PM R XXX (2015) 1-9

www.pmrjournal.org

Original Research

Kinematic, Cardiopulmonary, and Metabolic Responses of Overweight Runners While Running at Self-Selected and Standardized Speeds

Laura Ann Zdziarski, LAT, Cong Chen, MS, Marybeth Horodyski, EdD, LAT, Kevin R. Vincent, MD, PhD, Heather K. Vincent, PhD

Abstract

Objective: To determine the differences in kinematic, cardiopulmonary, and metabolic responses between overweight and healthy weight runners at a self-selected and standard running speed.
Design: Comparative descriptive study.
Setting: Tertiary care institution, university-affiliated research laboratory.
Participants: Overweight runners (n = 21) were matched with runners of healthy weight (n = 42).
Methods: Participants ran at self-selected and standardized speeds (13.6 km/h). Sagittal plane joint kinematics were captured simultaneously with cardiopulmonary and metabolic measures using a motion capture system and portable gas analyzer, respectively.
Main Outcome Measurements: Spatiotemporal parameters (cadence, step width and length, center of gravity displacement, stance time) joint kinematics, oxygen cost, heart rate, ventilation and energy expenditure.
Results: At the self-selected speed, overweight individuals ran slower (8.5 ± 1.3 versus 10.0 ± 1.6 km/h) and had slower cadence (163 versus 169 steps/min; $P < .05$). The sagittal plane range of motion (ROM) for flexion-extension at the ankle, knee, hip, and anterior pelvic tilt were all less in overweight runners compared to healthy weight runners (all $P < .05$). At self-selected speed and 13.6 km/h, energy expenditure was higher in the overweight runners compared to the their healthy weight counterparts ($P < .05$). At 13.6 km/h, only the frontal hip and pelvis ROM were higher in the overweight versus the healthy weight runners ($P < .05$), and energy expenditure, net energy cost, and minute ventilation were higher in the overweight runners compared to the healthy weight runners ($P < .05$).
Conclusion: At self-selected running speeds, the overweight runners demonstrated gait strategies (less joint ROM, less vertical displacement, and shorter step lengths) that resulted in cardiopulmonary and energetic responses similar to those of healthy weight individuals.

Introduction

The popularity of running is growing in the United States, and the demographics of this active group are shifting [1]. Runners of diverse body sizes and ages are participating in running, with more than 35% of new runners falling into the overweight classification [1,2]. Approximately 16% of runners may start running specifically because of weight concerns [1]. An assumption has been that overweight persons who run are at inherent risk for musculoskeletal injury due to their modified body geometry [3] and elevated mechanical stress on the load-bearing joints of the body [4]. It is not known, however, whether overweight people adjust motion strategies to control joint excursion and metabolic cost to maintain physical comfort. Despite the known benefits of running on cardiovascular fitness, metabolic and endocrine profiles, and mental outlook [5], there is a scientific gap regarding the simultaneous effects of running on joint kinematics and cardiopulmonary and metabolic responses in overweight runners compared to their healthy weight counterparts.

Weight management programs may use interval exercise in which running is performed at relatively low

http://dx.doi.org/10.1016/j.pmrj.2015.06.441

and high speeds. Alternating running intensities may enhance the weight loss benefits of exercise [6,7]. It is not currently known whether the energy cost and lower-body joint kinematics differ between overweight and healthy weight runners during self-selected and faster running speeds, such as those used in interval-style exercise. The available research that examined the energy cost of exercise and joint motion in obese persons has used only treadmill walking [8-11], or walking and jogging [12]. Other investigations have examined energetics and mechanics in obese children [7,13]. Biomechanics have been identified as a potential variable that may affect the energy cost during running [14]. Quantifying how overweight status affects the kinematics of running at both a self-selected and a standardized faster pace will provide important insight into the associations between metabolic and mechanical energetics and the related risk for injury or musculoskeletal pathology.

The aim of this study was to address this scientific gap by determining the differences in kinematic, cardiopulmonary, and metabolic responses between runners who are overweight and healthy weight. Due to relatively larger segmental volumes and masses [15], we hypothesized that overweight runners would generate less joint range-of-motion excursion during running at self-selected and standardized running speeds and would have a higher cadence compared to healthy weight runners. Moreover, we anticipated that the cardiopulmonary responses and oxygen cost would be greater for the overweight runners [15] than for the healthy weight runners at self-selected and standardized speeds.

Methods

Study Design

The present investigation was a subset of participants from a larger cross-sectional study (institutional review board [IRB] no. 672-11). A total of 63 runners comprised this analysis. This study and its procedures were approved by the University of Florida Institutional Review Board and comply with the guidelines of the Declaration of Helsinki for the treatment of human subjects.

Participants

Participants were recruited using Web-based advertisements, study flyers, and the clinical trials registry. Participants were required to meet the following criteria: age 25-75 years; currently running at least 12 km/wk; able to run on a treadmill continuously for at least 20 minutes; free of acute musculoskeletal injury; free of medical restriction for running; free of symptomatic cardiovascular disease; not taking medications that could affect balance; and free of dementia or other neurodegenerative diseases. All runners who met the definition of overweight comprised the overweight group. Overweight was classified as having body mass index (BMI) values exceeding 25.0 kg/m^2. The pool of runners was screened to identify 2 healthy weight runners; all were matched for age and gender. Participants were stratified based on BMI values for the statistical analysis of study outcomes.

