PM R 7 (2015) 26-33

www.pmrjournal.org

Original Research—CME

Metabolic, Cardiopulmonary, and Gait Profiles of Recently Injured and Noninjured Runners

Lucinda Peng, BS, Amanda N. Seay, BS, Cindy Montero, MS, Leslie L. Barnes, PT, PhD, Kevin R. Vincent, MD, PhD, Bryan P. Conrad, PhD, Cong Chen, MS, Heather K. Vincent, PhD

Abstract

Objective: To examine whether runners recovering from a lower body musculoskeletal injury have different metabolic, cardiopulmonary, and gait responses compared with healthy runners.
Design: Cross-sectional study.
Setting: Research laboratory at an academic institution.
Methods: Healthy runners (n = 50) were compared with runners who were recently injured but had returned to running (n = 50). Both groups were participating in similar cross-training modalities such as swimming, weight training, biking, and yoga. Running gait was analyzed on a treadmill using 3-dimensional motion capture, and metabolic and cardiopulmonary measures were captured simultaneously with a portable metabolic analyzer.
Main Outcome Measures: Rate of oxygen consumption, heart rate, ventilation, carbohydrate and fat oxidation values, gait temporospatial parameters and range of motion measures (ROM) in the sagittal plane, energy expenditure, and vertical displacement of the body's center of gravity (COG).
Results: The self-selected running speed was different between the injured and healthy runners (9.7 $\pm$ 1.1 km/h and 10.6 $\pm$ 1.1 km/h, respectively; $P = .038$). No significant group differences were noted in any metabolic or cardiopulmonary variable while running at the self-selected or standard speed (13.6 km/h). The vertical displacement of the COG was less in the injured group (8.4 $\pm$ 1.4 cm and 8.9 $\pm$ 1.4, respectively; $P = .044$). ROM about the right ankle in the sagittal plane at the self-selected running speed during the gait cycle was less in the injured runners compared with the healthy runners ($P < .05$).
Conclusions: Runners with a recent lower body injury who have returned to running have similar cardiopulmonary and metabolic responses to running as healthy runners at the self-selected and standard speeds; this finding may be due in part to participation in cross-training modes that preserve cardiopulmonary and metabolic adaptations. Injured runners may conserve motion by minimizing COG displacement and ankle joint ROM during a gait cycle.

Introduction

Lower extremity noncatastrophic injuries are common in runners, with annual estimates ranging from 37% [1] up to 68% [2]. Prevalence of specific injuries is estimated to be 5%-14% for iliotibial band syndrome [3], 7.4%-15.6% for patellofemoral syndrome [4], and between 9.5%-20.0% for tibial stress syndrome and plantar fasciitis, respectively [4]. Runners who have longer running histories are less likely to incur injury compared with runners who have fewer years of running experience [5]. During the return to run phase after injury, physiologic factors such as pain may affect overall performance and running economy. For example, altered gait patterns [6], foot strike, or cadence values may occur in an effort either consciously or subconsciously to offload the injured limb. Injury may cause runners to constrain running motion either by minimizing vertical displacement of the center of gravity (COG) or reducing the joint range of motion (ROM) excursion during a gait cycle, or both. All of these factors can contribute to metabolic and cardiopulmonary alterations that change the demand for oxygen delivery. A reduction in running economy can translate into significant additional caloric requirements over time, which results in increased heart rate (HR) and ventilation, premature fatigue [7], and suboptimal performance. Performance can also be limited by suboptimal

http://dx.doi.org/10.1016/j.pmrj.2014.06.013

energy management of fats and carbohydrates [8], with heavy reliance on carbohydrates leading to premature muscle fatigue. Also, it can be speculated that residual fear of reinjury during the return to run phase may cause the runner to adopt aberrant running mechanics, conserve running motion, or reduce training speed.

Presently, it is not known whether runners who are recovering from a recent, noncatastrophic lower body injury have similar metabolic, cardiopulmonary, or gait profiles as their healthy counterparts. A possible scenario is that runners who are coping with recent injury have since adopted symmetrical or conservative gait patterns to protect the body against further injury. The purpose of this study was to determine the metabolic, cardiopulmonary, and gait responses of runners recovering from a noncatastrophic lower body musculoskeletal injury compared with healthy noninjured runners. It was hypothesized that injured runners would demonstrate higher metabolic and cardiopulmonary responses to a given exercise workload than would noninjured healthy runners because of a decrease in training volume. It was also hypothesized that injured runners would demonstrate more constrained temporospatial gait parameters and less lower extremity joint ROM during running than would healthy runners. These findings will be clinically relevant in providing recovery performance expectations and customized, multicomponent rehabilitation programs for runners returning to running after a lower body musculoskeletal injury.

