Evaluation of lower extremity overuse injury potential in runners

ALAN HRELJAC, ROBERT N. MARSHALL, and PATRIA A. HUME

Kinesiology and Health Science Department, California State University, Sacramento, Sacramento, CA 95819-6073; and Sport and Exercise Science Department, University of Auckland, Auckland, NEW ZEALAND

ABSTRACT

HRELJAC, A., R. N. MARSHALL, and P. A. HUME. Evaluation of lower extremity overuse injury potential in runners. *Med. Sci. Sports Exerc.,* Vol. 32, No. 9, pp. 1635–1641, 2000. **Introduction:** The purpose of this study was to identify biomechanical and anthropometric variables that contribute to overuse injuries in runners. **Methods:** Comparisons were made between a group of runners who had sustained at least one overuse running injury and a group of runners who had been injury free throughout their running careers. Groups were well matched in important training variables. Synchronized kinetic and rearfoot kinematic variables of both feet were collected by filming subjects running over a force platform at a speed of 4 $m \cdot s^{-1}$. **Results:** The injury-free group demonstrated significantly greater posterior thigh (hamstring) flexibility, as measured by a standard sit and reach test. This was the only anthropometric variable in which the groups differed. Within each group, there were no significant differences between left and right foot landing for any biomechanical variable. Biomechanical variables that demonstrated significantly lower values for the injury free group were the vertical force impact peak and the maximal vertical loading rate, with the maximal rate of rearfoot pronation and the touchdown supination angle showing a trend toward being greater in the injury free group. **Conclusion:** These results suggest that runners who have developed stride patterns that incorporate relatively low levels of impact forces, and a moderately rapid rate of pronation are at a reduced risk of incurring overuse running injuries. **Key Words:** CHRONIC INJURIES, BIOMECHANICAL FACTORS

Overuse injuries of the musculoskeletal system generally occur when a structure is exposed to a large number of repetitive forces, each below the acute injury threshold of the structure, producing a combined fatigue effect over a period of time beyond the capabilities of the specific structure (8,43). Injuries such as stress fractures, medial tibial stress (shin splints), chondromalacia patellae, plantar fasciitis, and Achilles tendinitis could all be classified as overuse injuries. Running is one of the most common activities during which overuse injuries of the lower extremity occur, as noted by the large number of people who develop these injuries as a result of running. Various epidemiological studies of recreational and competitive runners (3,15,22–24,38) have estimated that between 27% and 70% of runners sustain overuse injuries during any 1-yr period.

The exact causes of overuse running injuries have yet to be determined. It could only be stated with certainty that the etiology of these injuries is multifactorial and diverse (24,39,47). The many factors attributed to causing running injuries could be placed into three general categories: training, anatomical, and biomechanical variables. Training vari-

ables that have been identified as contributing factors to running injuries are excessive running distance or intensity of the training program, rapid increases in weekly running distance or intensity, and the surface and shoes chosen for training (15–18,24,25,27,35). Some researchers (13,15,38) have also reported that people who stretch regularly before running experience a higher injury rate than those who do not stretch regularly, although others (2,23) have not found an association between stretching before running and 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.

A large number of anatomical factors have been implicated as possible causes of overuse running injuries, although the results from various studies have been conflicting. A number of authors (7,25,27,52) have reported that runners with high longitudinal arches (pes cavus) are at an increased risk of injury during running, whereas others (29,41,54) did not find arch height to be a risk factor in running injuries. Another anatomical factor that has been suggested to be related to running injuries is the range of motion in plantar and dorsiflexion. Some studies (18,27,52) have found that runners with a greater range of motion in plantar flexion have more injuries than runners with less mobility in plantar flexion. On the other hand, van Mechelen et al. (48) reported no difference in ankle range of motion between a group of runners with lower extremity injuries

and a group of controls, and Montgomery et al. (29) suggested that 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, rearfoot varus, and leg length discrepancies could be grouped together as lower extremity alignment abnormalities. These factors, and other problems related to alignment of the body have been reported to be associated with overuse running injuries by some authors (17,22,43), although others (29,42,50,54) did not find lower extremity alignment abnormalities to be associated with an increased risk of overuse injuries in runners.

