Review article

A biomechanical perspective of predicting injury risk in running

1†Associate Professor Alan Hreljac, PhD
2,3Dr Reed Ferber, PhD

1Department of Kinesiology and Health Science, California State University, Sacramento, CA, USA
2Running Injury Clinic, Calgary, Alberta, Canada
3Faculty of Kinesiology, University of Calgary, Canada

Abstract

Objective: The primary objective of this review was to synthesise the literature related to risk factors for running injuries, with an emphasis on predicting the risk of injury based upon biomechanical variables. Data sources: Literature sources from a broad range of scientific journals were searched, focusing primarily on literature describing studies which directly related to risk factors for overuse running injuries of the lower extremity. Study section: There were a total of 74 studies reviewed. Data were primarily reviewed from experimental and epidemiological studies. Data extraction: Only data from research published in refereed journals or professional conference proceedings were presented in this review. Data synthesis: Although many sources suggest that about 60% of running injuries are due to training errors, from a practical standpoint, it could be stated that all overuse running injuries are attributable to training variables. In order to sustain an overuse injury, a runner must have exceeded his/her limit of running distance and/or intensity in such a way that the remodelling of the injured structure predominated over the repair process. Biomechanical and anthropometric variables are very important in determining where the limits exist for an individual. Conclusions: Since all overuse running injuries could be attributed to training errors, then it would follow that these injuries should be preventable. A proactive approach may enable practitioners to predict running injury risk based upon biomechanical and anthropometric profiles of runners. Future prospective studies could further identify variables which are most responsible for running injuries, and determine easily measurable variables that may correlate to these risk factors. Keywords: chronic injuries, training errors, running, prevention, gait

Associate Professor Alan Hreljac, PhD

Dr Alan Hreljac is currently an Associate Professor of Biomechanics at California State University, Sacramento, CA, USA. He received his Bachelor of Science degree in Physics from the University of Waterloo prior to studying Biomechanics at San Diego State University where he received his Master of Science degree. His doctoral studies in biomechanics were completed at Arizona State University. He completed a post-doctoral fellowship at the University of Auckland. He is a member of the American Society of Biomechanics, and the International Society of Biomechanics. His primary areas of research have been in the realm of gait mechanics with special interests in gait transitions and running injuries.

†Corresponding author. Address at end of text.
Dr Reed Ferber, PhD

Dr Reed Ferber received a PhD in Biomechanics from the University of Oregon and is a certified athletic therapist. He has completed post-doctoral research fellowships in the Motion Analysis Laboratory in the Department of Physical Therapy at the University of Delaware and the Human Performance Laboratory at the University of Calgary, Canada. Dr Ferber has received the Outstanding Student Research Award from the Northwest Chapter of ACSM for his dissertation work, and was a finalist for the ISB Congress Scherb Award for outstanding biomechanical research in the area of human locomotion with emphasis on clinical application. Currently he is the Director of the Running Injury Clinic and an Adjunct Assistant Professor in the Faculty of Kinesiology at the University of Calgary, Canada. His current research interests include the aetiology and optimal treatment of running-related injuries.

Contact details:
Email: rferber@kin.ucalgary.ca

Introduction

Although runners often sustain traumatic injuries, such as ankle sprains and muscle strains, a vast majority of running injuries could be classified as overuse injuries. An overuse injury is an injury of the musculoskeletal system resulting from the combined fatigue effect over a period of time beyond the capabilities of a specific structure that has been stressed. These injuries occur when a large number of small magnitude repetitive forces are applied to a structure (such as a muscle or tendon), each less than the acute injury threshold of the structure. Although repeated stresses on various structures of the musculoskeletal system may result in an overuse injury, this does not imply that stresses to the musculoskeletal system should be minimised to avoid injury. All biological structures, such as muscles, tendons, ligaments, and bones, adapt both positively and negatively to the level of stress placed upon them. Positive adaptation (remodelling) occurs when the repeated applied stresses are below the tensile limit of a structure and adequate time period between stress applications is provided. On the other hand, injury or negative adaptation occurs when a single stress beyond the tensile limit is applied to a structure (traumatic injury), or repeated stresses below the tensile limit with insufficient time period between stress applications (overuse injury) are applied.