Demographics and Running Histories

An electronic health and training history survey was completed for self-reporting of demographics, comorbidities, previous injuries, and running experience. Additional information included self-classification of running competition (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 (weight, and heel to toe drop [the difference in height from the heel to the toe]) to account for potential variables that could affect kinematic parameters. The purpose of these histories was to ensure that participants were relatively well matched for multiple factors that could potentially confound the analyses.

Body Composition

Body composition measures were collected using air plethysmography (using the BOD POD; Life Measurement Inc, Concord, CA). This method is a reliable technique for measuring body volume and composition, and is highly correlated with the gold standard of underwater weighing [16]. The percentage of fat and lean mass values were obtained, and body fat mass and lean mass were calculated.

Experimental Protocol

Participants performed a treadmill running protocol during a single laboratory session. A static resting period of 3 minutes permitted capture of cardiopulmonary and metabolic data before running. During a 5-minute acclimatization period, participants walked on the treadmill. The speed of the treadmill was then increased to the participants' self-selected long-distance running pace. Participants ran for 10 minutes. Each of the participants then ran at a standardized speed of 13.6 km/h for 1 minute [17]. This standardized speed is within the range of previously tested speeds used by recreational runners [17,18]. The self-selected running speed has been used in previous studies of running kinetics and kinematics [19] to represent each participant's typical long-distance training pace [20]. Similar to previous work, the order of the 2 running speeds was incremental rather than randomized for practical reasons [18]. The grade of the treadmill was maintained at 0° for both speeds. The coefficient of multiple comparisons has been documented for similar testing protocols ranging from 0.706 to 0.989 for kinematic variables tested [21].

Data Collection

A high-speed, 12-camera, optical motion analysis system (Motion Analysis Corp, Santa Rosa, CA) was used to collect motion values during the last 30 seconds of each running speed to ensure that the runner obtained a steady pattern of motion before data capture. A high-speed camera captured motion at a sampling rate of 200 Hz from the sagittal and frontal planes. Reflective markers were applied to anatomical landmarks and body segments using a modified Helen Hayes Markers Set [22]. For the static calibration trials, markers were placed bilaterally on the acromion processes, triceps, lateral elbows, forearms, wrists, posterior superior iliac spine, anterior superior iliac spine, anterior thigh, medial, and lateral condyles of the femur, tibial tuberosity, medial and lateral malleoli, calcaneus, lateral to the head of the fifth metatarsal, and medial to the base of the hallux. An offset marker was placed on the right scapular inferior angle (Figure 1). For the running trials, medial knee and ankle markers were removed.

Kinematics and Spatiotemporal Parameters

Joint range of motion (ROM) of the ankle, knee, hip, and pelvis represented the angular excursion of the joint in the sagittal plane during 1 gait cycle (flexion/extension motion for the ankle, knee, and hip). The amount of change in anterior pelvic tilt during a gait cycle was also calculated. A pelvis segment was created from the anterior and posterior superior iliac spine markers, and the anterior orientation was expressed relative to the horizontal as 0° of anterior tilt. The difference of the maximal and minimal value for the anterior tilt was the overall tilt ROM. ROM of each joint are presented, as these represent the overall motion achieved during the whole gait cycle rather than using angles achieved at discrete gait cycle time points [23]. Cadence, center of gravity (COG) displacement, step length, step width, and ROM in the sagittal plane were calculated using commercially available software (Visual3D; C-motion, Inc, Germantown, MD). The COG was calculated using estimated body segmental masses and lengths, with segmental mass adjustments as described by de Leva [24]. A bone model of each runner was generated with the individual COG location.