The majority of biomechanical factors that have been linked to overuse running injuries could be classified as either kinetic variables 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 (31), and the magnitude of active (push off) forces (55). There seems to be little experimental evidence to support these speculations, although Messier et al. (26) did report that several kinetic variables, including the magnitude of active forces were significant discriminators between groups of injured and uninjured runners. In addition, Grimston et al. (11) found that female runners who had experienced stress fractures had significantly greater vertical ground reaction forces than subjects without stress fractures. The rearfoot kinematic variables that have most often been associated with overuse running injuries are the magnitude and rate of foot pronation (generally quantified by measuring calcaneal eversion). Several clinical studies and reviews of overuse running injuries (6,16–18,20,25,39,44) have suggested that excessive pronation is a contributing factor to overuse running injuries, although little experimental evidence (27,49) exists to support these contentions.

Over 60% of running injuries have been attributed to training errors (6,17,22,35). From a medical practitioner's viewpoint, 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 problem that would prevent a runner from training as long, or intensely as another runner before incurring an overuse injury.

The purpose of this investigation was to evaluate the lower extremity overuse injury potential of runners by identifying biomechanical stride characteristics and anatomical features that may predispose a runner to overuse injuries, while attempting to control for training variables by matching groups in terms of several important factors related to training. A number of variables were analyzed separately, and in combination with each other to determine which variables, or combinations of variables, contributed most to effecting lower extremity overuse injuries in runners.

METHODS

Subjects. Two groups of 20 runners (8 female, 12 male each), recruited from local running, orienteering, and triathlon clubs in the Auckland area participated in this project. An injury-free (IF) group consisted of runners who had never sustained an overuse injury throughout their running careers, whereas an injured (I) group was made up of runners who had suffered at least one overuse injury that could be attributed to running. Injured runners were not grouped by specific injury diagnosis because there does not appear to be any evidence to suggest that particular anatomical or biomechanical problems result in specific injury patterns (34). However, the I group was restricted to runners who had been injured at or below the knee, which accounts for the sites of approximately 75% of overuse running injuries (34,35,39,41). A majority of the injured runners had suffered multiple overuse injuries, and bilateral injuries, which prevented comparisons to be made between an injured and uninjured limb. At the time of the study, all injured runners were pain free, and had returned to training regularly for at least 3 months after recuperation from their most recent injury. All subjects in the study had been running on a regular basis for a minimum of 3 yr. In several instances, runners who had trained together had different injury histories, so were subsequently placed in different groups. Before data collection, all subjects signed informed consent forms.

Data collection procedures. Data pertaining to training were obtained through the use of a questionnaire and an interview process. Training variables gathered in this way included weekly running distance, workout intensity (average training pace), typical running surface, shoes worn, changes in training schedule over the previous year, and cross-training and stretching habits.

Anatomical (anthropometric) data collected included height, weight, longitudinal arch height, footprint index, and hamstring and ankle flexibility. To measure longitudinal arch height, subjects stood upright with both feet placed against a 10-cm-wide board, defining a neutral position. The board was removed while the subject kept one foot in the same position, resting the contralateral foot on a box (about 30 cm in height) placed slightly in front of the subject. Calipers (with 0.1-mm precision) were then used to measure the highest point on the soft tissue boundary of the medial plantar curvature. The procedure was repeated for both feet. Measurements were made twice for each foot, with results being averaged. If results differed by more than 3 mm, a third measurement was taken. The described method of measuring longitudinal arch height has been determined to have high reliability by previous researchers (14,30). The footprint index was calculated as the ratio of the width of the weight bearing area of the midfoot and the width of the weight bearing area of the forefoot. A cavus foot was indicated by an index of close to zero, while a planus (flat) foot was indicated by an index close to one (27). To obtain the data for calculating the footprint index, a digital photograph was taken from directly behind the subject while the
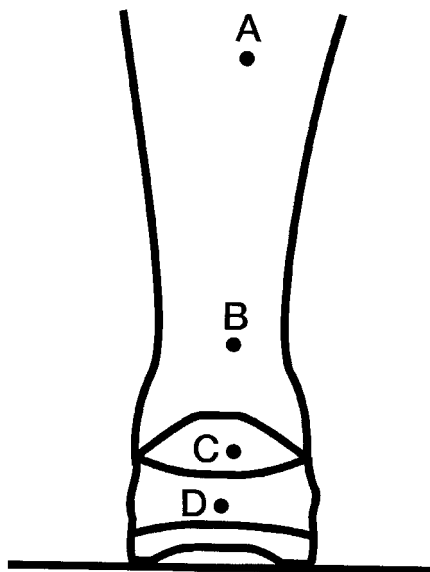
Figure 1—Marker placement on right leg.

