.*, 5(1), 9-18, 2012.

[57] Gruber, A. H., Umberger, B. R., Braun, B., and Hamill, J., Economy and rate of carbohydrate oxidation during running with rearfoot and forefoot strike patterns, *J. Appl. Phys.*, 115, 194-201, 2013.

[58] Di Michele, R. and Merni, F., The concurrent effects of strike pattern and ground contact time on running economy, *J. Sci. Med. Sport*, Epub ahead of print, doi:10.1016/j.jsams.2013.05.012, 2013.

[59] Ogueta-Alday, A., Rodriguez-Marroyo, J. A., and Garcia-Lopez, J., Rearfoot striking runners are more economical than midfoot strikers, *Med. Sci. Sports Exerc.*, 46(3), 580-585, 2014.

[60] Perl, D. P., Daoud, A. I., and Lieberman, D. E., Effects of footwear and strike type on running economy, *Med. Sci. Sports Exerc.*, 44(7), 1335-1343, 2012.

[61] Hayes, P., and Caplan, N., Foot strike patterns and ground contact times during high-calibre middle-distance races, *J. Sports Sci.*, 30(12), 1275-1283, 2012.

[62] Daoud, A. I., Geissler, G. J., Wang, F., Saretsky, J., Daoud, Y. A., and Lieberman, D. E., Foot strike and injury rates in endurance runners: a retrospective study, *Med. Sci. Sport Exerc.*, 44(7), 1325-1334, 2012.

[63] Lorenz, D. S. and Pontillo, M., Is there evidence to support a forefoot strike pattern in barefoot runners? A review, *Sports Health*, 4(6), 480-484, 2012.