Running is one of the most widespread activities during which overuse injuries of the lower extremity occur regularly. There is no agreed-upon standardised definition, but several authors have defined an overuse running injury as a musculoskeletal ailment attributed to running that causes a restriction of running speed, distance, duration, or frequency for at least one week. Using slight variations of this definition, various epidemiological studies have estimated that anywhere from 27% to 70% of recreational and competitive distance runners sustain an overuse running injury during any one year period. The runners in these studies vary considerably in their running experience, and training habits, but generally they run a minimum distance of 20-30km per week on a regular basis, and have been running consistently for at least 1-3 years.

The knee is the most common site of overuse running injuries, accounting for close to half of all running injuries. According to a recent clinical study of over 2000 injured runners, the most common knee injury is patella femoral pain syndrome (PFPS), followed by iliotibial band friction syndrome, meniscal injuries and patellar tendinitis. Injuries to the foot, ankle, and leg, such as plantar fasciitis, Achilles tendinitis, and medial tibial stress syndrome (shin splints) account for almost 40% of the remaining injuries reported by these researchers, while less than 20% of the running injuries reported occur superior to the knee. Other researchers have reported a fairly similar breakdown for the location of overuse running injuries. Although very few overuse running injuries have an established aetiology, the fact that over 80% of these injuries occur at or below the knee suggests that there may be some common mechanisms in the aetiology.
Although there has been a large amount of speculation regarding the mechanism of running injuries, the exact causes of overuse running injuries have yet to be determined. It could only be stated with certainty that the aetiology of these injuries is multifactorial and diverse.5,12,18 It has occasionally been suggested that particular running injuries, or sites of injuries are associated with specific risk factors, but some researchers19,20 have concluded that there are no specific risk factors that correlate with specific types of injury in a reliable fashion. There are, however, several risk factors which may actually be associated with a variety of running injuries. A large majority of the risk factors that have been associated with overuse running injuries could be placed into three general categories: training, anatomical, and biomechanical factors.

Aetiology of overuse running injuries

The training variables that have most often been identified as risk factors for overuse running injuries include running distance, training intensity, rapid increases in weekly running distance or intensity, and stretching habits.10,12,19,21-24 The general mechanism by which some of these training variables could lead to overuse injuries may be understood by examining how these variables would affect the stress-frequency relationship (Figure 1). Increasing running distance would increase the number of repetitions of the applied stress since the number of steps taken would be increased. Provided that running speed remained unchanged, the magnitude of the forces and moments produced at various musculoskeletal structures during each step would remain unchanged also (neglecting fatigue effects). Thus running a greater distance would place the involved musculoskeletal structures further to the right on the stress-frequency curve (Figure 1). Since this portion of the curve has a slight negative slope, locations further to the right on the curve require slightly lower stresses for a structure to enter the “injury” zone of the curve. Therefore the possibility that one or more structures would enter the injury zone of the graph would increase with increasing running distance.

![Figure 1: Effect on overuse injury occurrence due to the theoretical relationship between stress application and frequency](image)

In running, training intensity relates to running speed. Faster running speeds generally produce greater forces and moments on the involved musculoskeletal structures.25-28 When training intensity increases, all of these structures are placed higher on the stress-frequency graph (Figure 1). Locations higher on this graph require fewer repetitions for a structure to enter the injury zone. In this way, when training intensity increases without a decrease in running distance or frequency, the likelihood of injury would also increase.

