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Biomechanical, metabolic and cardiopulmonary responses of masters recreational runners during running at different speeds

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ABSTRACT
This study tested interactions between age and running speed on biomechanics, metabolic responses and cardiopulmonary responses. Three-hundred participants ran at preferred and standardized speeds. Age group (younger, masters [≥40 years]) by speed (self-selected 8.8 km/h, 11.2 km/h and 13.6 km/h) interactions were tested on main outcomes of sagittal kinematic, temporal spatial, metabolic and cardiopulmonary parameters. At all speeds, angular displacements of the ankle, pelvis and knee were less in masters than younger runners (Hedges g effect size range = 0.30–1.04; all $p < 0.05$). A significant age group by speed interaction existed for hip angular displacement (Wald $\chi^2 = 10.753$; $p = 0.013$). Masters runners ran at higher relative heart rates ($p < 0.05$) but at similar rates of oxygen use and energy expenditure. Masters runners used hip-dominant motion and step lengthening as running speed increased, but did not change centre of mass vertical displacement. This may increase mechanical stresses on tissues of the lower extremity in masters runners, especially hamstrings, hip joint and Achilles.

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Running; kinematics; energy expenditure; oxygen uptake; aged

Introduction

Regular running is associated with numerous positive physiological and psychological benefits, such as aerobic fitness, cardiovascular health, tolerance to moderate dehydration, emotional well-being, weight management and reduction of disability and mortality (Buchan et al., 2015; Chakravarty, Hubert, Lingala, & Fries, 2008; Hoffman & Stuempfle, 2014; Szabo & Abrahám, 2013; Williams, 1997, 2013). However, running is also related to musculoskeletal injuries, endocrine and renal dysregulation and unhealthy psychological functioning when this exercise mode is performed in excess (Beckvid Henriksson, Schnell, & Lindén Hirschberg, 2000; Kerr et al., 2016; Lipman et al., 2014; Lopes, Hespanhol Júnior, Yeung, & Costa, 2012; Shipway & Holloway, 2010). The demographics of the running population have shifted to consist of more masters athletes. In the United States alone, there has been a 300% increase in race finishers since 1990, with a 2–26% increase in

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participation in age brackets over 40 years of age (Running USA, 2015). This growth suggests that a strong understanding of the motion strategies and physiologic responses of masters athletes to running is needed to keep this contingent safely participating in this sport.

Compared to younger counterparts, masters runners have a higher musculoskeletal injury rate (McKean, Manson, & Stanish, 2006). Ageing itself is naturally related to a reduction in muscle-tendon stiffness (Karamanidis & Arampatzis, 2007), to a decline in aerobic fitness and to a relatively higher heart rate (HR) response to progressively higher running speeds (Quinn, Manley, Aziz, Padham, & MacKenzie, 2011). Masters runners have been shown to have slower preferred running speeds, slower competitive running times (Bus, 2003; Conoboy & Dyson, 2006; Li, 2015), greater internal knee rotation (Lilley, Dixon, & Stiles, 2011), and lesser ground reaction forces.(DeVita et al., 2016.) At preferred running speeds, masters runners demonstrate shorter stride length, longer stance time and less angular displacement of lower body joints compared to younger counterparts (Conoboy & Dyson, 2006). These differences may possibly maintain physical comfort and reduce fatigue and injury risk (Hafer, Freedman Silvernail, Hillstrom, & Boyer, 2016; Winter, Gordon, & Watt, 2016).

Maintenance of running over the long-term is dependent on avoidance of injury. Speed is a modifiable risk factor for musculoskeletal injury (Hespanhol Junior, Pena Costa, & Lopes, 2013). The lower extremity joint loads are impacted by faster speed (De David, Carpes, & Stefanyshyn, 2015) and the musculoskeletal structures become mechanically overloaded (Hespanhol Junior et al., 2013). An understudied area of running motion is the joint range of motion (ROM), or excursion, of the lower extremity joints and pelvis during the whole gait cycle. Available evidence of younger and older runners has focused on specific biomechanical elements or discrete mechanics at one set speed or the stance phase of the gait cycle (Conoboy & Dyson, 2006; Fukuchi & Duarte, 2008; Fukuchi, Stefanyshyn, Stirling, Duarte, & Ferber, 2014; Silvernail, Boyer, Rohr, Brüggemann, & Hamill, 2015). These study limitations are unfortunate because running is complex and involves both stance and flight phase, during which total joint excursions occur. The biomechanical strategy by which faster or slower running speeds is achieved has implications for impact forces, fatigue and metabolic efficiency of the motion (Schubert, Kempf, & Heiderscheit, 2014; Wille, Lenhart, Wang, Thelen, & Heiderscheit, 2014). For example, the ROM or joint excursion ROM that is achieved through step length or cadence at non-preferred speeds can affect risk factors for injury (Schubert et al., 2014; Winter et al., 2016). Older runners who demonstrate motion patterns that could lead to premature fatigue or tissue stress may be predisposed to injury.