Methods

Study Design

The subjects are a subset of participants from a larger cross-sectional study (N = 300). A total of 100 runners volunteered for this study. Subjects were stratified on the basis of their injury history (healthy or injured) for statistical analysis of study outcomes. This study and its procedures were approved by the University of Florida Institutional Review Board, and the study complies with the guidelines of Declaration of Helsinki for the treatment of human subjects.

Participants and Study Inclusion/Exclusion Criteria

Runners were recruited using study flyers, Web-based advertisements, and the clinical trials register. Inclusion criteria included persons aged 16-75 years who were currently running at least 12 km/wk and were able to run on a treadmill continuously for at least 20 minutes. Healthy runners reported no injuries within the preceding 6 months causing a decrease in weekly running mileage, a score no less than 72/80 on the Lower Extremity Functional Scale (LEFS) [9], and no greater than a 6% disability score on the Oswestry Disability Index [10].

Exclusion criteria included the presence of an acute or catastrophic injury that prevented the ability to run continuously for 20 minutes on a treadmill; physician orders to avoid running; symptomatic cardiovascular disease; severely impaired intellectual capacity; medications that could affect balance; and dementia or other neurodegenerative diseases that would preclude appropriate cognitive or physical ability to understand or perform the study protocol. All participants read and signed an informed consent form approved by the University's Institutional Review Board. A health history and training history form was completed for self-reporting of demographics, comorbidities, previous injuries, running experience, and foot strike. Participants were matched for gender, age, and body mass index (BMI).

Demographics and Running Histories

Demographics were collected on an electronic survey and included race, gender, height, weight, BMI, marital status, and self-classification of running competition (ie, elite, recreational competitive, recreational, high school, or college competitive). A detailed running history was documented on this electronic record and included preferred training surface, average weekly running distance, average distance of long runs, participation in and frequency of speed work, and current running shoes. Characteristics of the running shoe worn during the testing session were recorded (ie, weight and heel to toe drop [the length in millimeters that the sole of the shoe decreases in thickness from the heel to the toe]) to account for potential variables that could affect metabolic parameters. Other training modalities were assessed using checkbox choices for swimming, biking, stair climbing/stadium stairs, weights and resistance exercise, yoga, and other.

Injury Status

Participants' injury history included information about the side and area of injury and current discomfort levels. The LEFS was designed to measure a broad spectrum of lower extremity problems to address the difficulty of utilizing multiple joint or structure specific scoring systems. The LEFS is reliable and sensitive to changes in physical function of patients with lower extremity dysfunction. The LEFS is also efficient to administer and score and is applicable to research populations. An LEFS score of >72 out of 80 points was considered "injured" status. The injuries were self-reported as chronic conditions (pain onset over time) or as a nagging musculoskeletal pain that worsened after a competitive event. None of the injuries was catastrophic in nature. The injuries were grouped by region: 24.5% had knee and tibia injuries (ie, healing stress fractures, patellofemoral pain, patellar tendon inflammation, or iliotibial band friction syndrome). A total of 18.4% of the injured runners had hip/pelvis hamstring injuries (ie, piriformis syndrome, greater trochanteric pain syndrome, ischial bursitis, sacroiliac joint dysfunction, or labral tears). Ankle injuries comprised 14.3% of all injuries and included fibular stress fracture, peroneal tendon inflammation, and Achilles tendinopathy. A total of 24.5% of the runners had foot injuries (ie, recovering from metatarsal stress fracture, metatarsalgia, flexor hallicis longus tendonitis, plantar fasciitis, or a posterior tibialis tendon injury). A total of 14.6% of the injured group described having symptoms in the foot and ankle.

Body Composition

To characterize the participants and ensure that appropriate matching occurred between groups, body composition measures were collected using air plethysmography. Air plethysmography (with use of the BOD POD; COSMED USA Inc, Chicago, IL) is a reliable technique of body volume and composition and is highly correlated to the gold standard of underwater weighing [11].

Treadmill Testing

All runners performed a standard running gait test on a commercial-grade treadmill. The protocol consisted of a 3-minute warm-up, followed by a 10-minute run at a self-selected running speed and a standard speed of 13.6 km/h. This time duration was chosen after pilot testing participants at 5 through 10 minutes to determine when both metabolic and kinematic measures stabilized.