The means by which rapid changes in distance or intensity could increase the risk of injury could also be explained by the stress-frequency relationship. When a musculoskeletal structure is subjected to a
Several clinical studies have estimated that over 60% of overuse running injuries are a result of variables related to training. From a practical standpoint, it could be stated that all overuse running injuries are attributable to training variables. In order to sustain an overuse injury, a runner must have subjected some musculoskeletal structure to a stress-frequency combination which crossed over to the injury zone of the current stress-frequency curve for the injured structure. This could only be accomplished when an individual exceeds his/her current limit of running distance and/or intensity in such a way that the negative remodelling of the injured structure predominated over the repair process due to the stresses placed on the structure. It is obvious that the exact "location" of this limit would vary from structure to structure, and from individual to individual, but there is no doubt that each runner could have prevented these injuries by training differently based upon individual limitations, or in some cases by not training at all.

One of the most appealing aspects of grouping the causes of all overuse running injuries into the category of training variables is that all of these injuries could then be considered to be preventable, since training variables are factors over which a runner has control. To effectively prevent overuse running injuries, however, would require the knowledge of the current limits of all of the involved musculoskeletal structures. These limits would primarily be determined by anatomical and biomechanical variables, combined with the current state of training, and the integrity and injury status of various structures. Of course, it is not possible to know these limits exactly, but it may be possible to minimise the risk of injury by advising runners in terms of running speed, distance, frequency, and progression, based upon an assessment of anthropometric and biomechanical risk factors.

**Anthropometric risk factors**

There are several anthropometric (anatomical) variables that have been implicated as causes of overuse running injuries. More accurately, these variables may affect an individual's limitations regarding various aspects of training such as running distance, speed, and frequency. The anthropometric variables which have been implicated as causes of overuse running injuries include high longitudinal arches (pes cavus), ankle range of motion, leg length discrepancies, and lower extremity alignment abnormalities. For most of these variables, there is no consensus among researchers regarding their effect on...
overuse running injury potential based upon conflicting results reported in the literature.

While several studies\(^{22,34-36}\) have suggested that runners with pes cavus are at an increased risk of injury during running, others\(^{37-39}\) have concluded that arch height is not a risk factor in running injuries. Runners with a greater sagittal plane ankle range of motion have been determined to be at greater risk of overuse injuries than runners with less ankle mobility according to some researchers\(^ {20,22,35}\). Other studies\(^ {6,31}\) have reported that sagittal plane ankle range of motion does not differ significantly between groups of runners who had sustained lower extremity injuries and groups of uninjured control subjects. Still, one other study disagreed with both of these possibilities. Montgomery et al.\(^ {37}\) concluded that reduced ankle flexibility is actually a risk factor in overuse running injuries based upon a study that found military recruits who sustained stress fractures during training tended to have less ankle flexibility than recruits who did not sustain these injuries. Anatomical variables, such as tibia varum, rear-foot varus, excessive Q-angle, and leg length discrepancies, could be grouped together as lower extremity alignment abnormalities. These factors, and other problems related to alignment of the lower extremity have been reported to be associated with overuse running injuries by some authors\(^ {2,11,21}\), although others\(^ {37,40}\) have determined that lower extremity alignment abnormalities are not associated with an increased risk of overuse injuries in runners.

Part of the reason for discrepancies in studies searching for a link between anthropometric variables and overuse running injuries is the fact that these variables must combine with training and biomechanical factors to result in an injury. Training and biomechanical variables could vary considerably between individuals and between studies, producing mixed results. This does not necessarily preclude these anthropometric variables from being risk factors for overuse running injuries. In addition, it is very likely that few people who possess fairly severe abnormalities participated in most of these studies due to the protocols which generally included runners who were engaged in a regular running program at the time of the study. It is possible that many people with severe problems would have already realised that running is an activity in which they could not safely participate on a regular basis.

**Biomechanical risk factors**

The majority of biomechanical risk factors related to overuse running injuries could be classified as either kinetic or mediolateral control variables. Among the kinetic variables that have been speculated to be a cause of overuse running injuries are the magnitude of impact forces\(^ {41}\), the rate of impact loading\(^ {42}\), the magnitude of active forces\(^ {43}\), increased loading on the medial side of the foot\(^ {44}\), and the magnitude of knee joint forces and moments\(^ {45}\). The mediolateral control variables that have most often been associated with overuse running injuries are the magnitude and rate of foot pronation.

