A Multifactorial Approach to Overuse Running Injuries: A 1-Year Prospective Study

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Background: Because of the complex and multifaceted nature of running injuries, a multifactorial approach when investigating running injuries is required.

Hypothesis: Compared with uninjured runners, injured runners would exhibit different running biomechanics, display more fatigue changes, and would run a greater weekly running volume; more injured runners would also report having a previous injury.

Study Design: Prospective cohort study.

Level of Evidence: Level 4.

Methods: At commencement of the study, data were collected on demographics, anthropometrics, training history, previous injury history, and center-of-mass accelerations during a long-distance overground run. Participants completed weekly training diaries and were monitored for 1 year for an injury.

Results: A total of 76 runners completed the study, with 39 (22 male; 17 female) reporting an injury. Compared with male uninjured runners, male injured runners were heavier and ran a greater weekly distance. Male runners (injured and uninjured) exhibited increases in mediolateral center-of-mass accelerations during the run. Compared with female uninjured runners, female injured runners were heavier, ran with longer flight times and lower step frequencies, and more of them had reported an injury in the previous year and had increased speed training in the weeks prior to injury. Over 60% of male injured runners and over 50% of female injured runners had increased their weekly running distance by >30% between consecutive weeks at least once in the 4 weeks prior to injury.

Conclusion: Factors that may be related to injury for male runners include being heavier, running a greater weekly distance, and exhibiting fatigue changes in mediolateral center-of-mass accelerations. Factors that may be related to injury for female runners include being heavier, having an injury in the previous year, running with longer flight times and lower step frequencies, and increasing speed training prior to injury. Increases in weekly running distance in 1 consecutive week (particularly >30%) needs to be monitored in training, and this along with the other factors found may have contributed to injury development.

Clinical Relevance: This study found that multiple factors are related to running injuries and that some factors are sex specific. The findings can aid in injury prevention and management.

Keywords: fatigue; running; overuse; injury; training

Long-distance running is popular worldwide, yet unfortunately, running injuries are common.[17] Because of the repetitive nature of running, the majority of injuries are overuse.[17] Prospective studies have reported multiple factors related to injury, including previous injury,[4] demographic and anthropometric characteristics,[4,32] biomechanical issues,[23,24] and training factors.[19,35]

The majority of running injuries are attributed to training errors, including excessive running distance, a high training intensity, and rapid increase in weekly running distance or

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intensity.[12] Prospective studies investigating training factors and injury have mostly used "baseline" training data, including running distance, frequency, terrain, and surfaces[19,32,35]; however, these do not take into account training changes that may occur in the future and at the time of injury.

In addition to training factors, a previous injury, especially one sustained in the previous year,[26] is consistently reported as a factor that increases injury risk in runners.[13,26,33] Therefore, it is important to also investigate whether this could be a factor in injury development. Body mass, height, and body mass index may also contribute to injury.[13,20,33] This is most likely because of the large variation of participant and training characteristics of runners.

Fatigue is another factor that alters running biomechanics and may increase the risk of injury,[37] yet there is a paucity of research about the relationship between fatigue and overuse injuries. Until recently, running studies have mostly been conducted in a laboratory during treadmill or short overground runs, which does not provide a true representation of long-distance "in-field" running.[27,31] A single triaxial accelerometer placed on the low back provides a valid measure of running movement near the center of mass (COM) during a prolonged overground run.[38] These devices collect data for an extended period of time, which allows identification of fatigue-related changes during "in-field" running.[3,7,36] Alterations in running biomechanics may begin early into a long-distance run and continue throughout,[3,7,36] highlighting a need to analyze data regularly to understand the influence fatigue may have on running injuries. Previous studies have reported changes in COM acceleration–derived variables with fatigue, including a decrease in dynamic postural stability in mediolateral and anteroposterior directions,[14,29] a decrease in step regularity,[29] and an increase in contact time.[7] How these fatigue-related changes may contribute to injury is not yet understood.

The aims of this 1-year prospective study were to undertake a multifactorial approach in male and female runners and (1) investigate if participant, previous injury, training characteristics, COM acceleration–derived variables, and fatigue changes in these variables were different between those who do and do not develop an injury and (2) investigate whether changes or increases in training occurred prior to injury. We hypothesised that (1) more injured runners would have reported having a previous injury, (2) there would be significant differences in running COM acceleration–derived variables between injured and uninjured runners, (3) injured runners would display more fatigue changes, (4) injured runners would have greater weekly running volume during the 1-year follow-up period, and (5) some of these factors would be different for male and female runners.