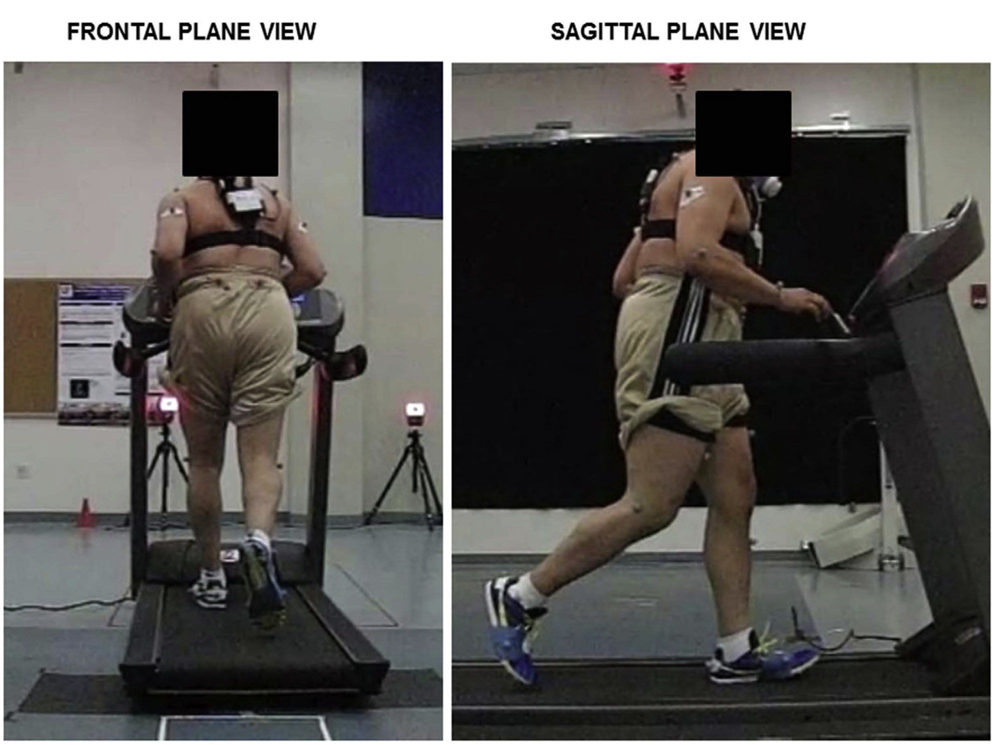

Figure 1. Testing setup for kinematic, spatiotemporal, and metabolic measures viewed in the frontal and sagittal planes. The metabolic device on the harness is a K4b^2 unit (COSMed, Rome, Italy).

Cardiopulmonary and Metabolic Measures

Cardiopulmonary and metabolic assessments were captured using a portable oxygen consumption device (K4b^2; COSMed, Rome, Italy). A telemetric heart rate (HR) monitor relayed the HR signal directly into the K4b^2 device. The K4b^2 unit acquired a breath-by-breath measurement of gas exchange via a rubberized facemask and a turbine for gas collection. Before testing, the K4b^2 unit was warmed up for a minimum of 30 minutes. After the warm-up period, the O_2 and CO_2 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 treadmill warm-up, and during the self-selected and standardized running speeds. The relative rate of oxygen consumption ($\dot{V}O_2$) and minute ventilation (Ve) were captured from the K4b^2 device. Measurements were collected after 5 minutes when a metabolic steady state had been achieved [9]. Breath-by-breath $\dot{V}O_2$ was averaged every 30 seconds. The last minute of each speed was considered the steady state, as the change in $\dot{V}O_2$ did not rise more than 100 mL [25]. The mean HR value was calculated as the average HR achieved during the final 30 seconds of the stage. The relative intensity of the running was reported as a percentage of the maximal HR and was calculated as follows: percentage of maximum HR(beats/min) = (mean HR/[220 − age]) × 100.

The energy cost of running per unit body mass and distance was determined as previously described: Gross energy cost (J/kg*m) = (rate of energy expenditure in J*min)/ (body weight in kg)*(running speed in meters/min), and net energy cost was then derived from the subtraction of the resting standing energy cost from the exercise energy cost [26,27].

Statistical Analysis

Data were managed using REDCap (Research Electronic Data Capture) [28]. Statistical analyses were performed using the Statistical Package for the Social Sciences (v. 22.0; IBM SPSS, Armonk, NY). Data are expressed as means ± standard deviations (SD) or as percentages of the study groups. Descriptive statistics and frequencies were obtained to characterize the 2 groups using χ^2 tests for categorical variables and Mann-Whitney *U* tests for continuous variables. Kolmogorov-Smirnov testing revealed normality of the participant characteristics, cardiopulmonary measures, metabolic variables, sagittal plane kinematics, and spatiotemporal parameters. Due to the unequal sample sizes, kurtosis, and skewness of some of the kinematic ROM variables, nonparametric Mann-Whitney *U* tests were used to determine whether differences existed between groups. The study group was the independent variable (overweight and healthy weight) and the cardiopulmonary, metabolic, and kinematic variables were the dependent variables (HR, rates of energy expenditure, $\dot{V}O_2$, Ve, spatiotemporal parameters, and joint ROM values).

Our descriptive statistics revealed significant differences in self-selected running speed and weekly distance. To account for baseline differences in self-selected speed and weekly running distance, univariate analyses of variance were performed on these same variables used in the non-parametric tests, with preferred running speed and weekly distance as covariates. The independent factor was the study group (overweight, healthy weight). Both parametric and nonparametric tests identified the same variables that were different between the overweight and healthy weight runners. Therefore, we present the nonparametric test results in the following sections. Significance was established at $P < .05$ a priori for all statistical tests.

Results

Participant Characteristics

Characteristics are shown in Table 1. Participants in the 2 groups were well-matched in several respects, except for the body composition parameters ($P < .05$). As expected, the BMI, body fat, and lean mass values were higher in the overweight group compared to the healthy weight group (all $P < .05$). The weekly distance was less in the overweight group compared to the healthy weight group ($P < .05$). The characteristics of the shoes worn were similar between the healthy weight and overweight groups.