Cardiopulmonary and Metabolic Measures

Metabolic variables represented the exchange of gases at the tissue level, whereas the cardiopulmonary measures were measured at the organ level (lung and heart). To determine whether a difference in oxygen cost existed between the 2 groups of runners, metabolic assessments were captured using a portable oxygen (O_2) consumption (VO_2) device ($K4b^2$; COSMED, Rome, Italy). The $K4b^2$ unit acquired a breath-by-breath measurement of gas exchange via a rubberized face mask and a turbine for gas collection. Prior to testing, the $K4b^2$ unit was warmed up for a minimum of 30 minutes. After the warm-up period, the O_2 and carbon dioxide analyzers were calibrated using reference gases of known concentrations. Participants wore the $K4b^2$ unit continuously during a 5-minute pre-exercise baseline period, during the 3-minute treadmill warm-up, during the 10-minute self-selected speed, and during the standardized running speed of 13.6 km/h. To ensure an adequate seal of the face mask during running, the study team used gel seals around the mask edge and cotton on the inside of the mask to secure the seal to the skin. Seals were tested before data collection by having the runner exhale hard while the tester blocked the front of the mask to detect if air leakage occurred. The average O_2 use was calculated for the stable period of 10 minutes during the running session. Participants subsequently ran at a standard speed of 13.6 km/h, and the average cardiopulmonary and metabolic data of the self-selected speed and 13.6 km/h speed were calculated. The self-selected running speed represented a typical long-distance training run pace. Because O_2 consumption does not increase linearly with body mass [12], the VO_2 values were also allometrically scaled to prevent errors from occurring in metabolic calculations in persons with higher body weight. VO_2 values were raised to a recommended exponent of 0.75 [9]. In addition to the VO_2 values, minute ventilation (VE) and nonprotein respiratory exchange ratio values were collected. Carbohydrate and fat oxidation values were generated from this ratio, and the percent of the fat and carbohydrate used at the self-selected speed and a standard speed were documented.

Cardiopulmonary variables consisted of HR and VE. HR and VE were obtained continuously during the test. HR was captured in parallel with the $K4b^2$ assessments with the use of an integrated telemetric HR monitor worn on the chest of the participant. All variables were captured continuously throughout testing and were averaged as 30-second intervals. The mean HR and VE values were determined for the 10-minute duration.

Gait Analysis

Running cadence and COG vertical displacement were captured using a high-speed 12-camera optical motion analysis system (Motion Analysis Corp, Santa Rosa, CA). Reflective markers were applied to anatomic landmarks and body segments. For the static calibration trials, markers were placed bilaterally on the posterior superior iliac spine, anterior superior iliac spine, anterior thigh, medial and lateral condyles of the femur, tibial tuberosity, medial and lateral malleoli, and calcaneus, as well as lateral to the fifth metatarsal and medial to the great toe. For the running trials, medial knee and ankle markers were removed. Cadence, COG displacement, temporospatial parameters, and ROM in the sagittal plane were calculated using commercially available software (Visual3D, C-Motion, Inc, Germantown, MD). Temporospatial parameters included cycle time, stance time of each leg, swing time for each leg, stride and step lengths, and stride width. Joint ROM of the ankle, knee, hip, and pelvis represented the angular excursion of the joint from foot strike to the subsequent foot strike of the same foot. This kinematic measure was selected for this study because it would represent the overall motion of each joint during the entire gait cycle rather than angles at discrete gait cycle time points and would be more closely related to metabolic parameters.

Statistics

Statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS version 20.0, IBM, Armonk, NY). Data are expressed as means ± standard deviations (SDs) or as the percent of the study groups. Data were managed using Research Electronic Data Capture (REDCap) [10]. Descriptive statistics and frequencies were obtained to characterize the 3 BMI groups; χ^2 tests were used for categorical variables. Wilcoxon rank-sum tests were used to determine whether group differences existed in joint pain symptoms and in the self-reported limitations with walking or stair climbing. χ^2 tests were performed to determine whether differences existed in cross-training participation of various exercise modes between groups. As confirmed by Levene's test, the assumptions of the F tests were met for all data presented. A one-way analysis of variance was used to determine if differences existed between groups for the outcome measures, with the study group as the independent variable and the cardiopulmonary and metabolic variables, cadence, COG displacement, and temporospatial and lower extremity joint ROM values as the dependent variables. Significance was established at $P < .05$ for all statistical tests.