Figure 2—Definition of Achilles tendon and rearfoot angles.

subject stood on a glass plated platform with his/her feet in a neutral position (see above). A mirror was placed under the platform at an angle of 45° to obtain a view of the plantar surface of the subject's feet. The picture of the plantar surface of the feet was digitized to obtain the measurements required to calculate a footprint index for both feet. Hamstring flexibility was measured using a standardized sit and reach test. Before this measurement, subjects were allowed the opportunity to warm up in a manner and duration of their choice. The best of three trials was recorded as the hamstring flexibility measure for each subject. Total ankle range of motion in the sagittal plane was measured by digitizing markers (using procedures similar to those described for obtaining biomechanical data) placed on the head of the fibula, the lateral malleolus, and the head of the fifth metatarsal while subjects repeatedly maximally plantar and dorsiflexed from a seated position with the foot comfortably raised off the floor. The maximum range of motion of a single trial was considered to be the ankle range of motion. Range of motion was not determined separately for plantar and dorsiflexion. The procedure was repeated for both ankles.

All biomechanical data were acquired in a laboratory setting as subjects ran over a floor mounted force platform (480 Hz) at a speed of 4 m·s^{-1} while wearing their normal running footwear. Simultaneously, the motion of four reflective markers, placed on the posterior aspect of the landing leg, defining the leg and rearfoot segments (Fig. 1) were recorded by a system of four Motion Analysis Falcon cameras at a frequency of 120 Hz. Kinetic and kinematic data collection was synchronized. Running speed was monitored by three sets of photocell timers (two timing intervals), placed 1.5 m apart, with one located at the midpoint of the force platform, and the other two placed equidistantly before and after the midpoint of the force platform. A trial was considered acceptable when a subject maintained a constant speed (within 3% of the test speed of 4 m·s^{-1}) throughout
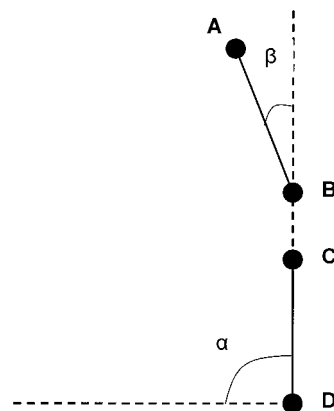
both timing intervals, landed with the appropriate foot completely on the force platform, and maintained a normal stride pattern (i.e. did not "target" the force platform). The order of the landing foot was randomized, with one acceptable trial of each landing foot collected. Before the data collection period, subjects were given as much time as desired to warm up.

A standard direct linear transformation (DLT) method (1) was used to reconstruct three dimensional coordinate data of the four markers. The coordinate system was oriented so that the positive x-direction was in the direction of the forward movement, the positive z-direction was vertically upward, and the positive y-direction was to the subject's left, which was the same coordinate system used for force platform data. Before the running trials, a calibration trial, in which the subject stood with both feet in a neutral position, was obtained for each leg. The neutral standing posture was assumed to display an Achilles tendon angle, β (angle between the leg and rearfoot segments, Fig. 2), of 0°. In the running trials, a negative value of β represented pronation, whereas a positive β represented supination (5). The rearfoot angle, α, was defined as the angle between the rearfoot segment and the horizontal.