Spatiotemporal Parameters of Running Gait

Table 2 provides the spatiotemporal and parameters of running gait at both speeds. At the self-selected

Table 1
Participant characteristics

Characteristic	Overweight (n = 21)	Healthy Weight (n = 42)	*P*
Age (y)	41.9 ± 11.0	43.6 ± 12.4	.637
Women (%)	55.6	59.6	.942
Height (cm)	170.8 ± 11.9	170.9 ± 9.4	.973
Weight (kg)	86.2 ± 15.6	64.1 ± 9.9	.0001*
BMI (kg/m^2)	29.4 ± 3.1	21.8 ± 1.9	.0001*
Body fat (%)	33.7 ± 8.6	19.3 ± 8.1	.0001*
Fat mass (kg)	28.1 ± 9.9	12.2 ± 5.1	.0001*
Lean mass (kg)	55.7 ± 16.9	51.8 ± 10.4	.276
Running experience (y)	8.3 ± 8.9	14.2 ± 12.1	.070
Weekly distance (km)	23.5 ± 8.5	36.9 ± 25.4	.037*
Shoe weight (oz)	9.4 ± 1.4	9.6 ± 1.4	.669
Heel-to-toe drop (mm)	7.3 ± 3.1	8.1± 3.6	.474

Values are mean ± standard deviation or percentage of group.
BMI = body mass index; Heel to toe drop = height differential from heel to toe.
* Asterisks in *P* column denote significant difference between groups.

Table 2
Spatiotemporal parameters during an average gait cycle at a self-selected and standardized speed

Parameter	Overweight (n = 21)	Healthy Weight (n = 42)	P
Self-selected speed (km/h)	8.5 ± 1.3	10.0 ± 1.6	.001*
Cadence (step/min)	163 ± 9	169 ± 9	.035*
Step length (cm)	85.8 ± 5.0	79.9 ± 22.1	.406
COG displacement (cm)	7.7 ± 1.7	8.6 ± 1.4	.017*
Stance time (% of gait cycle)	32.7 ± 7.0	32.3 ± 4.6	.842
Stride width (cm)	10.1 ± 2.2	8.7 ± 2.2	.021*
Running speed, 13.6 km/h			
Cadence (step/min)	167 ± 18	176 ± 11	.132
Step length (cm)	121.8 ± 12.2	119.7 ± 22.1	.806
COG displacement (cm)	8.9 ± 1.7	8.9 ± 1.7	.357
Stance time (% of gait cycle)	33.3 ± 2.9	31.0 ± 3.1	.071
Stride width (cm)	8.4 ± 3.7	8.4 ± 2.3	.988

Values are mean ± standard deviation.
COG = center of gravity displacement.
* Asterisks in *P* column denote significant difference between groups.

speed, overweight runners preferred a slower running speed and cadence than runners with healthy weight ($P < .05$). COG vertical displacement was an average of 0.9 cm lower, and cadence was 3.6% slower, in the overweight runners compared to the healthy weight runners (both $P < .05$) . At the standardized speed, there were no differences in any spatiotemporal parameter between the 2 groups.

Kinematic Parameters of Running Gait

The kinematic parameters of running gait in the 3 planes of motion are shown in Table 3. At the self-selected speed, the overweight runners demonstrated lower ROM excursions during an average gait cycle in the sagittal plane for ankle (plantar-dorsiflexion), knee (flexion-extension), hip (flexion-extension), and anterior pelvic tilt than the healthy weight runners (all $P < .05$). At the standardized speed of 13.6 km/h, the overweight runners did not demonstrate any differences in kinematic variables except for greater hip and pelvis ROM in the frontal plane compared to those of healthy weight runners ($P < .05$).

Cardiopulmonary and Metabolic Responses

The cardiopulmonary and metabolic responses to running at the 2 speeds are shown in Table 4. At the self-selected speed, there were no significant differences between the 2 groups in the energy cost, Ve, RER, HR, or percentage of the maximal HR. The ventilation rate was significantly higher in the overweight runners ($P < .05$). At the standardized speed, the rate of energy use, net energy cost, and Ve were significantly higher in the overweight runners compared to the healthy weight controls (all $P < .05$).

Table 3
Joint range of motion (ROM) in the sagittal, frontal, and transverse planes during an average gait cycle at self-selected and standardized speeds