Results

Characteristics

The characteristics of the injured and noninjured runners are shown in Table 1. Overall, the 2 groups were well matched for most of the demographic and physical parameters. Among the injured runners, 24.5% had knee injuries, 18.4% had hip/back injuries, 14.3% had ankle injuries, and 24.5% had foot injuries (14.6% had selected both foot and ankle injuries). Self-reported running histories and current training volumes were similar, but the typical long-run distance was greater in the healthy than in the injured runners ($P = .017$). Fewer injured runners preferred to run on trails or track surfaces than did the healthy runners ($P = .006$). More injured runners than noninjured runners preferred to run on a treadmill or on the street. Running shoe characteristics were also very similar between groups. Shoe weights were 10.2 ± 1.6 oz and 9.9 ± 1.9 oz for the injured and noninjured groups, respectively; the heel to toe drop values for these same groups were 9.4 ± 3.6 mm and 9.2 ± 3.6 mm, respectively. The weekly run distance was 24.4 ± 15.1 km for the injured runners and 31.8 ± 17.2 km for the healthy runners ($P = .001$). The average long-run distances were 11.1 ± 5.6 km and 14.8 ± 5.6 km for the injured and healthy runners, respectively ($P = .001$). The proportions of injured and healthy runners who participated in cross-training modalities, respectively, were 53.4% and 56.3% in biking, 33.8% and 40.0% in swimming, 62.7% and 65.3% in weight training, 6.9% and 23.2% in stair climbing and stadium stairs, and 41.9% and 35.9% in yoga. Only participation in stair climbing activity was found to be less in the injured group compared with the healthy group (χ^2 score 5.884; $P = .008$).

Table 1
Characteristics for injured and noninjured runners

Characteristic	Injured (n = 50)	Healthy (n = 50)	*P* (significance)
Age (y; mean ± SD)	40.5 ± 15.0	39.6 ± 11.9	.737
BMI (kg/m^2; mean ± SD)	23.2 ± 2.8	22.1 ± 3.1	.102
Body fat (mean ± SD)	18.1 ± 8.2	22.2 ± 8.0*	.025
Lean mass (kg; mean ± SD)	53.2 ± 13.3	59.9 ± 17.9	.051
Fat mass (kg; mean ± SD)	14.7 ± 5.7	14.2 ± 13.9	.829
Race (%)			
White	88.5	96.0	.134
African American	4.1	4.0	.984
Asian	6.1	0.0	.077
Other	1.3	0.0	.900
Years running (mean ± SD)	10.7 ± 10.5	16.2 ± 10.4*	.011
Recreational competitive (%)	65.3	74.0	.349
Recreational (%)	34.7	16.0*	.033
Currently doing speed work (%)	36.2	69.6*	.001
Speed work (times/wk; mean ± SD)	1.4 ± 0.6	1.3 ± 0.7	.661

SD = standard deviation; BMI = body mass index.
* Denotes significance at $P < .05$.

The proportions of injury regions were the hip (26.8%), knee (32.5%), ankle (21.9%), and foot (29.3%). The distribution between right and left limb for each site was almost identical. One runner experienced foot injury on both feet (metatarsalgia), and 2 runners reported a knee injury in both knees (patellofemoral pain). A total of 10.5% of the injured runners reported injuries in more than one joint.

Metabolic and Cardiopulmonary Responses

The metabolic and cardiopulmonary responses to running at the self-selected pace and the standard speed (13.6 km/h) are shown in Table 2. At the self-selected speed, the overall energy expenditure during the 10-minute run was not different between the 2 groups ($P = .145$). No group differences were detected in the HR, pulmonary variables, or allometrically scaled VO_2 measures. Only nonsignificant trends occurred with the percentages of carbohydrates and fats that were used during the 2 speeds tested, with the injured runners tending to use more carbohydrates for fuel at the