METHODS

Participants

A group of 92 recreational and competitive runners (57 male; 35 female), were recruited from local running clubs. Participants were included if they were aged 18 to 65 years, ran at least 30 km per week, had been regularly running for at least 1 year, and were injury-free at the time of data collection. Participants were excluded if they had any neurological deficits, known lower limb deformities (eg, leg-length discrepancies), a systemic disease or any medical condition that may affect their running, pregnancy, or a skin sensitivity to adhesive sprays or double-sided tape. Participants provided written informed consent before participating in the study. The study was approved by James Cook University's human research ethics committee.

Data Collection

Participant Characteristics

At the commencement of the study, participant characteristics (age, sex, height, weight), training history (years running, weekly distance, sessions per week), and previous injury history were collected via a questionnaire.

Acceleration Data Collection

A wireless triaxial accelerometer (52 mm × 30 mm × 13 mm, mass 23 g; resolution 16-bit, full-scale range ±16*g*, sampling at 250 Hz; SABEL Labs) collected acceleration data and was positioned over the L5/S1 vertebrae, which corresponds to the COM,[3,38] and attached using double-sided adhesive foam tape. A moisture-wicking fabric was then placed around the accelerometer and secured with an elastic bandage.

Running Protocol

Participants completed 20 laps (8 km) of an outdoor 400-m athletics track at a time-trial pace. Individualized test speeds are important when runners differ in skill level and running speed.[25,28] A stopwatch recorded the participants' finishing time and the time when they passed the 70-m line on the home straight of the running track for each lap. This ensured that acceleration data were analyzed at the same point each lap and when participants were running on the straight, as running movement changes when running the curves of the track.[1]

Training Data

Training data were collected via diaries emailed out and commenced the week after the run. The diary collected information on running sessions per week, distance and duration of runs, type of run and running surface, and duration of other sports undertaken. Participants were free to continue their own training schedules.

Data Analysis

Speed and Acceleration-Derived Variables

Average lap speed and acceleration data were analyzed at the 70-m point on the home straight on laps 2 (730 m), 6 (2330 m), 10 (3930 m), 14 (5530 m), and 18 (7130 m). Average running speed was calculated for these laps using the times collected at the 70-m mark for that lap and the consecutive lap.

Analysis of acceleration data was performed using a custom written program in MATLAB R2014a (The Mathworks Inc). Data were filtered using a zero-lag fourth-order low-pass Butterworth filter with a cutoff frequency of 25 Hz. Spatiotemporal variables of contact time, flight time, and step frequency were calculated from vertical acceleration data.[8,28] Dynamic loading measures during stance were determined using peak positive vertical (impact) and peak negative anteroposterior (braking) accelerations.[3,28] A higher absolute value indicates greater impact or braking accelerations. Dynamic postural stability was measured using ratio of root mean square (RMSR) and represents the ratio between root mean square (RMS) in each acceleration direction normalized by the magnitude of RMS in all directions.[30] A higher RMSR value indicates a greater proportion of acceleration in that direction to overall movement. Step and stride regularity were calculated in each acceleration axis using unbiased autocorrelation procedures.[21,29] A lower regularity value indicates a decrease in step or stride regularity and more irregular or unsmooth steps or strides. The detailed procedures of acceleration data analysis and calculation of the variables have been explained previously.[36]

Prospective Training Data

Average weekly values were calculated for all runners for all training variables—that is, average kilometers per week; average duration (minutes) per week; average frequency per week; average duration of terrain, surface, and type of run; and average duration of other exercise. These variables were compared between injured and uninjured runners.

To investigate changes in training prior to injury for injured runners, 2 analyses were performed. First, an observational analysis was performed to identify increases in training distance between consecutive weeks in the 4 weeks prior to injury, by calculating the percentage difference between each consecutive week. The difference was then categorized into 4 groups: progression <10%, >10%, >30%, and >50%. These groups were chosen because of the common belief that an increase of 10% in training distance is a safe weekly progression, and runners who increased weekly distance by >30% were more vulnerable to injury.[22] Runners were also grouped into a higher percentage group of >50% because of the number of runners observed to have these increases in this study.

Second, training variables for the entire prospective study period were compared with the average values of the 1, 2, 3, and 4 weeks prior to injury. This analysis was performed to investigate whether there were changes in the specific training variables in the weeks prior to injury. Five injured runners were excluded from this analysis, as they had sustained an injury within 4 weeks from the commencement of the study.

