Impact and Overuse Injuries in Runners

ALAN HRELJAC

Kinesiology and Health Science Department, California State University, Sacramento, Sacramento, CA

ABSTRACT

HRELJAC, A. Impact and Overuse Injuries in Runners. *Med. Sci. Sports Exerc.*, Vol. 36, No. 5, pp. 845–849, 2004. Forces that are repeatedly applied to the body could lead to positive remodeling of a structure if the forces fall below the tensile limit of the structure and if sufficient time is provided between force applications. On the other hand, an overuse injury could result if there is inadequate rest time between applied forces. Running is one of the most widespread activities during which overuse injuries of the lower extremity occur. The purpose of this article is to review the current state of knowledge related to overuse running injuries, with a particular emphasis on the effect of impact forces. Recent research has suggested that runners who exhibit relatively large and rapid impact forces while running are at an increased risk of developing an overuse injury of the lower extremity. Modifications in training programs could help an injured runner return to running with decreased rehabilitation time, but it would be preferable to be able to advise a runner regarding injury potential before undertaking a running program. One of the goals of future research should be to focus on the prevention or early intervention of running injuries. This goal could be accomplished if some easily administered tests could be found which would predict the level of risk that a runner may encounter at various levels of training intensity, duration, and frequency. The development of such a screening process may assist medical practitioners in identifying runners who are at a high risk of overuse injury.
Key Words: CHRONIC INJURIES, GROUND REACTION FORCE, STRESS, RUNNING, IMPACT FORCE

It was established over 100 years ago (51) that biological tissue adapts to the level of stress placed upon it. Repeated applied stresses that are below the tensile limit of a structure lead to positive remodeling if sufficient time is provided between stress applications, whereas inadequate time between stress applications ultimately results in an overuse injury (8,36,41). A fatigue curve has often been used to illustrate how the amount of stress applied to a structure and the number of repetitions of the applied stress are related to injury potential of a particular structure. In the simple situation of a load being applied to a structure at regular intervals, the fatigue curve would look similar to that shown in Figure 1. Injury would result when the structure is subjected to a stress/frequency combination that is above the curve, whereas injury would be avoided in situations where the stress/frequency combination falls below the theoretical curve.

The relationship between stress application and injury demonstrated by the fatigue curve does not imply that stress should be minimized in order to avoid injury. Because this curve is dynamic in nature, there must exist an "optimal" level of applied stress for any biological structure based upon the number of stress applications and the frequency of loading. If a given number of repetitions of this optimal level of stress (or close to it) is applied to a structure, along with an adequate recovery time provided, the structure would increase in strength (11), which would tend to shift the theoretical stress-frequency curve upward. When applied stresses are maintained at very low levels or removed completed, which happens in a number of situations such as prolonged bed rest or space flight (34), tissue resorption may occur, weakening the structure, thereby shifting the theoretical stress-frequency curve downward. This, in turn, would increase the likelihood of subsequent overuse injuries.

In addition to the frequency of application of a stress to a structure, another critical factor affecting the relationship between stress/frequency and injury is the type of stress applied to the structure. One of the most important types of stress, in terms of its effect on the human body, is impact force. Impact force has been defined as a force resulting from the collision of two bodies over a relatively short time period (29). In addition to having a short duration, impact forces generally possess a relatively high magnitude, although there are no defined limits of either magnitude or duration related to impact forces on the human body. In activities such as landing from a jump, impact forces may exceed 10–12 body weights and have a duration of less than 10 ms. During slow walking, impact forces are only slightly greater than body weight and may last for over 50 ms (28,30). Impact forces during running vary in magnitude from approximately 1.5 to 5 body weights and last from about 10–30 ms (31). It has been suggested by several authors (4,6,18,30) that impact forces are associated with overuse running injuries. The purpose of this paper is to examine the literature related to overuse running injuries,

Address for correspondence: Alan Hreljac, Ph.D., Kinesiology and Health Science Department, California State University, Sacramento, 6000 J Street, Sacramento, CA 95819-6073; E-mail: ahreljac@hhs4.hhs.csus.edu.
Submitted for publication January 2003.
Accepted for publication April 2003.