The raw 3-D coordinate data were smoothed using a fourth order, zero lag, Butterworth filter, with optimal cutoff frequencies uniquely chosen for each coordinate of all markers using the residual method (53). Angular data were determined from the smoothed coordinate values, with angular velocities calculated using finite difference equations.

Biomechanical variables recorded included: contact time (T), vertical force impact peak (F_{zi}), maximal vertical loading rate (G_{zi}), maximum active force peak (F_{za}), maximum push-off force (F_{xmax}), Achilles tendon angle at touchdown (β_o), maximal angle of pronation (β_{max}), total change in Achilles tendon angle ($\Delta\beta$), and maximal pronation velocity (MPV). The data for all kinetic variables were normalized to body weight (BW) to allow for comparison between subjects of different mass. Although data were collected and analyzed for both left and right foot landing, the reported value of all biomechanical variables represents the average of the left and right foot landings.

Statistical analysis. All training variables were analyzed first, and separately, to determine whether the groups

TABLE 1. Anthropometric data for both groups.

Variable	P-Value	Group I (N = 12)	IF (N = 12)
Height (cm)	0.53	170.9 ± 9.5	172.7 ± 8.5
Weight (N)	0.90	672.6 ± 138.2	677.6 ± 103.4
Sit and Reach (cm)	0.05	−3.7 ± 11.6	3.2* ± 10.2
Left Long. Arch Height (mm)	0.19	21.0 ± 3.7	19.4 ± 3.9
Right Long. Arch Height (mm)	0.64	20.0 ± 4.4	19.3 ± 4.9
Left Ankle ROM (°)	0.52	60.5 ± 8.1	62.0 ± 6.6
Right Ankle ROM (°)	0.80	61.2 ± 7.1	61.8 ± 7.3
Left Footprint Index	0.25	0.30 ± 0.14	0.35 ± 0.14
Right Footprint Index	0.52	0.32 ± 0.15	0.35 ± 0.14

* $P < 0.05$.
Values shown for each group are: mean ±1 SD.

TABLE 2. Biomechanical data for both groups.

Variable	P-Value	Group I (N = 12)	IF (N = 12)
T (ms)	0.42	216 ± 21	220 ± 21
F_{zi} (BW)	0.004	2.40* ± 0.41	2.13 ± 0.42
G_{zi} (BW·s^{-1})	0.001	93.1* ± 23.8	76.6 ± 19.5
F_{za} (BW)	0.60	2.73 ± 0.30	2.69 ± 0.29
F_{xmax} (BW)	0.90	0.28 ± 0.15	0.28 ± 0.12
β_o (°)	0.07	4.0 ± 4.1	5.9 ± 6.7
β_{max} (°)	0.22	−7.6 ± 3.9	−6.9 ± 4.4
$\Delta\beta$ (°)	0.13	11.7 ± 4.1	12.8 ± 5.1
MPV (°·s^{-1})	0.08	−289 ± 106	−334 ± 126

* $P < 0.05$.
Values shown for each group are: mean ±1 SD.
Variables are: contact time (T), vertical force impact peak (F_{zi}), maximal vertical loading rate (G_{zi}), maximum active force peak (F_{za}), maximum pushoff force (F_{xmax}), Achilles tendon angle at touchdown (β_o), maximal angle of pronation (β_{max}), total change in Achilles tendon angle ($\Delta\beta$), and maximal pronation velocity (MPV).

were actually matched in important training variables within limits of statistical significance. To accommodate statistical procedures, all dichotomous training variables, such as stretching habits (Do you stretch before running? After running?) were assigned a value of zero for a "no" answer, and a value of one for a "yes" answer. There was no need to make adjustments to continuous variables. All variables were compared between groups using a multivariate analysis of variance (MANOVA), with the significance level set at $\alpha = 0.05$. If the groups were deemed to be sufficiently matched in training variables, anatomical and biomechanical variables would be compared between groups, using a similar MANOVA procedure to test for differences between groups in the mean values of the dependent variables.