Running Injuries

During the 1-year study, participants reported immediately if they sustained a running injury. A running injury was defined as "any pain of musculoskeletal origin attributed to running by the runner themselves and severe enough to prevent the runner from performing or completing at least 1 training session."[10,19,35] All injured runners were assessed by an experienced health or medical professional.

Statistical Analysis

Statistical analyses were performed using IBM Statistical Package for Social Sciences (SPSS) software, version 22 (IBM Corp). Results were considered statistically significant at $P < 0.05$. Outliers were identified by using box-and-whisker plots in SPSS. All extreme outliers, which were 3 times the interquartile range, were excluded from the relevant analyses. Participant characteristics, training history, previous injury, speed, COM acceleration–derived variables, and prospective training data were compared between male and female injured and uninjured runners. Speed and COM acceleration variables were compared between injured and uninjured runners at lap 2 (730 m), which is approximately 10% of the run, when a runner would be in a "natural" stride. Independent *t* tests were used to compare all injured and uninjured runners on variables of interest. The Levene statistic for homogeneity of variances was used. If homogeneity was violated then the 'equal variances was not assumed' result was used. Mann-Whitney *U* tests were used to compare male injured and male uninjured runners and female injured and female uninjured runners for variables of interest. Effect size was computed for differences between groups; an *r* of 0.1 represents a small effect size, 0.3 represents a moderate effect size, and 0.5 represents a large effect size.[5]

To investigate fatigue-related changes during the run for male and female injured and uninjured runners, repeated-measures analyses of variance (ANOVAs) were performed comparing average speed and acceleration-derived variables at the first measurement time point (lap 2) with each of the subsequent time points (eg, laps 6, 10, 14, and 18).

To investigate if fatigue-related changes were different between injured and uninjured male and female runners, 2-way repeated-measures ANOVAs were performed for average speed and acceleration-derived variables at laps 2 and 18, where laps (time) were the repeated measures. Laps 2 and 18 were only used in this analysis to reduce the number of variables analyzed and reduce the risk of a type I error. Furthermore, these 2 laps have exhibited the most consistent changes in COM acceleration variables compared with other laps during a long-distance run.[7,36] Sphericity was verified by the Mauchly test for sphericity. If the assumption of sphericity was violated, significance of the *F* ratios was adjusted to the Greenhouse-Geisser procedure. Post hoc tests were performed using Bonferroni adjustment. Effect size, η^2, of 0.02 represents a small effect size, 0.13 represents a medium effect size, and 0.26 represents a large effect size.[2]

To investigate changes in training prior to injury, Wilcoxon signed-rank tests were performed for injured runners, comparing average values of all running training variables for the entire prospective study period with the 1, 2, 3, and 4 weeks of training prior to injury.

RESULTS

Participants

Of the 92 runners recruited, 76 (82.6%) completed the study (45 male and 31 female runners). Seven participants withdrew from the study because of personal reasons, time constraints, and work commitments, and 9 were lost during the prospective study period due to incomplete diaries or were unable to be contacted.

Running Injuries

Thirty-nine runners (51.3%; 22 male [48.9%] and 17 female [54.8%]) sustained a running injury. The most common area of injury was the Achilles/calf complex (28.2%), followed by the lower leg/ankle (15.4%), hip/pelvis area (15.4%), hamstring (12.8%), knee (12.8%), foot (7.7%), and low back (7.7%).

Participant Characteristics and Previous Injury

Male injured runners had a significantly greater body mass than uninjured male runners ($P = 0.006$; $r = 0.39$) (Table 1). Female injured runners also had a significantly greater body mass ($P = 0.028$; $r = 0.39$), and significantly more injured female runners reported sustaining a running injury in the previous year ($P = 0.002$; $r = 0.53$) (Table 1).

Average Speed and Acceleration-Derived Variables

There were no significant differences observed at lap 2 between male injured and uninjured runners ($P > 0.05$). Female injured runners demonstrated significantly longer flight times ($P = 0.010$; $r = 0.50$), and lower step frequencies ($P = 0.002$; $r = 0.52$) compared with uninjured runners (Appendix Table A1, available in the online version of this article).

Changes in Average Speed and Acceleration-Derived Variables Throughout the Run

Compared to lap 2, there were no significant changes in speed at lap 6, 10, 14, and 18 in either the male or female injured or uninjured runners.