0195-9131/04/3605-0845
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/01.MSS.0000126803.66636.DD

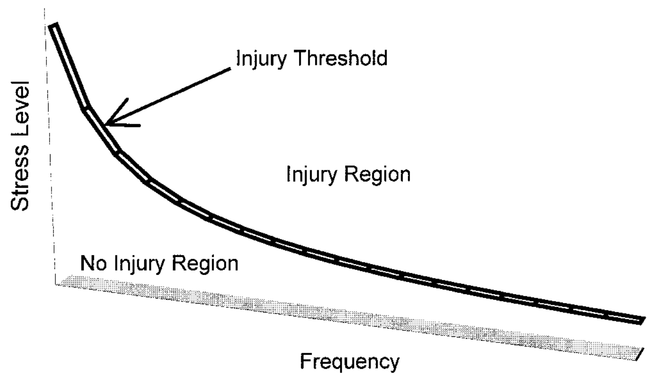

FIGURE 1—Fatigue curve showing the theoretical relationship between stress application and frequency, and the effect of these variables on overuse injury potential.

with an emphasis on how impact forces pertain to these injuries.

IMPACT FORCES DURING RUNNING

When running on level ground at slow to moderate speeds, a large majority of runners are heelstrikers, making first ground contact with the posterior third of the foot (1,31). This running style produces a characteristic vertical ground reaction force-time curve, in which there are two peaks (Fig. 2). The initial force peak, often referred to as the impact peak, occurs within the first 10% of the stance period. The magnitude of the impact force during running is determined by what a runner does before contact with the ground. Depending upon speed and landing geometry, impact forces vary in magnitude from approximately 1.5 to 5 body weights and last for a very brief period of time (<30 ms). A number of variables have an effect on impact forces including the foot and center of mass velocity at contact, the effective mass of the body at contact, the area of contact, and the material properties of the damping elements such as soft tissue, shoes, and the surface of contact (30).

The second vertical ground reaction force peak that is generally produced during heelstrike running is often referred to as the active peak (29). Active forces take place over the latter 60–75% of the stance period and have a duration of up to 200 ms, with the active peak occurring at approximately mid-stance. Due to the relatively long lasting

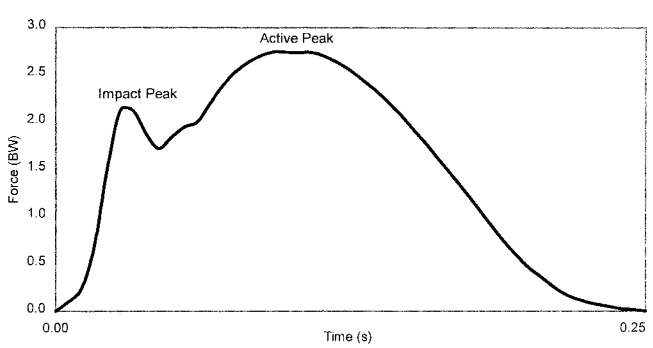

FIGURE 2—Representative vertical ground reaction force versus time curve for running.

time period of the active force, it is considered to be the low frequency component of the vertical ground reaction force curve. Active forces are mainly determined by the movement of a runner during foot contact (30). Although it is impact forces that have most often been implicated in overuse running injuries, evidence exists which suggests that active forces also play a significant role in a variety of overuse running injuries (25).

OVERUSE RUNNING INJURIES

Running is one of the most widespread activities during which overuse injuries of the lower extremity occur. Various epidemiological studies of recreational and competitive runners (3,15,21–23,37,47) have estimated that up to 70% of runners sustain overuse injuries during any 1-yr period. There is no standard definition of an overuse running injury, but several authors (14,20–22) have defined it as a musculoskeletal ailment attributed to running that causes a restriction of running speed, distance, duration, or frequency for a least one week. Examples of overuse injuries that commonly occur during running include stress fractures, medial tibial stress (shin splints), chondromalacia patellae, plantar fasciitis, and Achilles tendinitis.

Although the exact causes of overuse running injuries have yet to be determined, it can be stated with certainty that the etiology of these injuries is multifactorial and diverse (23,36,44). A large majority of the factors identified as causes of overuse running injuries could be placed into three general categories: training, anatomical, and biomechanical factors.