Table 2
Cardiopulmonary and metabolic responses

Speed	Injured (mean ± SD)	Healthy (mean ± SD)	P (significance)
Self-selected speed			
Running speed (km/h)	9.7 ± 1.1	10.6 ± 1.1*	.038
Maximum HR (bpm)	160 ± 24	163 ± 23	.735
VE (L/min)	68.1 ± 14.7	69.6 ± 13.0	.764
VO_2 (kg/m/min)	33.5 ± 5.0	36.1 ± 5.0	.145
VO_2 (kg/m/min)$^{0.75}$	13.9 ± 3.4	14.8 ± 3.3	.145
Average HR (bpm)	141 ± 27	143 ± 12	.748
Rate of EE (kJ/min)	46.1 ± 8.7	46.4 ± 11.2	.587
Total EE (kJ)	560.6 ± 130.7	681.1 ± 255.2	.070
Fat use	19.0 ± 18.0	23.8 ± 19.2	.493
Carbohydrate use	81.0 ± 18.0	76.2 ± 19.2	.505
Standard speed (13.6 km/h)			
Maximum HR (bpm)	160 ± 35	154 ± 20	.638
VE (L/min)	85.4 ± 17.6	85.4 ±17.6	.214
VO_2 (kg/m/min)	38.0 ± 4.6	36.4 ± 10.4	.537
VO_2 (kg/m/min)$^{0.75}$	15.3 ± 3.1	14.8 ± 5.8	.537
Average HR (bpm)	153 ± 32	150 ± 21	.765
Rate of EE (kJ/min)	52.7 ± 12.5	50.6 ± 12.5	.700
Fat use	8.7 ± 20.7	22.5 ± 19.2	.091
Carbohydrate use	91.1 ± 20.4	77.3 ± 18.6	.085

SD = standard deviation; HR = heart rate; bpm = beats per minute; VE = minute ventilation; VO_2 = rate of oxygen consumption; EE = energy expenditure.
* Denotes difference between groups at $P < .05$.

standard speed of 13.6 km/h than did the healthy runners ($P = .08$).

Gait Analyses

The cadence values for the injured and healthy runners were 168 ± 10 steps/min and 168 ± 8 steps/min, respectively ($P = .203$). The COG displacement values were 8.4 ± 1.4 cm for the injured runners and 8.9 ± 1.4 cm for the healthy runners ($P = .044$). At the standard speed of 13.6 km/h, the cadence decreased in the injured and noninjured groups to 130 ± 82 steps/min and 142 ± 71 steps/min, respectively ($P = .582$). The vertical displacement of the COG did not significantly change from the self-selected speed to the standard speed.

Table 3 provides the temporospatial parameters during self-selected and standard speeds. The injured and healthy runners demonstrated similar cycle times, stance and swing times, step and stride lengths, and step widths for both running speeds. The overall ROM (angular excursion) results are shown in Table 4. At the self-selected speed, the injured runners demonstrated a lower ankle ROM (right leg) than did the healthy runners ($P = .031$) and tended to have a lower left ankle and left knee ROM than did the healthy runners, although this finding did not reach significance ($P = .069$-$.087$). At the standard speed of 13.6 km/h, no differences existed in ROM between groups.

Discussion

The purpose of this study was to determine the metabolic, cardiopulmonary, and gait responses of runners recovering from a noncatastrophic lower body musculoskeletal injury compared with healthy noninjured runners. We tested the hypotheses that injured runners would generate higher metabolic and cardiopulmonary responses to a given exercise workload and demonstrate more constrained temporospatial gait parameters and less lower extremity joint ROM than would healthy runners. In contrast to our hypotheses, runners with a recent injury did not have higher rates of O_2 consumption and greater cardiopulmonary responses compared with healthy runners. At self-selected speeds, the temporospatial parameters were not different based on injury status, but the ROM about the right ankle was less in the injured runners compared with the healthy runners at the self-selected speed. At the faster standard speed, no differences in any study variable were identified between the groups. After accounting for numerous variables (shoewear and running surface preference), the physiologic responses to self-selected and standard speeds were similar between healthy runners and those who are returning to running, despite remaining differences in weekly training volume and average long-distance runs. An interpretation could be that as the recently injured runners returned to normal training volume and speed, different COG patterns and metabolic responses may emerge. Alternatively, the fact that injured runners had a similar prevalence of maintaining participation in other cross-training modalities could suggest that this participation was a sufficient stimulus to prevent a dramatic decrement in cardiopulmonary fitness during the recovery period.