Appendix Figures A1-A3 (available online), present speed and COM acceleration–derived variables at laps 2, 6, 10, 14, and 18, for male and female injured and uninjured runners. Male injured runners demonstrated a significant decrease in vertical RMSR, $F(56, 4) = 14.074$; $P = 0.001$; $\eta^2 = 0.501$, and a significant increase in mediolateral RMSR, $F(56, 4) = 45.038$; $P = 0.001$; $\eta^2 = 0.763$, at all subsequent laps compared with lap 2 ($P < 0.05$) (Appendix Figure A2, available online). Step regularity in mediolateral acceleration significantly increased, $F(56, 4) = 3.938$; $P = 0.007$; $\eta^2 = 0.220$, at lap 10 ($P = 0.012$) compared with lap 2 (Appendix Figure A3, available online). Male uninjured runners demonstrated a significant decrease in vertical RMSR, $F(72, 4) = 9.738$; $P = 0.001$; $\eta^2 = 0.351$, at laps 10 ($P = 0.044$) and 18 ($P = 0.003$), and a significant increase in mediolateral RMSR, $F(72, 4) = 16.143$; $P = 0.001$; $\eta^2 = 0.473$, at all subsequent laps compared with lap 2 ($P < 0.05$) (Appendix Figure A2, available online).

Female injured runners demonstrated a significant decrease in flight time, $F(36, 4) = 7.070$; $P = 0.001$; $\eta^2 = 0.440$), at laps 10 ($P = 0.019$), 14 ($P = 0.029$), and 18 ($P = 0.005$) compared with lap 2 (Appendix Figure A1, available online). There were no significant differences between laps for female uninjured runners.

Differences Between Injured and Uninjured Runners for Changes in Average Speed and Acceleration-Derived Variables at Beginning and End of the Run

The only significant group-by-time effect was for female runners for flight time, $F(1.00, 22.00) = 9.490$ $P = 0.005$ $\eta^2 = 0.301$. Female injured runners' flight time decreased at lap 18, whereas uninjured female runners' flight time increased at lap 18 compared with lap 2.

Prospective Training Variables Between Injured and Uninjured Runners

Male injured runners had a significantly greater average weekly running distance compared with male uninjured runners ($P = 0.046$; $r = 0.32$). There were no significant differences between female injured and uninjured runners for any of the training variables. The prospective training variables are shown in Appendix Table A2 (available online).

Increase in Running Distance Prior to Injury

Twenty male injured runners (91%), and 10 female injured runners (59%) increased their running distance by >10% between consecutive weeks at least once in the 4 weeks prior to injury. Of these, only 2 injured male and 1 injured female runner increased running distance >10% on 2 occasions in the 4 weeks prior to injury. Of the 18 male injured runners who increased running distance by >10% on 1 occasion, 11 (61%) increased by >30% and 5 (28%) increased by >50%. Of the 9 female injured runners who increased running distance by >10% on 1 occasion, 5 (56%) increased by >30% and 3 (33%) increased by >50%. Figure 1 presents the percentage of male and female injured runners that increased weekly running distance between consecutive weeks in the 4 weeks prior to injury.

Changes in Training Variables Prior to Injury

Male injured runners did more aerobic training ($P = 0.022$; $r = 0.36$; 25.46% increase) in the 3 weeks prior to injury. Female injured runners ran longer on the treadmill ($P = 0.036$; $r = 0.53$; 125.18% increase) and did more speed training ($P = 0.036$; $r = 0.53$; 215.08% increase) in the 4 weeks prior to injury. In the second and third weeks prior to injury, female injured runners did more speed training ($P = 0.036$; $r = 0.53$; 304.09% increase, and $P = 0.036$; $r = 0.53$; 243.32% increase, respectively).

DISCUSSION

This prospective study used a multifactorial approach to investigate differences between injured and uninjured runners. While the incidences of running injuries were similar between sexes, the majority of factors related to injury were different for male and female runners. This is in agreement with previous prospective studies[19,32] and supports our decision to perform sex-specific analyses.