	Overweight (n = 21)	Healthy Weight (n = 42)	P
Self-selected speed (km/h)			
Sagittal plane			
Ankle ROM (°)	44.1 ± 7.1	49.4 ± 7.1	.005*
Knee ROM (°)	75.0 ± 10.8	84.1 ± 12.8	.003*
Hip ROM (°)	52.4 ± 6.4	56.0 ± 6.4	.011*
Pelvis ROM (°)	7.2 ± 2.4	8.3 ± 1.9	.033*
Frontal plane			
Ankle ROM (°)	14.1 ± 3.1	14.9 ± 4.3	.698
Knee ROM (°)	10.3 ± 4.7	9.9 ± 3.4	.978
Hip ROM (°)	22.9 ± 5.1	20.9 ±5.3	.244
Pelvis ROM (°)	11.8 ± 3.7	11.5 ± 3.3	.854
Transverse plane			
Ankle ROM (°)	13.6 ± 2.7	13.7 ± 3.2	.999
Knee ROM (°)	21.4 ± 6.4	19.5 ± 4.6	.406
Hip ROM (°)	20.8 ± 6.5	19.5 ± 6.1	.305
Pelvis ROM (°)	14.2 ± 5.6	13.8 ± 4.6	.803
Standardized speed, 13.6 km/h			
Sagittal plane			
Ankle ROM (°)	49.1 ± 4.6	52.8 ± 7.3	.128
Knee ROM (°)	99.6 ± 15.4	97.8 ± 12.1	.865
Hip ROM (°)	72.5 ± 10.5	67.7 ± 6.0	.154
Pelvis ROM (°)	8.6 ± 2.7	9.1 ± 2.2	.410
Frontal plane			
Ankle ROM (°)	15.2 ± 3.1	16.8 ± 5.2	.525
Knee ROM (°)	11.2 ± 3.8	11.0 ± 3.3	.988
Hip ROM (°)	29.8 ± 6.9	23.6 ± 5.6	.040*
Pelvis ROM (°)	18.8 ± 4.3	14.5 ± 3.8	.008*
Transverse plane			
Ankle ROM (°)	15.1 ± 2.1	15.9 ± 4.1	.745
Knee ROM (°)	17.6 ± 3.5	19.2 ± 5.6	.745
Hip ROM (°)	23.6 ± 6.4	20.5 ± 7.6	.137
Pelvis ROM (°)	20.3 ± 6.5	17.0 ± 5.0	.206

Values are mean ± standard deviation.
ROM = range of motion (difference between maximum and minimum joint angles for ankle, knee and hip, and pelvis during gait cycle).
* Significant differences between groups.

Discussion

The novel findings of this study were that trained overweight runners prefer to run at a slower speed associated with less COG vertical displacement and sagittal plane ROM excursion in the lower body joints at self-selected speed. Moreover, the energetic cost and Ve were higher in overweight runners at the standardized speed compared to the healthy weight runners. At relatively faster standardized speeds, however, overweight runners are capable of running with lower extremity kinematics similar to those of runners with healthy weight. These findings are in partial agreement with our hypotheses, showing that overweight runners can achieve similar sagittal and frontal plane joint ROM excursions. These data suggest that trained overweight individuals prefer to self-modulate movement strategies that control the metabolic expense [29] of running and potentially reduce joint forces [29,30]. The general runner

Table 4
Cardiopulmonary and metabolic responses at the self-selected and standardized running speeds

	Overweight (n = 21)	Healthy Weight (n = 42)	*P*
Self-selected speed (km/h)			
Average $\dot{V}O_2$ (mL/kg*min)	32.3 ± 6.3	35.7 ± 6.7	.095
Rate of energy expenditure (kJ/min)	54.2 ± 10.9	47.5 ± 11.4	.440
Energy cost, net (J/m*kg)	4.7 ± 1.2	4.3 ± 0.7	.336
Nonprotein RER	0.89 ± 0.06	0.92 ± 0.11	.983
Ve (L/min)	72.9 ± 12.3	67.9 ± 12.7	.166
Heart rate (beats/min)	151 ± 25	146 ± 19	.299
% Maximal heart rate	85.1 ± 15.8	82.4 ± 10.0	.450
Standardized speed, 13.6 km/h			
Average $\dot{V}O_2$ (mL/kg*min)	40.4 ± 6.7	40.2 ± 6.7	.647
Rate of energy expenditure (kJ/min)	70.6 ± 12.2	54.6 ± 10.4	.001*
Energy cost, net (J/m*kg)	7.1 ± 1.2	5.4 ± 1.0	.001*
Nonprotein RER	1.08 ± 0.10	1.09 ± 0.13	.798
Ve (L/min)	95.4 ± 15.4	83.8 ± 11.3	.050*
Heart rate (beats/min)	166 ± 14	154 ± 28	.651
% Maximal heart rate	92.8 ± 5.7	86.3 ± 15.7	.300

Values are mean ± standard deviation.
LBM = lean body mass; $\dot{V}O_2$ = rate of oxygen consumption; Ve = minute ventilation.
* Asterisks in *P* column denote significant differences between groups.

self-modulates motion to an extent to manage energy cost and perceived comfort. However, this modulation is of particular importance to individuals with additional mechanical challenges (eg, heavy limb segments, abdominal girth, and higher joint moments) to increase exercise comfort and to minimize joint stress over the long term.