A challenge of the present study is a dearth of literature with which to compare our results. Because ethical

Table 3
Temporospatial parameters of running gait

Speed	Injured (mean ± SD)	Healthy (mean ± SD)	*P* (significance)
Self-selected speed			
Cycle time (sec)	0.71 ± 0.12	0.74 ± 0.03	.211
Stance time, left foot (sec)	0.29 ± 0.12	0.29 ± 0.12	.937
Stance time, right foot (sec)	0.31 ± 0.10	0.31 ± 0.12	.685
Swing time, left (sec)	0.37 ± 0.13	0.36 ± 0.14	.746
Swing time, right (sec)	0.36 ± 0.12	0.35 ± 0.14	.894
Step length, left (m)	0.76 ± 0.26	0.72 ± 0.34	.557
Stride length, left (m)	1.53 ± 0.52	1.47 ± 0.63	.655
Step length, right (m)	0.77 ± 0.27	0.75 ± 0.30	.759
Stride length, right (m)	1.53 ± 0.52	1.47 ± 0.62	.657
Stride width (cm)	8.7 ± 2.8	8.8 ± 3.1	.966
Standard speed (13.6 km/h)			
Cycle time (sec)	0.47 ± 0.30	0.55 ± 0.27	.317
Stance time, left foot (sec)	0.20 ± 0.15	0.23 ± 0.14	.493
Stance time, right foot (sec)	0.21 ± 0.15	0.23 ± 0.15	.509
Swing time, left (sec)	0.25 ± 0.18	0.30 ± 0.17	.318
Swing time, right (sec)	0.24 ± 0.18	0.29 ± 0.17	.355
Step length, left (m)	0.79 ± 0.57	0.91 ± 0.56	.426
Stride length, left (m)	1.6 ± 1.14	1.82 ± 1.13	.428
Step length, right (m)	0.80 ± 0.57	0.92 ± 0.57	.432
Stride length, right (m)	1.59 ± 1.14	1.82 ± 1.13	.425
Stride width (cm)	6.0 ± 4.3	6.4 ± 3.9	.689

issues exist with experimentally testing runners who have acute injuries, investigators have been limited to testing runners who have musculoskeletal deficits or who are returning to running after injury. For example, one study presented a comparison of the metabolic economy (VO_2) of jogging between runners with and without anterior cruciate ligament deficiency [7]. Runners with anterior cruciate ligament deficits had significantly higher rates of O_2 consumption at the highest speed tested (160.9 m/min) compared with the healthy runners. It is reasonable to surmise that injured runners or those recovering from injury may alter their running form to protect the injured area, thereby increasing O_2 consumption. Although energy or O_2 cost did not differ between the runner groups in the present study, the vertical displacement of the COG was lower and the frequency of runners who had foot contact on the midfoot was higher in the injured group at the self-selected speed. These findings were supported by a lower right ankle ROM and tendencies of lower knee ROM at the self-selected speed in the injured group, suggesting less joint excursion. Propelling body mass higher vertically with greater displacement costs more energy than a lower vertical displacement. The injured runners may have used a mechanically conservative form with less vertical motion to constrain their motion, which might explain why O_2 consumption and caloric expenditure rates were not different between groups despite a slower self-selected speed in the injured group. Other studies support the importance of minimizing vertical displacement to decrease metabolic cost of running [13].

From the metabolic perspective, the injured runners demonstrated only a trend in higher carbohydrate oxidation than did healthy runners at the 13.6 km/h pace. Training increases fat oxidation and trafficking into skeletal muscle [14] and helps to prolong carbohydrate availability and onset of fatigue. The fact that fuel use was not significantly different between groups at this time point in the return-to-run phase could suggest 2 possibilities. First, the runners were outside of the acute injury window when detraining occurs and fuel oxidation processes were being restored to preinjury levels. Second, the injury was not sufficient to completely prevent training, and thus even small exposures of running exercise stimulation may preserve training adaptations to fat

Table 4
Range of motion (degrees) during a running gait cycle

Speed	Injured (mean ± SD)	Healthy (mean ± SD)	*P* (significance)
Self-selected speed			
Ankle, right	46.6 ± 6.9	50.3 ± 6.2	.031
Ankle, left	46.7 ± 7.3	49.9 ± 7.2	.087
Knee, right	77.5 ± 11.9	82.1 ± 11.6	.125
Knee, left	77.9 ± 11.8	83.3 ± 10.8	.069
Hip, right	51.1 ± 6.0	52.8 ± 5.6	.252
Hip, left	67.0 ± 6.7	68. 7 ± 5.5	.178
Pelvis	7.6 ± 2.7	8.1 ± 2.3	.363
Standard speed (13.6 km/h)			
Ankle, right	50.5 ± 7.6	53.1 ± 7.2	.238
Ankle, left	50.5 ± 7.3	53.2 ± 6.6	.186
Knee, right	92.6 ± 12.7	97.9 ± 11.3	.132
Knee, left	93.2 ± 12.6	98.8 ± 11.4	.117
Hip, right	65.7 ± 6.7	66.7 ± 5.7	.571
Hip, left	67.0 ± 6.7	68. 7 ± 5.5	.363
Pelvis	8.5 ± 2.4	9.1 ± 2.1	.342