Training variables that have most often been associated with overuse running injuries are running frequency, duration, distance, and speed (15–18,23,24,26,32). Some researchers (12,15,37) have also reported that people who stretch regularly before running experience a higher injury rate than those who do not stretch regularly, although others (2,22) have not found an association between stretching before running and injuries. Although some researchers (22,23,47) have suggested that a previous injury history increases the likelihood of sustaining new running injuries, Taunton et al. (42) did not find a relationship between injury history and running injuries in a group of over 2000 patients with running injuries. Because the studies that have reported an association between training variables and overuse running injuries have generally relied on surveys and/or self reporting for the data acquired, these results must be considered cautiously. In a majority of these studies, a single survey that relied upon respondents to report the level of various training variables (such as running distance) and describe any injuries incurred as a result of running was employed. It has been noted (13) that runners who are monitored more continuously appear to report injury occurrences more accurately than those who receive only a single questionnaire.

Observations from clinical studies (6,18,21) have estimated that over 60% of running injuries could be attributed to training errors. In actual fact, it could be stated that all overuse running injuries are the result of training errors. An individual who has sustained an overuse running injury must have exceeded his/her limit of running distance and/or intensity in such a way that the remodeling of the injured structure predominated over the repair process due to the stresses placed on the structure. The exact "location" of this limit in terms of the forces imparted, the rest periods taken, and the number of repetitions tolerated before injury occurred would differ from one individual to another and would be dependent upon several other variables such as the surface run on, shoes worn, and a variety of anatomical variables. There is no doubt, however, that each runner could have avoided these injuries by training differently based upon individual limitations or in some cases by not training at all. It is important to understand that there is a link between most overuse running injuries and training so that injured runners may be advised correctly to modify their training program if it could be determined what aspect of the training program had been producing deleterious effects. However, with most overuse injuries, there must also exist some underlying anatomical or biomechanical feature that would prevent a runner from training as long, or intensely as another runner before incurring an overuse injury.

Several anthropometric variables have been implicated as causes of overuse running injuries, including high longitudinal arches (pes cavus), ankle range of motion, leg length discrepancies, and lower-extremity alignment abnormalities. There is no consensus among researchers regarding the effect of these variables on overuse running injuries based upon the conflicting results reported in the literature. Whereas several studies (7,24,26,48) have suggested that runners with pes cavus are at an increased risk of injury during running, others (27,38,49) have concluded that arch height is not a risk factor in running injuries. Some studies (14,45) 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, whereas other studies (17,26,48) have reported that runners with greater ankle range of motion have more overuse injuries than runners with less ankle mobility. On the other hand, Montgomery et al. (27) concluded that reduced ankle flexibility is 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. Anthropometric variables that could be grouped together as lower extremity alignment abnormalities such as leg length discrepancies and excessive Q-angle, have been shown to be associated with overuse running injuries by some authors (18,21,40), although others (27,33,38,49) did not find lower extremity alignment abnormalities to be 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 running injuries is the fact that these variables must combine with biomechanical factors which could vary considerably between individuals to produce deleterious effects on the body.

The majority of biomechanical factors that have been linked to overuse running injuries could be classified as either kinetic or rearfoot kinematic variables. Among the kinetic variables that have been speculated to be a cause of overuse running injuries are the magnitude of impact forces (4,6), the rate of impact loading (30), the magnitude of active (propulsive) forces (50), and the magnitude of knee joint forces and moments (39). The assumption that these kinetic variables lead to overuse injuries has generally been based upon theoretical models, although recent experimental studies appear to be in general agreement with these models. Ferber et al. (9) reported that female subjects who had a stress fracture history exhibited greater peak vertical impact ground reaction forces, loading rates, and peak tibial acceleration than a control group of uninjured female runners. Similar results were reported by Grimston et al. (10), who found that female runners who had experienced stress fractures produced significantly greater peak vertical impact ground reaction forces than subjects without stress fractures. These results are in agreement with a study by Hreljac et al. (14) in which previously injured runners (both males and females) were compared with runners who had never sustained an overuse injury. These authors also found that the group of previously injured runners exhibited greater vertical impact forces and loading rates than the uninjured runners.