Few directly comparative metabolic data are available, but our data are not entirely supportive of our hypotheses. We anticipated that the energy cost for the overweight persons would be higher during running (large displacement of body segments) than that of persons with healthy weight, as was previously found by Lafortuna et al [15]. In contrast, Taboga et al reported no differences in energetic cost between obese and nonobese persons (130.7 kg versus 64.1 kg) during treadmill running at 8 km/h [31]. There were also no differences in other metabolic values such as RER and metabolic efficiency. The authors interpreted the findings to mean that that higher body masses are not associated with higher mechanical energy cost and that less energy is consumed [31]. LeCheminant et al collected metabolic responses from untrained obese/overweight and healthy weight controls during a 1.609-km jog. The oxygen cost ($\dot{V}O_2$) values tended to be lower in the obese-overweight group, but the net energy expenditure was higher in the overweight group (431 kJ versus 336 kJ) [12]. In our study, the rate of energy use and net energy cost were different only at the standardized speed but not the self-selected speed. We also did not find differences between groups for nonprotein RER values, suggesting that the overweight runners used similar fat and carbohydrate proportions while running at both speeds. Our findings did not support the hypothesis that overweight runners consistently run with faster cadence and less ROM in the sagittal and frontal planes. Cadence was less at the self-selected speed, and ROM was not different at the faster speed. These findings suggest that the less rapid turnover of heavier limb segments of the overweight runners at either speed may have been energetically more efficient that fast turnover of heavy limb segments.

Several adaptations to regular running may have occurred in our overweight runners to explain our findings. First, connective tissue adaptations may have occurred with overweight individuals to improve muscle storage of elastic energy, and thereby attenuates the amount of energy required for running [31]. Thicker fascia may contribute to increased ability for energy storage during stance phase of loading, and to transfer of the stored energy into propulsion forward [32] during running. Tendon stiffness can be increased with endurance training and is related to lower oxygen cost during running activity at different speeds [33]. Second, the overweight runners might have improved muscle activation patterns that contained the energy cost of running similar to those of healthy weight persons at self-selected speeds. It is possible that our overweight runners developed a passive gait strategy during their training to help with energy recovery. Specifically, overweight children have greater gastrocnemius activation during stance to help with stability and propulsion when compared to normal or underweight peers at similar gait speeds [34]. During the swing phase, however, gastrocnemius, tibialis anterior, and vastus lateralis muscle activation was significantly lower [34]. When applied to our study, "self-optimization" of muscle recruitment patterns might have controlled the metabolic demand between the overweight and healthy weight runners. Third, our trained overweight runners likely experienced metabolic adaptations to running by training regularly and habituating to the self-selected pace. For example, short-term running/cycling exercise increases fat use [35] and aerobic capacity in obese persons [36]. Our participants are distinctly different from sedentary overweight persons from other studies that have examined walking gait [9,10,37-39] and jogging in untrained individuals [12,31]. Additional investigation of the connective tissue properties, electromyographic activity, and muscle cell adaptations would address these possibilities.

Our data may indicate that overweight persons adopt a running strategy that is most comfortable and has a relative energy cost similar to that of healthy weight persons. Importantly, the overweight runners chose a running speed 1.5 km/h slower than the healthy weight controls. However, both groups were running at paces that yielded similar ventilation rates, heart rates, and intensities corresponding to 85% and 82% of their age-predicted maximal HR values. One interpretation is the recognition that these overweight runners were simply slower runners. Another likely possibility is that the slower speeds allowed self-regulation of joint stresses with exercise participation over the long-term. In studies of walking, adiposity adversely affects knee flexion and extension velocities [39] and reduces the range of motion of knee flexion-extension during the gait cycle [40]. Anterior pelvic tilt during walking is also exaggerated with obesity [40]. Browning and Kram [30] postulated that adopting a slower walking speed may reduce excessive knee joint moments. Excessive weight affects walking gait patterns by decreasing knee ROM excursion [41], increasing pelvic obliquity [38], and shortening step lengths [29].

These collective motion strategies combined with others may maximize dynamic stability in running. For example, less sagittal ROM occurred in all lower body joints, and wider step width and less vertical displacement of the COG stabilize the landing in each gait cycle by facilitating a wider base of support and foot strike closer to vertical alignment with the COG. Additional studies are needed to determine whether these spatiotemporal and kinematic running characteristics can attenuate ground reaction forces and joint moments. It is not yet clear how modifying each spatiotemporal factor such as step length, width, cadence, or stance time would change the lower extremity kinetics, metabolic responses, and energy cost. However, this information would be very valuable in developing safe running programs for overweight runners.

The present findings agree with previous studies of acute exercise responses in obese individuals. Obese persons generated higher heart rates and metabolic responses than persons with healthy weight at the same walking or cycling exercise workload [42,43]. In another study, untrained obese adults who jogged for a standard test distance expended 31% more energy than their nonobese counterparts [12]. Here, overweight runners demonstrated a greater Ve and energy cost at the relatively higher standardized running speed compared to healthy weight runners. Prospective training research that determined the time course and magnitude of the cardiopulmonary adaptations to running among persons of different BMI values would help to clarify the training effects on the cardiopulmonary system and energy expenditure.