Table 1. Participant characteristics and previous injury history of all, male, and female injured and uninjured runners at the commencement of study[a]

	All (n = 76)		Male (n = 45)		Female (n = 31)	
	Injured (n = 39)	Uninjured (n = 37)	Injured (n = 22)	Uninjured (n = 23)	Injured (n = 17)	Uninjured (n = 14)
Sex, n (%)						
Male	22 (48.89)	23	0	0	0	0
Female	17 (54.84)	14	0	0	0	0
Age, y	40.74 (12.46)	44.78 (12.46)	48.00 (35.00-53.50)	47.00 (32.00-56.00)	35.00 (23.00-47.50)	44.50 (32.50-51.75)
Height, m	1.74 (0.09)	1.70 (0.09)	1.80 (1.72-1.83)	1.78 (1.72-1.80)	1.66 (1.62-1.73)	1.64 (1.57-1.68)
Mass, kg	70.59 (11.28)[b]	65.35 (10.56)	78.00 (73.75-83.25)[b]	72.00 (65.00-77.00)	61.00 (54.50-66.50)[b]	56.50 (49.00-60.75)
BMI, kg/m^2	23.34 (2.84)	22.23 (2.11)	24.40 (21.99-26.98)	22.60 (21.72-24.62)	22.13 (19.67-23.93)	20.60 (19.25-21.74)
Previous RI (n =)						
<1 year	20[b]	10	12	10	8[b]	0
>1 to 2 years	14	10	5	6	9	4
>2 to 3 years	9	9	3	5	6	4
>3 years	17	16	8	8	9	8
Years running	15.90 (12.35)	16.54 (12.29)	10.00 (5.75-31.25)	12 (7-30)	14.00 (5.50-24.00)	10.50 (6.38-21.50)
Weekly distance, km	44.33 (13.34)	48.81 (18.42)	41.00 (30.00-51.88)	42.50 (35.00-51.25)	45.00 (31.25-51.25)	45.00 (30.00-67.00)
Frequency	4.21 (1.02)	4.68 (1.20)	3.75 (3.00-5.13)	4.00 (4.00-5.00)	4.00 (4.00-4.50)	4.00 (4.00-6.25)
Run finishing time, min	38.07 (4.51)	36.95 (4.56)	36.31 (32.43-38.62)	37.02 (33.59-38.30)	42.15 (36.44-43.73)	36.02 (33.50-40.76)

BMI, body mass index; RI, running injury.
[a]Data presented as mean (SD) for all runners and as median (interquartile range) for male and female runners.
[b]Significant at $P < 0.05$.

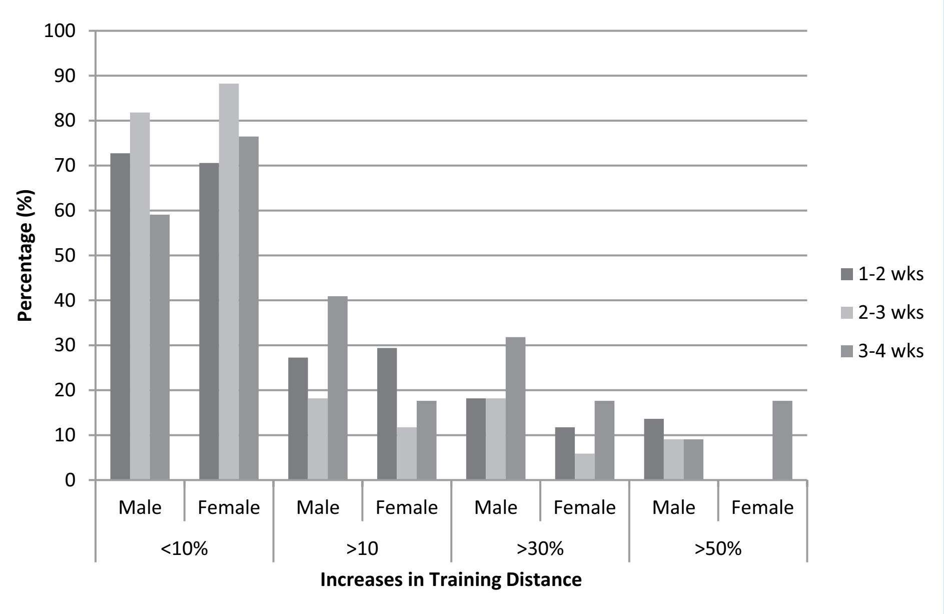

Figure 1. Percentage increases in weekly training distance between weeks 1 and 2, weeks 2 and 3, and weeks 3 and 4 prior to injury for male injured runners and female injured runners.

Male Runners

Moderate effects were found for injured male runners being heavier and running a greater average weekly running distance in the follow-up period compared with uninjured male runners. Limited evidence exists to ascertain the contribution body mass has on injury risk in runners because of the varied effect direction (either higher or lower) among studies.[13] Heavier runners may have a greater likelihood of running injuries as a result of greater loads on the bones, joints, or connective tissue.[34] This, along with a greater prospective weekly running distance further increasing load, may be related to injury in male runners.