The rearfoot kinematic variables that have most often been associated with overuse running injuries are the magnitude and rate of foot pronation. Excessive pronation has been implicated as a contributing factor to overuse running injuries in several clinical studies and reviews of overuse running injuries (5,16–19,24,36,41). In many of the clinical studies, a static evaluation of pronation was conducted on injured runners, with the results suggesting that injured runners were often overpronators. Although it has been suggested (43) that static measures of pronation may be used to approximate maximum pronation during gait, the little experimental evidence that exists relating dynamic measures of pronation to overuse running injuries is conflicting. In one study (26), it was reported that groups of injured runners exhibited more pronation and had greater pronation velocities than a group of uninjured control subjects. In this study (26), the results were most evident in the group of subjects who suffered from shin splints. Viitasalo and Kvist (46) reported similar results in a comparison between shin splint sufferers and uninjured control subjects during barefoot running. Somewhat contradictory results were found in a recent study (14) that found that runners who had never sustained an overuse injury exhibited a greater pronation velocity than runners who had previously sustained an overuse injury.

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 is a protective mechanism during running since it allows impact forces to be attenuated over a longer period of time. Pronation is detrimental to a person only if the level of pronation falls outside of "normal" physiological limits (too low or too high), and if it continues beyond midstance (44). After midstance, it is necessary for the foot to become more rigid in preparation of toeoff.

CONCLUSIONS

From the results of these studies, it appears that runners who have developed stride patterns which incorporate relatively low levels of impact forces and a moderately rapid rate of pronation are at a reduced risk of incurring overuse running injuries. Although it may not be possible or practical to teach people to run with a stride that incorporates lower impact forces and greater rates of pronation, there are training habits that runners could adopt that would reduce impact forces and minimize the effects of these forces on the body. Injured runners, or runners who are at risk of sustaining an injury, should be advised to reduce training speed as a means of reducing impact forces because impact forces generally increase as speed increases (35). Longer rest periods should be encouraged to assure that positive remodeling is able to occur between training sessions.

This retrospective treatment of running injuries may assist runners to heal after an overuse injury, but a preferable approach to the problem would be to act proactively. If injury threshold limits of relevant biomechanical and anatomical variables at various levels of training could be established, runners would be able to be advised regarding safe levels of training by means of a screening process. Future research should focus on developing relatively simple screening processes that may assist medical practitioners in identifying runners who are at a high risk of overuse injury.