RESULTS

There were no significant differences between the groups in average running pace (I = 5.6 ± 0.7 min·km^{-1}, IF = 5.4 ± 0.8 min·km^{-1}), weekly distance run (I = 77.8 ± 43.4 km, IF = 72.5 ± 39.6 km), or any of the other training variables that were analyzed during this study, indicating that the groups were well matched in terms of these important training variables.

The only anatomical variable in which there was a significant difference between groups was the performance in the sit and reach test. In this test, the IF group performed significantly better than the I group (IF = 3.2 ± 10.2 cm, I = −3.7 ± 11.5 cm). There were no significant contralateral differences within or between groups in measurements that were taken on both sides of the body. The results obtained for all anatomical variables are shown in Table 1.

Biomechanical data for both groups are summarized in Table 2. The values reported represent the average of the left and right foot landings. Within each group, there were no significant differences between left and right foot landing for any variable. The only biomechanical variables which exhibited significant differences between groups were the vertical force impact peak (F_{zi}), and the maximal vertical loading rate (G_{zi}).

DISCUSSION

The results of the present study suggest that subjects who utilize a running stride characterized by relatively low im-

pact forces and a moderately rapid rate of pronation are at a reduced risk of incurring overuse running injuries. The experimental groups did not differ significantly in several important training factors, allowing for a between-group comparison of anatomical and biomechanical variables without the confounding factor of differences in training. This does not imply that training variables did not play an important role in several of the injuries that were reported by subjects. Although training variables were matched at the time of data collection, it is possible that some of the injured runners had modified their training program after repeated injuries. Within the year preceding testing, however, there were no significant differences in training modifications.

In the present study, subjects were tested while wearing their own footwear. It has been found that running shoes have an effect on biomechanical stride characteristics (31). However, controlling footwear by forcing subjects to wear similar, but unfamiliar running shoes would likely alter a subject's biomechanical stride characteristics from a "normal" pattern. In this study, comparisons between groups could only be valid if the data collected were representative of a subject's normal running stride characteristics. It was felt that there would be a greater chance of achieving this condition by testing subjects while wearing their "normal" running footwear.

The testing speed (4 m·s^{-1}) during this study was greater than the average training speed for the majority of subjects. Several preliminary subjects were tested at a range of running speeds, with a majority indicating that the testing speed was the most comfortable pace for running down a relatively short runway. Analysis of the results from these preliminary subjects demonstrated that there were similar patterns in the data at all speeds tested, suggesting that the pattern of results would be consistent over a range of running speeds.

Training variables. Although there appears to be a consensus among researchers (15,17,22,24,39) that variables relating to training are the cause of a large majority of overuse running injuries, in a general sense, it could be stated that *all* overuse running injuries are the result of training errors. It is evident that any individual who has suffered 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 running surface, shoes worn, and a variety of anatomical variables. However, there is no doubt that each individual could have avoided these injuries by training differently based upon individual limitations, or in some cases by not training at all. Although it is important to recognize that correct training methods may reduce the risk of running injuries, there are undoubtedly anatomical and/or biomechanical variables that determine the limits of an individual's injury free training program.

Anatomical variables. The sit and reach test, in which the IF group performed better than the I group, was the only anthropometric variable that differed significantly between the groups. This result appears to support the speculation of several authors (6,25,46,51) who have suggested that a lack of flexibility could lead to overuse injuries in runners. Lack of flexibility may increase the stiffness of a muscle, possibly placing more stress on the adjacent joints. Poor flexibility could also be indicative of a muscular imbalance, which would facilitate the earlier onset of fatigue, thereby leading to improper mechanics during the latter stages of a run. Interestingly, there is no experimental evidence to demonstrate that stretching before or after running reduces the risk of overuse injuries (2,9,13,48). Similar results were found in the present study, with no differences reported in stretching habits between groups. These results suggest that maintaining flexibility of the hamstrings may be important in preventing overuse running injuries, while the use of stretching as a means of warm up or cool down is not effective in reducing overuse injury risk.