use. Cross-training may have helped some of these injured runners maintain fitness during recovery. The participation of the injured runners in swimming, biking, strength training, and yoga may have provided enough physical stimulus to prevent or minimize the cardiopulmonary and metabolic decline that can occur during recovery from an injury. Additional research is warranted to determine the time course of changes in fat and carbohydrate oxidation during the return-to-run phase to help in the development of combined rehabilitation and nutrition programs that facilitate transition to full running with minimal fatigue. Further, opportunities exist to develop cross-training rehabilitation programs to maintain aerobic fitness and metabolic status in trained runners who are recovering from injuries.

A unique aspect of the present study is the comparison of groups using a self-selected and a standard faster speed. The potential exists that the injury induced favorable changes in gait that would prevent subsequent injury or worsening of existing pain. An interpretation could be that these constraints to lower extremity joint ROM are actually improvements in running form relative to preinjury running form. The injured runners may be compensating for the injury by adopting slower self-selected running speeds, conserving on joint motion, and reducing joint impact with less vertical motion. At the faster standard speed, metabolic, temporospatial, and ROM responses were similar between injured and healthy runners. Irrespective of injury status, it is likely that at faster speeds, running form becomes more similar among varied runners in order to keep pace with the treadmill belt.

Limitations and Future Directions

This cross-sectional study of runners with varying histories of lower extremity injury has some limitations that deserve comment. The findings may not be directly generalizable to runners of varying injury severity, duration, or anatomic location of injury. Prospective assessment of runners from the time of injury to the full functional restoration of normal running volume would provide unique insight as to the metabolic responses during the return-to-run phase. The current study included runners with noncatastrophic injuries. Future studies of catastrophic injuries that require a long, slow recovery (eg, knee cruciate ligament tears or lower extremity or lumbopelvic stress fractures) may elicit different metabolic, cardiopulmonary, and gait pattern recoveries compared with those in the present study. The collective evidence would help rehabilitation specialists determine the physical recovery pattern and develop specific gait retraining or improvement programs. Finally, determination of whether a specific mode of cross-training exercise or a combination of exercise modes are more effective in maintaining training adaptations during recovery in the injured runner would be helpful.

Conclusions

Runners with a recent noncatastrophic lower body musculoskeletal injury who have returned to running demonstrated similar cardiopulmonary and metabolic responses to running as healthy runners. This finding may be due in part to participation in other non-running cross-training modes such as swimming, biking, weight training, and yoga. Recently injured runners appear to have less vertical displacement, more constrained ROM about the right ankle, and a lower self-selected running speed than do noninjured runners. Therefore rehabilitation programs for injured runners should consider correcting gait issues for optimal recovery and using aerobic cross-training methods to help the runner reintegrate into running activity.