REFERENCES

1. Bates, B. T., L. R. Osternig, B. Mason, and S. L. James. Lower extremity function during the support phase of running. In: *Biomechanics VI-A*, E. Asmussen and K. Jorgensen (Eds.). Baltimore: University Park Press, 1978, pp. 30–39.
2. Blair, S. N., H. W. Kohl, and N. N. Goodyear. Rates and risks for running and exercise injuries: Studies in three populations. *Res. Q. Exerc. Sport* 58:221–228, 1987.
3. Caspersen, C. J., K. E. Powell, J. P. Koplan, R. W. Shirley, C. C. Campbell, and R. K. Sikes. The incidence of injuries and hazards in recreational and fitness runners. *Med. Sci. Sports Exerc.* 16: 113–114, 1984.
4. Cavanagh, P. R., and M. A. LaFortune. Ground reaction forces in distance running. *J. Biomech.* 13:397–406, 1980.
5. Clarke, T. E., E. C. Frederick, and C. L. Hamill. The effects of shoe design parameters on rearfoot control in running. *Med. Sci. Sports Exerc.* 15:376–381, 1983.
6. Clement, D. B., and J. E. Taunton. A guide to the prevention of running injuries. *Can. Family Physician* 26:543–548, 1980.
7. Cowan, D., B. Jones, and J. Robinson. Medial longitudinal arch height and risk of training associated injury. *Med. Sci. Sports Exerc.* 21:S60, 1989.
8. Elliott, B. C. Adolescent overuse sporting injuries: a biomechanical review. *Australian Sports Commission Program* 23:1–9, 1990.
9. Ferber, R., I. McClay-Davis, J. Hamill, C. D. Pollard, and K. A. McKeown. Kinetic variables in subjects with previous lower extremity stress fractures. *Med. Sci. Sports Exerc.* 34:S5, 2002.
10. Grimston, S. K., B. M. Nigg, V. Fisher, and S. V. Ajemian. External loads throughout a 45 minute run in stress fracture and non-stress fracture runners. In: *Proceeding of the 14th ISB Congress*, Paris, 1993, pp. 512–513.
11. Grimston, S. K., and R. F. Zernicke. Exercise-related stress responses in bone. *J. Appl. Biomech.* 9:2–14, 1993.
12. Hart, L. E., S. D. Walter, J. M. McIntosh, and J. R. Sutton. The effect of stretching and warmup on the development of musculoskeletal injuries (MSI) in distance runners. *Med. Sci. Sports Exerc.* 21:S59, 1989.
13. Hoeberigs, J. H. Factors related to the incidence of running injuries: a review. *Sports Med.* 13:408–422, 1992.
14. Hreljac, A., R. N. Marshall, and P. A. Hume. Evaluation of lower extremity overuse injury potential in runners. *Med. Sci. Sports Exerc.* 32:1635–1641, 2000.
15. Jacobs, S. J. and B. L. Berson. Injuries to runners: a study of entrants to a 10,000 meter race. *Am. J. Sports Med.* 14:151–155, 1986.
16. James, S. L. Running injuries of the knee. *AAOS Instr. Course Lect.* 47:407–417, 1998.
17. James, S. L. and D. C. Jones. Biomechanical aspects of distance running injuries. In: *Biomechanics of Distance Running*, P. R. Cavanagh (Ed.). Champaign, IL, Human Kinetics, 1990, pp. 249–269.
18. James, S. L., B. T. Bates, and L. R. Osternig. Injuries to runners. *Am. J. Sports Med.* 6:40–50, 1978.
19. Jones, D. C. Achilles tendon problems in runners. *AAOS Instr. Course Lect.* 47:419–427, 1998.
20. Koplan, J. P., K. E. Powell, R. K. Sikes, R. W. Shirley, and C. C. Campbell. The risk of exercise: an epidemiological study of the benefits and risks of running. *JAMA* 248:3118–3121, 1982.
21. Lysholm, J., and J. Wiklander. Injuries in runners. *Am. J. Sports Med.* 15:168–171, 1987.
22. Macera, C. A., R. R. Pate, K. E. Powell, K. L. Jackson, J. S. Kendrick, and T. E. Craven. Predicting lower-extremity injuries among habitual runners. *Arch. Intern. Med.* 149:2565–2568, 1989.
23. Marti, B., J. P. Vader, C. E. Minder, and T. Abelin. On the epidemiology of running injuries: the 1984 Bern Grand-Prix study. *Am. J. Sports Med.* 16:285–293, 1988.
24. McKenzie, D. C., D. B. Clement, and J. E. Taunton. Running shoes, orthotics, and injuries. *Sports Med.* 2:334–347, 1985.
25. Messier, S. P., S. E. Davis, W. W. Curl, R. B. Lowrey, and R. J. Pack. Etiologic factors associated with patellofemoral pain in runners. *Med. Sci. Sports Exerc.* 23:1008–1015, 1991.
26. Messier, S. P., and K. A. Pittala. Etiologic factors associated with selected running injuries. *Med. Sci. Sports Exerc.* 20:501–505, 1988.
27. Montgomery, L. C., F. R. T. Nelson, J. P. Norton, and P. A. Deuster. Orthopedic history and examination in the etiology of overuse injuries. *Med. Sci. Sports Exerc.* 21:237–243, 1989.
28. Nilsson, J., and A. Thorstensson. Ground reaction forces at different speeds of human walking and running. *Acta Physiol. Scand.* 136:217–227, 1989.
29. Nigg, B. M. External force measurements with sport shoes and playing surfaces. In: *Biomechanical Aspects of Sport Shoes and Playing Surfaces*, B. M. Nigg and B. A. Kerr (Eds.). Calgary: University Press, 1983, pp. 11–23.
30. Nigg, B. M. Biomechanical aspects of running, In: *Biomechanics of Running Shoes*, B. M. Nigg (Ed.). Champaign IL, Human Kinetics, 1986, pp. 1–25.
31. Nigg, B. M., J. Denoth, and P. A. Neukomm. Quantifying the load on the human body: problems and some possible solutions. In: *Biomechanics VII-B*, A. Morecki, K. Fidelus, K. Kedzior, and A. Wit (Eds.). Baltimore: University Park, 1981, pp. 88–99.
32. Paty, J. G., Jr. Running injuries. *Curr. Opin. Rheumatol.* 6:203–209, 1994.
33. Pollard, C. D., K. A. McKeown, R. Ferber, I. McClay-Davis, and J. Hamill. Selected structural characteristics of female runners with and without lower extremity stress fractures. *Med. Sci. Sports Exerc.* 34:S177, 2002.
34. Rambaut, P. C., and R. S. Johnston. Prolonged weightlessness and calcium loss in man. *Acta Astonautica* 6:1113–1122, 1979.