Limitations and Strengths

This was a small secondary analysis from a large cohort of runners, and the analysis was therefore not powered to detect differences in all of the study variables if differences did exist. For example, interindividual differences in body weight distribution [14] and skill of running technique may have contributed to the variation in energy cost. We acknowledge the challenges of kinematic measurements in persons with excessive body fat. Additional work using joint center determination could help to confirm whether the frontal motion differences in the pelvis and hip at the standardized speed between the overweight and healthy weight were due to soft tissue artifact or true differences in joint displacement. It would have been interesting to have captured electromyographic data of the patterns of muscle recruitment and perceptual responses to workload to determine factors related to muscle fatigue or energy cost. Other studies have revealed that the self-selected walking in overweight and obese people does not meet the requirements for moderate physical activity [10]. Thus, the self-selected running speed that is the most metabolically efficient by overweight runners in the long run may not be the best for weight loss goals and overall long-term joint health. Addressing these issues is clinically important from the exercise prescription and injury prevention perspectives. The strengths of the study include the use of trained overweight runners familiar with running on treadmills. This novel population provided the first look at how overweight runners respond metabolically and kinematically to different running speeds. The simultaneous collection of metabolic and motion data provides a strong combination of information to help understand the exercise responses to running in this population.

Conclusions

Overweight runners may adopt slower self-selected speeds and gait strategies to minimize energy expenditure and to reduce joint stress. From a kinematic and metabolic perspective, overweight individuals who participate regularly in moderate to vigorous running are just as capable as healthy weight individuals of running at a standard speed.

Acknowledgments

The authors thank Amanda S. Stevenson and Cindy Montero for their assistance with data collection. This work was supported by the Interdisciplinary Center for Musculoskeletal Training and Research (ICMTR).

References

1. Running USA. Available at: http://www.runningusa.org/index.cfm?fueseaction=news.details&ArticleID=1539&returnTo=annual-reports. Accessed November 4, 2014.
2. Chorley JN, Cianca JC, Divine JG, Hew TD. Baseline injury risk factors for runners starting a marathon training program. Clin J Sport Med 2002;12:18-23.
3. Rodacki AL, Fowler NE, Provensi CL, Rodacki Cde L, Dezan VH. Body mass as a factor in stature change. Clin Biomech (Bristol, Avon) 2005;20:799-805.