In a recent study\(^ {46}\), female subjects with a history of stress fractures were shown to exhibit greater peak vertical impact ground reactions forces, loading rates, and peak tibial acceleration than a control group of uninjured female runners. Similar results were reported by Grimston et al.\(^ {37}\), who found that female runners that had experienced stress fractures produced significantly greater vertical impact forces than subjects without stress fractures. These results were in agreement with another study\(^ {6}\), which reported that a group of previously injured runners exhibited greater vertical impact forces and loading rates than a group of uninjured runners. In a study using similar methodology\(^ {48}\), it was concluded that runners who have developed patellofemoral pain syndrome display greater active vertical forces than uninjured control subjects. Although no other studies have found vertical active forces to be a risk factor for overuse running injuries, it should be pointed out that many researchers who have studied the contribution of kinetic variables to overuse running injuries have not reported active forces in their studies. So, it is possible that this variable may actually be a risk factor that has not been examined extensively.
Another risk factor that has been associated with overuse running injuries is the pressure distribution under the foot during running. Willems et al. 44 found that runners who sustained an overuse injury had an increased amount of pressure under the medial side of the foot at midstance compared to uninjured runners. It is very possible that this factor could combine with one of the mediolateral control factors, as these researchers 44 also reported that the injured runners exhibited a significantly greater amount of pronation than the uninjured runners.

Excessive pronation, or rate of pronation has often been implicated as a contributing factor to overuse running injuries 5,19-21,30,48,49. In many of these studies, a static evaluation of pronation was conducted on injured runners, with the results suggesting that injured runners were more often overpronators than uninjured runners. The small amount of experimental evidence that exists relating to these parameters is conflicting. One study 22 which partially supported the speculation of these clinical studies, reported that groups of injured runners exhibited greater maximum pronation angles and had greater maximum pronation velocities than a group of uninjured control subjects. The results were most evident in the group of subjects who suffered from shin splints. Viitasalo and Kivist 50 reported similar results when comparing shin splint sufferers to uninjured control subjects during barefoot running. Somewhat contradictory results were found in another study 5, in which it was reported that runners who had never sustained an overuse injury exhibited a greater pronation velocity than runners who had previously sustained an overuse injury. In a study that compared runners who suffered from PFPS to a group of uninjured control subjects 48, no differences in any mediolateral control variables were found between groups.

Pronation is a combination of ankle dorsiflexion, rear-foot evasion, and forefoot abduction and occurs during the first half of the stance period in running. In weight-bearing exercises such as running, there is a direct relationship between the amount of pronation and internal tibial rotation 51. It is generally believed that the effect that a particular level of impact force has on a body during running is related to the amount and rate of pronation. Pronation, however, is a necessary and protective mechanism during running since it allows impact forces to be attenuated over a longer period of time than would occur without pronation. For this reason, some researchers 52,53 have suggested that it is conceivable that a higher level of pronation is favorable during running, provided that it falls within "normal" physiological limitations, and that it does not continue beyond midstance. After midstance, it is necessary for the foot to become more rigid in preparation of toe-off. Severe overpronators, who may have been excluded from some previous studies, may be at an increased risk of injury due to the potentially large torques generated, and the subsequent increase in internal tibial rotation.