35. RICARD, M. D., and S. VEATCH. Effect of running speed and aerobic dance jump height on vertical ground reaction forces. *J. Appl. Biomech.* 10:14–27, 1994.
36. ROLF, C. Overuse injuries of the lower extremity in runners. *Scand. J. Med. Sci. Sports* 5:181–190, 1995.
37. ROCHCONGAR, P., J. PERNES, F. CARRE, and J. CHAPERON. Occurrence of running injuries: a survey among 1153 runners. *Sci. Sports* 10:15–19, 1995.
38. RUDZKI, S. J. Injuries in Australian army recruits. Part III: the accuracy of a pretraining screen in predicting ultimate injury outcome. *Mil. Med.* 162:481–483, 1997.
39. SCOTT, S. H., and D. A. WINTER. Internal forces at chronic running injury sites. *Med. Sci. Sports Exerc.* 22:357–369, 1990.
40. STANISH, W. D. Overuse injuries in athletes: a perspective. *Med. Sci. Sports Exerc.* 16:1–7, 1984.
41. SUBOTNICK, S. I. The biomechanics of running: implications for the prevention of foot injuries. *Sports Med.* 2:144–153, 1985.
42. TAUNTON, J. E., M. B. RYAN, D. B. CLEMENT, D. C. MCKENZIE, D. R. LLOYD-SMITH, and D. B. ZUMBO. A retrospective case control analysis of 2002 running injuries. *Br. J. Sports Med.* 36:95–101, 2002.
43. TORBURN, L., J. PERRY, and J. K. GRONLEY. Assessment of rearfoot motion: passive positioning, one-legged standing, gait. *Foot Ankle Int.* 19:688–693, 1998.
44. VAN MECHELEN, W. Can running injuries be effectively prevented? *Sports Med.* 19:161–165, 1995.
45. VAN MECHELEN, W., H. HLOBIL, H. C. G. KEMPER, W. J. VOORN, and H. R. DE JONGH. Prevention of running injuries by warm-up, cool-down, and stretching exercises. *Am. J. Sports Med.* 21:711–719, 1993.
46. VIITASALO, J. T., and M. KVIST. Some biomechanical aspects of the foot and ankle in athletes with and without shin splints. *Am. J. Sports Med.* 11:125–130, 1983.
47. WALTER, S. D., L. E. HART, J. M. MCINTOSH, and J. R. SUTTON. The Ontario Cohort Study of running-related injuries. *Arch. Intern. Med.* 149:2561–2564, 1989.
48. WARREN, B. L., and C. J. JONES. Predicting plantar fasciitis in runners. *Med. Sci. Sports Exerc.* 19:71–73, 1987.
49. WEN, D. Y., J. C. PUFFER, and T. P. SCHMALZRIED. Lower extremity alignment and risk of overuse injuries in runners. *Med. Sci. Sports Exerc.* 29:1291–1298, 1997.
50. WINTER, D. A. Moments of force and mechanical power in jogging. *J. Biomech.* 16:91–97, 1983.
51. WOLFF, J. *The Law of Bone Remodeling*, P. G. J. Maquet and R. Furlong (Trans.). Berlin: Springer-Verlag, 1986 (original work published in 1892), 126 pp.