Longitudinal arch height, footprint index, and ankle flexibility (among other anatomical variables) were not found to differ significantly between the groups. Although the results of previous experimental studies that have analyzed these variables have been mixed, the lack of a difference between the groups was surprising based upon the diagnoses hypothesized in several clinical studies (6,17,19,22,25) and reviews (16,39,44–46) in which these variables have been associated with a variety of overuse running injuries. It is possible that the relatively small sample size (compared with some clinical studies) in the present study prevented differences from being detected. It is also possible that runners with fairly severe anatomical abnormalities would be less likely to join running clubs since running distance and intensity for this population may have to be minimal to reduce injury risk. If this were the case, these runners would not have been recruited into this study.

Overall, the present study did not find any evidence that an orthopaedic screening process would be successful as a tool for predicting running injuries. This supports the conclusions of Rudzki (42), who reported that a pretraining orthopaedic screening had poor sensitivity in detecting military recruits who were at risk of overuse injuries during training.

Biomechanical variables. In the present study, there was a trend toward more rapid pronation ($P = 0.08$) and greater touchdown supination ($P = 0.07$) in the IF group, although there were no significant differences between groups in any rearfoot kinematic variable. These results contradict some previous studies (10,27,49) which reported that injured subjects exhibited greater total change in Achilles tendon angle, and greater maximum pronation velocity than uninjured control subjects. Methodological differences may account for some of the discrepancies in results. In these cited studies, currently injured (at the time of the study) subjects were tested, whereas the present study utilized subjects who had been chronically injured but were pain free at the time of the investigation. Because pronation during stance is necessary to dissipate stress (44), it is possible that the increased pronation noted by other researchers was a protective mechanism designed to attenuate high-impact forces. In actual fact, high impact forces over a prolonged period of time may have been a major contributing factor to the injuries. It is conceivable that a higher level of pronation is favorable during running, provided that it falls within "normal" physiological limitations. Generally, pronation allows forces to be attenuated over a longer period of time, although it has been stated (44) that pronation must end before midstance to allow the foot to become more rigid for push off. In this study, the IF group pronated more rapidly, which may have assured that the foot became stable before push off. Severe overpronators may be at an increased risk of injury due to the large torques generated and the potential instability associated with running in this style. However, in this study, none of the subjects fit the profile of a "severe" overpronator.

Both the magnitude and rate of impact loading were found to be significantly greater in the I group compared with the IF group, indicating that these variables may be associated with overuse running injuries as has been hypothesized by several authors (4,17,30,31,37) even though there has been scant experimental evidence to support these speculations. These results also seem to comply with some general overuse injury models (21,33) which suggests that repeated excessive loading causes functional adaptations, leading to further overload, eventually causing tissue injury, and the emergence of clinical symptoms. Excessive impact forces and rates of loading were the most important factors differentiating the I from the IF group of runners in this study. It is logical to assume that the musculoskeletal system of runners could recover and repair itself rapidly enough from relatively low levels of impact forces, but some threshold level of impact force, repeated for some threshold level of repetitions would result in injury. It is also likely that a runner who has maintained a training program in which these threshold levels have not been exceeded would have the various related structures remodeled in such a manner as to become more resistant to injury.

The combination of factors that most clearly differentiated the IF from the I group was lower values of F_{zi} and greater values of MPV. Both of these factors could be

thought of as protective mechanisms during running. Runners who have developed stride characteristics that incorporate both of these strategies seem to be at the lowest risk of developing overuse running injuries.

CONCLUSIONS

The stride characteristics which appear to lead to a reduced risk of overuse running injuries are relatively low impact forces and a moderately rapid rate of pronation. Because impact forces generally increase as speed increases (12,28,32,36), it would be prudent to advise injured runners to reduce training speed as a means of reducing impact forces. Future research in this area should focus on establishing a criterion tolerance level of the lower extremity to repetitive impact loading, in terms of magnitude and number of repetitions, which would enable medical practitioners to act more proactively in the area of overuse running injuries. The ultimate goal of this line of research should be to work toward injury prevention by identifying potential problems before they result in injury.

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.

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