Researchers have focused on the relationship between rear-foot eversion and internal tibial rotation because it was thought to provide insight into where an injury is most likely to occur. It has been suggested that runners with relatively greater rear-foot eversion motion would be at greater risk for foot injuries. Conversely, those with relatively more tibial motion would be at greater risk for knee-related injuries 54-56. However, only two studies have actually related rear-foot:tibia ratios to injury site. Contrary to the expected results, Williams et al. 56 reported that low arched individuals with relatively greater rear-foot eversion had a higher incidence of knee-related injuries and those with high arches and relatively more tibial motion experienced more foot-related injuries. These results were in agreement with Nawoczenski et al. 55 who also found that high-arch runners demonstrated greater relative tibial motion and reported a greater incidence of foot injuries. Therefore greater number of foot injuries in high-arched individuals may be due to other factors, such as foot stiffness, rather than relative joint excursions. Ferber et al. 57 compared the relationship of rear-foot eversion and internal tibial rotation during running in treated runners versus healthy controls to better understand the mechanisms behind running injuries and the success of orthotic devices. No significant differences in relative rear-foot:tibia motion were observed between the treated and control subjects. In addition, no significant differences were noted with the use of.
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orthotic devices in the treated group. These results suggest that foot orthotic devices do not produce significant changes in rear-foot-tibial coupling and therefore may not be a factor to consider in the treatment of running injuries. However, McClay and Manal 54 compared the rear-foot-tibial coupling relationship between runners with normal rear-foot mechanics to those of healthy, but excessive pronators. They reported similar rear-foot eversion excursions during the first half of stance between the groups. The pronator group involved in that study exhibited greater internal tibial rotation excursions resulting in a surprisingly lower coupling ratio than the runners with normal rear-foot mechanics. While the relationship between rear-foot eversion and internal tibial rotation may be related to arch structure, conflicting evidence makes it difficult to understand how this mechanical relationship plays a role in the aetiology or treatment of injuries in runners. Further studies are therefore necessary to better understand how relative rear-foot:tibia motion influence knee injuries.

Predicting running injury risk

The knowledge of the risk factors associated with overuse running injuries would definitely enhance the ability of a medical practitioner to treat these injuries, and to properly advise runners regarding how to modify a training programme to minimise the likelihood of subsequent injuries. Although this type of retrospective treatment of running injuries may assist runners to heal following an overuse injury, a preferable approach to the problem would be to act proactively. A proactive approach could take many forms, such as the education of current and prospective runners regarding a sensible approach to training, proper fitting and selection of shoes, and the establishment of a screening process whereby medical practitioners could identify runners who are at high risk of overuse injuries, and advice these runners accordingly.

In order for a screening process to have widespread appeal, it must be simple to administer and it must be reliable. Unfortunately, there is no such screening process that is currently available for the assessment of running injuries. Minimally, an effective screening process would require an accurate assessment of a subject's anthropometric and biomechanical risk factors, combined with the knowledge of the subject's current state of training, and integrity of the involved musculoskeletal structures. Due to the limited availability of biomechanical testing facilities, and the need for trained personnel, this type of screening process could not realistically become widespread. But assuming that researchers could identify a small number anthropometric and biomechanical parameters associated with overuse running injuries, follow-up studies could then be conducted which would attempt to find easily measurable variables that are highly correlated to these variables determined to be associated with overuse running injuries. Prospective studies are critical to determine which variables could predict injuries and would serve as the screening tool to help prevent injuries. If this is able to be established, then the widespread screening of runners and prospective runners could become feasible. At the present time, a clinical assessment by a trained individual is probably the most effective means of predicting a subject's risk for running injuries, and for establishing an individual training schedule which could provide the positive benefits of a running programme, while minimising the risk of injury 54.