References

1. van Gent RN, Siem D, van Middelkoop M, van Os AG, Bierma-Zeinstra SM, Koes BW. Incidence and determinants of lower extremity running injuries in long distance runners: A systematic review. Br J Sports Med 2007;41:469-480.
2. Tenforde AS, Sayres LC, McCurdy ML, Collado H, Sainani KL, Fredericson M. Overuse injuries in high school runners: Lifetime prevalence and prevention strategies. PM R 2011;3:125-131.
3. van der Worp MP, van der Horst N, de Wijer A, Backx FJ, Nijhuis-van der Sanden MW. Iliotibial band syndrome in runners: A systematic review. Sports Med 2012;42:969-992.
4. Schache AG, Blanch PD, Dorn TW, Brown NA, Rosemond D, Pandy MG. Effect of running speed on lower limb joint kinetics. Med Sci Sports Exerc 2011;43:1260-1271.
5. Fredericson M, Misra AK. Epidemiology and aetiology of marathon running injuries. Sports Med 2007;37:437-439.
6. Lee MJ, Reid SL, Elliott BC, Lloyd DG. Running biomechanics and lower limb strength associated with prior hamstring injury. Med Sci Sports Exerc 2009;41:1942-1951.
7. McHugh MP, Spitz AL, Lorei MP, Nicholas SJ, Hershman EB, Gleim GW. Effect of anterior cruciate ligament deficiency on economy of walking and jogging. J Orthop Res 1994;12:592-597.
8. Rapoport BI. Metabolic factors limiting performance in marathon runners. PLoS Comput Biol 2010;6:e1000960.
9. Faulkner JA, Woolley BP, Lambrick DM. The effect of estimation and production procedures on running economy in recreational athletes. J Sci Sports Med 2012;15:568-573.
10. Harris PA, Taylor R, Thielke R, Payne J, Gonzalez N, Conde JG. Research Electronic Data Capture [REDCap] — A metadriven methodology and workflow process for providing translational research informatics support. J Biomed Inform 2009;42:377-381.
11. Ginde SR, Geliebter A, Rubiano F, et al. Air displacement plethysmography: Validation in overweight and obese subjects. Obesity Res 2005;13:1232-1237.
12. Saunders PU, Pyne DB, Telford RD, Hawley JA. Factors affecting running economy in trained distance runners. Sports Med 2004;34:465-485.
13. Halvorsen K, Eriksson M, Gullstrand L. Acute effects of reducing vertical displacement and step frequency on running economy. J Strength Cond Res 2012;26:2065-2070.
14. Bergouignan A, Momken I, Lefai E, et al. Activity energy expenditure is a major determinant of dietary fat oxidation and trafficking, but the deleterious effect of detraining is more marked than the beneficial effect of training at current recommendations. Am J Clin Nutr 2013;98:648-658.

This journal-based CME activity is designated for 1.0 AMA PRA Category 1 Credit™ and can be completed online at www.me.aapmr.org. This activity is FREE to AAPM&R members and available to non-members for a nominal fee. For assistance with claiming CME for this activity, please contact (847) 737-6000.

Disclosure

L.P. Department of Orthopaedics and Rehabilitation, Interdisciplinary Center for Musculoskeletal Training and Research, University of Florida, Gainesville, FL
Disclosure: nothing to disclose

A.N.S. Department of Orthopaedics and Rehabilitation, Interdisciplinary Center for Musculoskeletal Training and Research, University of Florida, Gainesville, FL
Disclosure: nothing to disclose

C.M. Department of Orthopaedics and Rehabilitation, Interdisciplinary Center for Musculoskeletal Training and Research, University of Florida, Gainesville, FL
Disclosures outside this publication: grants/grants pending, NIH, Obesity Society (money to author)

L.L.B. Department of Orthopaedics and Rehabilitation, Interdisciplinary Center for Musculoskeletal Training and Research, University of Florida, Gainesville, FL
Disclosure: nothing to disclose

K.R.V. Department of Orthopaedics and Rehabilitation, Interdisciplinary Center for Musculoskeletal Training and Research, University of Florida, Gainesville, FL
Disclosures outside this publication: grants/grants pending, NIH (money to institution)

B.P.C. Department of Orthopaedics and Rehabilitation, Interdisciplinary Center for Musculoskeletal Training and Research, University of Florida, Gainesville, FL
Disclosure: nothing to disclose

C.C. Department of Orthopaedics and Rehabilitation, Interdisciplinary Center for Musculoskeletal Training and Research, University of Florida, Gainesville, FL
Disclosure: nothing to disclose

H.K.V. Department of Orthopedics and Rehabilitation, Division of Research, University of Florida Orthopaedics and Sports Medicine Institute, Gainesville, FL. Address correspondence to: H.K.V., University of Florida Orthopaedics and Sports Medicine Institute, PO Box 112727, Gainesville, FL 32611; e-mail: vincehk@ortho.ufl.edu
Disclosures outside this publication: grants/grants pending, NIH, Obesity Society, Accordia (money to institution)

This study was supported by the University of Florida (UF) Orthopaedics Interdisciplinary Center for Musculoskeletal Training and Research, the UF Health Sports Performance Center, and the UF Running Medicine Clinic. Study data were collected and managed using REDCap electronic data capture tools hosted at the University of Florida (CTSA grant UL1 TR000064).

Submitted for publication October 7, 2013; accepted June 29, 2014.

CME Question

When studying recently injured runners compared to healthy runners, the researchers found that during a 10 minute treadmill run the injured runners had a

a) slower self-selected running speed
b) slower heart rate
c) higher overall energy expenditure
d) higher rate of oxygen consumption

Answer online at me.aapmr.org