Separate studies have been conducted to compare metabolic and cardiovascular responses in younger and masters runners at a variety of speeds (preferred, set speeds or speeds based on ventilatory threshold values) (Dias Pantoja, Morin, Peyré-Tartaruga, & Brisswalter, 2016; Hagberg et al., 1985; Peiffer, Abbiss, Sultana, Bernard, & Brisswalter, 2016; Quinn et al., 2011). Evidence is conflicting with respect to energy cost of running in older runners. Some studies show that trained masters runners demonstrate lower running efficiency at set speeds (Peiffer et al., 2016; Sultana et al., 2012), whereas others fail to find age-related differences in exercise economy relative to younger counterparts (Tanaka & Seals, 2008). Part of these discrepancies may be due to low average age of “older” runners, small study samples, different study designs, running speeds tested and characteristics of younger and masters runners.

The existing evidence gap is the comparative biomechanical and metabolic responses of masters runners to while running a range speeds in masters and younger runners. Addressing this gap will provide novel insight on speed-related effects that may accelerate metabolic fatigue and place unaccustomed stress on musculoskeletal tissues, both of which have been postulated to contribute to injury (Jewell, Boyer, & Hamill, 2016). The purpose of this study was to determine whether interactions existed between the age category (younger, masters) and running speed on the biomechanics, metabolic responses and cardiopulmonary responses. Due to the inconsistency of the evidence, we hypothesized that masters and younger runners would have similar biomechanical (temporal spatial, kinematic) responses and metabolic responses (oxygen use, ventilation, respiratory quotient and rate of energy expenditure) to each running speed. However, we hypothesized that masters runners would have greater cardiopulmonary responses to standardized speeds than younger comparators.

Methods

Study design

This was a cross-sectional, comparative study. This study and its procedures were approved by the University of Florida Institutional Review Board (study number 672-11). This study complies with the guidelines of Declaration of Helsinki for the treatment of human subjects. All participants read, understood and signed the approved informed consent document.

Participants

Male and female runners (N = 300) were included. Inclusion criteria were as follows: age 25–75 years, currently running at least 12 km/week, free of orthopaedic injury which prevented the ability to run on a treadmill and free of symptomatic cardiovascular disease. Exclusion criteria were as follows: use of medications that impaired gait or balance, and pregnancy. Runners were dichotomized by age, where masters runners were ≥40 years of age (n = 114) (Barnard, Grimditch, & Wilmore, 1979), and non-masters runners were <40 years of age (n = 186). These age brackets were selected to represent the USA Track and Field definitions for masters athletes. All participants were familiar with using treadmills for training purposes.

Participant characteristics

Health and training histories were completed using an electronic data repository system (REDCap) (Harris et al., 2009). Demographics, comorbidities, previous injuries and running experience were self-reported by each participant. Average weekly running distance, average distance of long runs, participation in and frequency of speed work and years of running experience were recorded. Body mass and body fat can impact energy cost (Bunc, 2000; Taboga et al., 2012) of running and mechanics (Zdziarski, Chen, Horodyski, Vincent, & Vincent, 2016). Body composition measures were collected using the technique of air plethysmography (BOD POD®; Life Measurement Inc., Concord, CA).

During the running test, participants wore their own shoes to promote normal running mechanics. Age-graded running performance scores were determined using USA Track and Field calculations to provide relative performance scores of running quality (Jones, 2015).