Clinical considerations

Recently several studies have begun to link common clinical variables, such as muscle strength and anatomical alignment, and the development of running-related injuries. For example, Ferber et al. 58 compared differences in kinematic and kinetic patterns of the hip and knee in male and female recreational runners. They reported that female runners exhibited significantly greater peak hip adduction angle and hip frontal plane negative work while running compared to men and speculated that this may be the result of a greater hip width to femoral length ratio observed in women which was found in another study. 59. Female runners also demonstrated a significantly greater peak knee abduction angle and were in a more abducted knee position throughout stance compared to males. These authors speculated that the combination of greater hip adduction and
knee abduction may be related to the greater genu valgum\textsuperscript{60} and increased Q-angle\textsuperscript{59,61,62} reported in females compared to their male counterparts. These results are in support of Malinzak et al.\textsuperscript{63} who also reported that female runners exhibited a significantly greater knee abduction angle throughout the stance phase of running and demonstrated a significantly greater peak hip adduction and hip internal rotation angle compared to men, which may be the result of a greater Q-angle. An increased Q-angle has also been associated with an increase in lateral patellar contact forces\textsuperscript{64} and is thought to play a partial role in the aetiology of PFPS\textsuperscript{48,65}.

Bone structure has been hypothesised to contribute to the risk of developing tibial stress fractures in both male military recruits\textsuperscript{66} and male runners\textsuperscript{67}. Mediolateral tibial width and tibial area moment of inertia are smaller in those male military recruits who develop a stress fracture. In addition, tibial cross-sectional area, a strong determinant of area moment of inertia, is also smaller in male runners with a history of stress fracture. However, no association between tibia cross-sectional area or bone width has been observed in female runners with a history of tibial stress fractures\textsuperscript{68-70}. Therefore other factors, such as training factors and running biomechanics, may be a more effective means of predicting a female runner’s risk for developing stress fractures.

Hip muscle strength has also been suggested to play a significant role in the aetiology and treatment of running-related injuries. For example, the gluteus medius muscle is the primary abductor of the hip joint and the posterolateral fibres also assist in external rotation\textsuperscript{71}. Therefore weakness of this muscle may lead to increased hip adduction and hip internal rotation and thus increased stress to the lower extremity while running. In support of this hypothesis, it has been reported that runners with ITBS exhibited significantly weaker hip abductor muscle strength in the affected limb compared to the unaffected limb and healthy controls\textsuperscript{72}. These authors also reported that following a 6-week hip abductor strengthening program, 22 of 24 ITBS patients demonstrated a 34.9%-51.4% increase in muscle strength and were free of ITBS pain while running. More recently, Niemeth et al.\textsuperscript{73} investigated a group of runners with a variety of musculoskeletal injuries and reported that injured runners demonstrated significantly weaker hip abductor and hip flexor muscles compared to the non-injured limb. In addition, hip muscle strength of the non-injured limb was similar compared to the control group. Therefore these studies suggest that a relationship exists between hip muscle weakness and side-to-side imbalances and overuse injuries. While these studies demonstrate a possible link between anatomical alignment, hip muscle strength, and the development of lower extremity injuries, there is a paucity of literature related to running mechanics and the aetiology of running-related injuries.

Nohren et al.\textsuperscript{74} examined differences in hip biomechanics between runners who had previously sustained ITBS and runners with no knee-related running injuries. The ITBS group exhibited a significantly greater peak hip adduction angle and significantly greater frontal plane knee joint moments compared to the control group. It was speculated that weakness of the hip abductor muscles may result in greater hip adduction which may necessitate greater passive restraint from the IT band and result in the greater frontal plane knee joint moments while running.

**Conclusions**

From a clinical point of view, overuse running injuries could largely be controlled by making adjustments in training variables. A proactive approach, however, may enable practitioners to predict running injury risk based upon biomechanical and anthropometric profiles of runners. Due to the great deal of conflicting evidence related to the biomechanical and anthropometric risk factors, there is a need for a quantitative assessment of the existing literature. It is possible that this could be accomplished by conducting a meta-analysis of the available research. In addition, prospective studies are needed to further identify variables which are most responsible for running injuries, and to help determine easily measurable variables that may correlate to these risk factors.
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Address for correspondence:
Associate Professor Alan Hreljac,
Kinesiology and Health Science
Department, California State University,
Sacramento, 6000 J Street, Sacramento,
CA 95819-6073, USA.
Tel.: +1 (916) 278 5411
Fax: +1 (916) 2787664
Email: ahreljac@csus.edu

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