Both injured and uninjured male runners demonstrated a significant increase in mediolateral RMSR throughout the run, indicating a decrease in dynamic postural stability and an increase in postural sway in this direction.[15,36] Running predominantly occurs in the sagittal plane in the vertical and anteroposterior directions, with less activity occurring in the frontal plane or mediolateral direction.[25] The increase in mediolateral postural movement suggests a loss of coordination in this direction that does not contribute effectively to forward propulsion.[14] While these alterations in running biomechanics throughout the run were observed in both injured and uninjured male runners, these alterations along with the extra body mass and greater weekly running distance may have resulted in further increases in load and resulted in injury. However, further investigation into this is needed.

Female Runners

Female injured runners were significantly heavier and demonstrated longer flight times and lower step frequencies compared with their uninjured counterparts. Similarly, Luedke et al[18] found that high school runners who ran with lower step frequencies were at a greater likelihood of shin injury. Injured and uninjured female runners ran at a similar speed in this current study. It has been reported that when running at a given speed, lower step frequencies result in an increase in ground reaction forces, lower limb loading, and energy absorption at the hip and knee joints.[9,11] The increase in energy absorption and lower limb loading from the lower step frequencies, along with the greater loads from being heavier,[34] may be related to injury in female runners in this study.

More female injured runners reported having sustained an injury in the previous year, and they significantly increased the duration of speed training in the few weeks prior to injury. An increase in training intensity may cause the remodeling or adaptation of a structure to be predominant over the repair process, resulting in an overuse injury.[12] This increase in training intensity may have exacerbated a previous injury that was not completely recovered.[10,26]

Increases in Running Distance Prior to Injury

In the 4 weeks prior to injury, considerably more male injured runners, compared with female injured runners, increased their running distance between consecutive weeks at least once by >10%, which may have contributed to injury development. Of these, over 60% of male injured runners and over 50% of female injured runners increased their weekly running distance by >30%.[22] The increases in training between consecutive weeks prior to injury may indicate that some structural compromise may have occurred, which resulted in immediate injury (between weeks 1 and 2) or, with continued training (increases between weeks 2 and 3, and 3 and 4), resulted in injury. Taken together, an increase in weekly running distance between only 1 consecutive week (particularly >30%) needs to be monitored in training, and this along with the other factors found may have contributed to injury development.

Strengths

This study used acceleration data collected during a long-distance outdoor overground run for ecological validity and performed regular analyses to assess for changes throughout the run. The collection of training data during the 1-year follow-up period provided current and accurate year-round data. This was evident in that male injured and uninjured runners reported similar weekly training distance at commencement of the study, yet the weekly training distances in the follow-up period were significantly different. The participants were free to continue their own training schedules, which is a practical and realistic way to analyze changes that may occur prior to injury. Sex-specific analyses were conducted, and results indicate that future running injury studies should include this analysis.

Limitations

Despite best efforts, only 92 runners were recruited, with 76 runners completing the study. The sample size allowed us to perform comparison-only statistics, and we were unable to perform logistical regression analysis to assess for risk factors or predictors of overuse injuries.[16] This affects the robustness of our findings and limits our ability to conclude that the findings may be related to injury, rather than risk factors for injury. Participants were trusted to fill in the diaries correctly; however, there is always a degree of error in this process.

While body mass was significant between injured and uninjured runners, these data were self-reported. This reduces the accuracy of the body mass data and is a further limitation of this study.

Although this study monitored participants for 1 year with training data collected during the monitoring period, other data such as anthropometric and running biomechanical data were collected at baseline. Longitudinal studies where anthropometric and biomechanical data are collected regularly throughout the monitoring period are required. A potential limitation of this study is that the participants also participated in other sports. While no significant differences were found between injured and uninjured runners for duration of other sports participated in, there is potential that participation in other sports may have also contributed to injury development. Furthermore, this study used a wide range of runners of different abilities. Although on average there were no differences observed in speed, differences in COM acceleration variables between runners of different abilities have been found in a previous study,[36] which may have affected the results.

CONCLUSION

A number of sex-specific factors may be related to running injuries. Male runners exhibited alterations in dynamic postural stability during the long-distance run. These alterations, along with a greater body mass and running a longer average weekly distance, may be related to injury in male runners. For female runners, a combination of being heavier, running with longer flight times and lower step frequencies, a previous injury in the past year, and an increase in speed training in the few weeks prior to injury may be related to injury. Increases in weekly running distance by >30% at least once between consecutive weeks prior to injury may have contributed to injury and should be monitored in training.

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