Temporal spatial and kinematic parameters

Participants ran on a commercial-grade treadmill (Landice, Inc; Randolph, NJ, USA; model L7). The rear structural supports of the treadmill were placed over two in-ground force plates to synchronize force data with the motion data for the purpose of detecting gait cycle time points (AMTI Watertown, Waltham MA, USA). A high-speed, 12-camera optical motion analysis system (Motion Analysis Corp, Santa Rosa, CA, USA) was used to collect motion data at a sampling rate of 300 Hz . A static L-frame and calibration wand with three reflective markers of known distance (500 mm) were used to calibrate the system. Motion was captured during a 30 s window at each running speed. Reflective markers were applied to anatomical landmarks and body segments using an established marker set by Kadaba et al. (1990). 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 fifth metatarsal and medial to the base of the hallux. An offset marker was placed on the right scapula. For running trials, medial knee and ankle markers were removed. The pelvis segment was developed from the anterior and posterior superior iliac spine markers, and the anterior orientation was expressed relative to the horizontal as 0° of anterior tilt.

Joint angular displacements in the sagittal plane were calculated using commercially available software (Visual3D, C-motion, Inc). Sagittal kinematics were chosen because these can estimate ground reaction forces and resultant joint kinetics.(Wille et al., 2014) Angular displacement of the ankle, knee, hip and pelvis represented the flexion/extension angular excursion of the joint in the sagittal plane during one gait was calculated from the difference between the maximum and minimum flexion angle. Anterior pelvic tilt angular displacement was calculated from the difference of the greatest and least anterior tilt values. Temporal spatial parameters included cadence, centre of mass (COM) displacement, step length and stance time. A gait cycle was defined as the time from foot contact with the treadmill to the point of the following contact of the same foot with the treadmill. The foot strike was detected when the calcaneal marker reached the greatest anterior distance from the trailing foot's calcaneal marker. Toe-off was detected at the point at which the minimal force data occurred from the force plates under the treadmill. Computer algorithms were developed to detect these thresholds across 10 gait cycles. Cadence was defined as the number of gait cycles per minute. The vertical displacement of the COM was calculated from Visual 3D as the difference in the maximal and minimal vertical height of the estimated COM during an average gait cycle. The stance time was determined as the percent of the gait cycle during which the foot made contact with the treadmill.

Metabolic and cardiopulmonary measures

Metabolic and cardiopulmonary parameters were estimated using a portable oxygen consumption (VO_2) device (COSMed, K4b$^{2;}$ Rome, Italy). A telemetric HR monitor relayed the HR signal directly into the K4b^2 device. Breath-by-breath measurements of gas exchange were collected via a rubberized facemask and a turbine for gas collection. Prior to each testing session, the unit was warmed-up 30 min and the O_2 and CO_2 analysers were calibrated using reference gases of known concentrations. Runners wore the K4b^2 unit during the stationary baseline period (3 min), the treadmill warm-up (3 min) and during the treadmill protocol (12 min; self-selected speed, standardized speeds of 8.8, 11.2 and 13.6 km/h). The average rate of energy expenditure (kilojoules per minute) and HR were determined from the last 30 s of each running speed. Breath-by-breath VO_2 and minute ventilation were averaged every 30 s (Fletcher, Esau, & Macintosh, 2009). To normalize the running intensity between younger and masters runners, the mean HR was expressed as percentage of the maximal HR using the following calculation: percentage of maximum HR (beats/min) = (mean HR/[220 − age]) × 100.

Treadmill running protocol

All participants performed a treadmill running protocol during one testing session. After standing for 3 min, participants walked for 3 min to warm-up. The speed of the treadmill was then increased to each participant's self-selected long-distance running pace. The following standardized instructions were provided to each runner: "Please select the running speed that feels what you would choose for a 9.6–12.8 km run." The treadmill speed was adjusted by a study team member until the participant acknowledged that the speed felt correct. Three standardized progressively faster speeds were then applied to the treadmill (8.8, 11.2 and 13.6 km/h). Previous studies of running kinetics and kinematics have used the self-selected running speed to represent each participant's typical long-distance training pace (Dierks, Davis, & Hamill, 2010). The standardized speeds used here represented the range that may be performed during interval work or during a race environment. Similar to previous work, the order of the running speeds was incremental rather than randomized for practicality (Petersen, Nielsen, Rasmussen, & Sørensen, 2014). All participants ran for approximately 18 min. The treadmill grade was 0° for all running speeds.

Statistical analysis

Data were managed using REDCap (Harris et al., 2009). Statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS; v.23.0). Data are expressed as means ± standard deviations or as the percent of the study groups. The assumptions were that data were normally distributed, independent and homogenous in variance. We assumed that the sample of runners tested was random. Normality of the data was first confirmed using Shapiro–Wilk tests for study variables. Variables that were not normally distributed (metabolic) were transformed prior to analysis (Log10). Descriptive statistics and frequencies were obtained to characterize the two groups using *t*-tests for continuous variables and chi-square tests for categorical variables.