4. Nielsen RO, Bertelsen ML, Parner ET, Sørensen H, Lind M, Rasmussen S. Running more than three kilometers during the first week of a running regimen may be associated with increased risk of injury in obese novice runners. Int J Sports Phys Ther 2014;9: 338-345.
5. Williams PT. Relationship of running intensity to hypertension, hypercholesterolemia, and diabetes. Med Sci Sports Exerc 2008;40: 1740-1748.
6. Sijie T, Hainai Y, Fengying Y, Jianxiong W. High intensity interval exercise training in overweight young women. J Sports Med Phys Fitness 2012;52:255-262.
7. Huang L, Chen P, Zhuang J, Walt S. Metabolic cost, mechanical work, and efficiency during normal walking in obese and normal-weight children. Res Q Exerc Sport 2013;84:S72-S79.
8. Browning RC, Kram R. Energetic cost and preferred speed of walking in obese versus normal weight women. Obes Res 2005;13: 891-899.
9. Browning RC, Reynolds MM, Board WJ, Walters KA, Reiser RF. Obesity does not impair walking economy across a range of speeds and grades. J Appl Physiol (1985) 2013;114:1125-1131.
10. Ehlen KA, Reiser RF 2nd, Browning RC. Energetics and biomechanics of inclined treadmill walking in obese adults. Med Sci Sports Exerc 2011;43:1251-1259.
11. Freedman Silvernail J, Milner CE, Thompson D, Zhang S, Zhao X. The influence of body mass index and velocity on knee biomechanics during walking. Gait Posture 2013;37: 575-579.
12. LeCheminant JD, Heden T, Smith J, Covington NK. Comparison of energy expenditure, economy, and pedometer counts between normal weight and overweight or obese women during a walking and jogging activity. Eur J Appl Phys 2009;106: 675-682.
13. Peyrot N, Morin J, Thivel D, et al. Mechanical work and metabolic cost of walking after weight loss in obese adolescents. Med Sci Sports Exerc 2010;42:1914-1922.
14. Pedersen AV, Stokke R, Mamen A. Effects of extra load position on energy expenditure in treadmill running. Eur J Appl Phys 2007;102: 27-31.
15. Lafortuna CL, Chiavaroli S, Rastelli F, et al. Energy cost and cardiovascular response to upper and lower limb rhythmic exercise with different equipments in normal-weight and severely obese individuals. J Endocrinol Invest 2011;34:131-139.
16. Ginde SR, Geliebter A, Rubiano F, et al. Air displacement plethysmography: Validation in overweight and obese subjects. Obes Res 2005;13:1232-1237.
17. Moore IS, Jones AM, Dixon SJ. Relationship between metabolic cost and muscular coactivation across running speeds. J Sci Med Sport 2014;17:671-676.
18. Petersen J, Nielsen RO, Rasmussen S, Sørensen H. Comparisons of increases in knee and ankle joint moments following an increase in running speed from 8 to 12 to 16km·h(-1.). Clin Biomech (Bristol, Avon) 2014;29:959-964.
19. Bigelow EM, Elvin NG, Elvin AA, Arnoczky SP. Peak impact accelerations during track and treadmill running. J Appl Biomech 2013; 29:639-644.
20. Dierks TA, Davis IS, Hamill J. The effects of running in an exerted state on lower extremity kinematics and joint timing. J Biomech 2010;43:2993-2998.
21. Queen RM, Gross MT, Liu HY. Repeatability of lower extremity kinetics and kinematics for standardized and self-selected running speeds. Gait Posture 2006;23:282-287.
22. Kadaba MP, Ramakrishnan HK, Wootten ME. Measurement of lower extremity kinematics during levels walking. J Orthop Res 1990;8: 383-392.
23. Nigg S, Vienneau J, Maurer C, Nigg BM. Development of a symmetry index using discrete variables. Gait Posture 2013;38:115-119.
24. de Leva P. Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. J Biomech 1996;29:1223-1230.
25. Fletcher JR, Esau SP, MacIntosh BR. Economy of running: Beyond measurement of oxygen uptake. J Appl Physiol (1985) 2009;107: 1918-1922.
26. Maffiuletti NA, Malatesta D, Agosti F, Sartorio A. Unstable shoes increase energy expenditure of obese patients. Am J Med 2012;5: 513-516.
27. Delextrat A, Matthew D, Cohen DD, Brisswalter J. Effect of stride frequency on the energy cost of walking in obese teenagers. Hum Mov Sci 2011;30:115-124.
28. 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.
29. Lai PP, Leung AK, Li AN, Zhang M. Three-dimensional gait analysis of obese adults. Clin Biomech (Bristol, Avon) 2008;23:S2-S6.
30. Browning RC, Kram R. Effects of obesity on the biomechanics of walking at different speeds. Med Sci Sports Exerc 2007;39: 1632-1641.
31. Taboga P, Lazzer S, Fessehatsion R, Agosti F, Sartorio A, di Prampero PE. Energetics and mechanics of running men: The influence of body mass. Eur J Appl Physiol 2012;112:4027-4033.
32. Eng CM, Pancheri FQ, Lieberman DE, Biewener AA, Dorfmann L. Directional differences in the biaxial material properties of fascia lata and the implications for fascia function. Ann Biomed Eng 2014;42:1224-1237.
33. Kubo K, Tabata T, Ikebukuro T, Igarashi K, Tsunoda N. A longitudinal assessment of running economy and tendon properties in long-distance runners. J Strength Cond Res 2010;24: 1724-1731.
34. Blakemore VJ, Fink PW, Lark SD, Shultz SP. Mass affects lower extremity muscle activity patterns in children's gait. Gait Posture 2013;38:609-613.
35. Carter SL, Rennie C, Tarnopolsky MA. Substrate utilization during endurance exercise in men and women after endurance training. Am J Physiol Endocrinol Metab 2001;280:898-907.
36. Louche K, Badin PM, Montastier E, et al. Endurance exercise training up-regulates lipolytic proteins and reduces triglyceride content in skeletal muscle of obese subjects. J Clin Endocrinol Metab 2013;98:4863-4871.
37. Browning RC, Modica JR, Kram R, Goswami A. The effects of adding mass to the legs on the energetics and biomechanics of walking. Med Sci Sports Exerc 2007;39:515-525.
38. Lerner ZF, Board WJ, Browning RC. Effects of obesity on lower extremity muscle function during walking at two speeds. Gait Posture 2013;39:978-984.
39. Page Glave A, Di Brezzo R, Applegate DK, Olson JM. The effects of obesity classification method on select kinematic gait variables in adult females. J Sports Med Phys Fitness 2014;54: 197-202.
40. Ranavolo A, Donini LM, Mari S, et al. Lower-limb joint coordination pattern in obese subjects. Biomed Res Int 2013;2013: 142323.
41. DeVita P, Hortobagyi T. Obesity is not associated with increased knee joint torque and power during level walking. J Biomech 2003; 36:1355-1362.
42. Lafortuna CL, Agosti F, Galli R, Busti C, Lazzer S, Sartorio A. The energetic and cardiovascular response to treadmill walking and cycle ergometer exercise in obese women. Eur J Appl Physiol 2008; 103:707-717.
43. Norman AC, Drinkard B, McDuffie JR, Ghorbani S, Yanoff LB, Yanovski JA. Influence of excess adiposity on exercise fitness and performance in overweight children and adolescents. Pediatrics 2005;115:e690-e696.

Disclosure

L.A.Z. Department of Orthopaedics and Rehabilitation, Divisions of Research and Physical Medicine 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, Divisions of Research and Physical Medicine and Rehabilitation, Interdisciplinary Center for Musculoskeletal Training and Research, University of Florida, Gainesville, FL
Disclosure: nothing to disclose

M.H. Department of Orthopaedics and Rehabilitation, Divisions of Research and Physical Medicine 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, Divisions of Research and Physical Medicine and Rehabilitation, Interdisciplinary Center for Musculoskeletal Training and Research, University of Florida, Gainesville, FL
Disclosure: nothing to disclose

H.K.V. Division of Research, UF Orthopaedics and Sports Medicine Institute, University of Florida, PO Box 112727, Gainesville, FL 32611. Address correspondence to: H.K.V.; e-mail: vincehk@ortho.ufl.edu
Disclosure: nothing to disclose

Submitted for publication April 3, 2015; accepted June 11, 2015.