Hedges *g* test were used to find effect sizes for the two groups to allow for weighting of different sample sizes. Interactions between age group (younger, masters) and running speed (self-selected, 8.8, 11.2 and 13.6 km/h) were tested using linear mixed models. The kinematic, metabolic and cardiopulmonary variables were the dependent variables (temporal spatial parameters, angular displacements, HR, rates of energy expenditure, ventilation and VO_2). If interactions were significant, main effects of age group and speed were tested. Significance was established at $p < 0.05$ for all statistical tests.

Results

Characteristics

Table 1 provides the participant characteristics. The young and masters runners were well-matched for all characteristics. No differences existed in body composition or body mass index. The years of running experience and typical long run distances were greater in the masters runner group (Hedges $g = 0.959$ and 0.278, respectively; $p < 0.05$). Age-grade performance scores were not different between the younger and masters runners, respectively (younger: 60.0% ± 13.0% [95% CI 56.8–63.1%] and masters 63.1% ± 12.3% [95% CI 59.9%–66.2%]; $p = 0.176$). Foot strike patterns in each group were as follows: young (82.0% heel strikers, 18.0% mid-forefoot strikers) and masters (87.3% heel strikers, 12.7% mid forefoot strikers; χ^2 test statistic = 1.620; $p = 0.203$). The characteristics of the shoes between groups were not found to be different. For the young and masters runners, respectively, the shoe characteristics were the following: weight (in g) = 279 and 280 ($p = 0.932$), heel-to-toe drop (in mm) = 8.66 and 8.35 ($p = 0.545$) and heel height (in mm) = 28.26 and 27.97 ($p = 0.755$).

Kinematic parameters

Table 2 shows the temporal spatial parameters for the young and masters groups running at self-selected speed, 8.8, 11.2, and 13.6 km/h. The self-selected speed of the masters runners was lower than the self-selected speed of the younger runners (Hedges g = 0.278; $p < 0$ .05). Age group by speed interactions was not significant for cadence,

Table 1. Characteristics of the young and masters runners.

	Young (<40 years)	Masters (≥40 years)	
	n = 186	n = 114	p (sig)
Women (%)	54.3	52.2	0.731
Age (years)	28.7 ± 6.2	51.1 ± 8.4	0.0001
Height (cm)	172 ± 8.9	173 ± 11.5	0.231
Mass (kg)	68.0 ± 12.8	69.4 ± 13.5	0.361
BMI (kg/m^2)	22.8 ± 3.5	23.1 ± 3.3	0.530
Body fat (%)	20.2 ± 8.7	21.7 ± 8.9	0.157
Lean mass (%)	79.8 ± 8.7	78.3 ± 8.9	0.891
Fat mass (kg)	13.7 ± 6.9	15.1 ± 7.8	0.140
Lean Mass (kg)	53.4 ± 11.5	53.5 ± 12.4	0.890
Running experience (years)	8.1 ± 6.2	17.0 ± 12.8	0.0001
Weekly distance (km)	33.1 ± 24.8	32.9 ± 18.7	0.963
Typical long run distance (km)	13.3 ± 6.9	15.5 ± 9.3	0/022

BMI, body mass index. Values are means ± SD or % of the group.

Table 2. Temporal spatial parameters of young and masters runners.

	Young (<40 years)	Masters (≥40 years)	p (sig) Age	Speed	Interaction
Cadence					
Self-selected speed (km/h)	167.0 ± 10.9	167.5 ± 10.3			
8.8 km/h	160.6 ± 15.6	162.3 ± 8.9			
11.2 km/h	168.1 ± 10.7	169.8 ± 10.5			
13.6 km/h	174.8 ± 11.9	175.9 ± 11.5	0.122	0.0001	0.947
Centre of mass displacement (cm)					
Self-selected speed (km/h)	9.0 ± 1.4	8.5 ± 1.5			
8.8 km/h	8.9 ± 1.4	8.7 ± 1.4			
11.2 km/h	9.1 ± 1.4	8.7 ± 1.3			
13.6 km/h	9.0 ± 1.4	8.7 ± 1.2	0.0001	0.629	0.447
Step length (m)					
Self-selected speed (km/h)	0.82 ± 0.22	0.79 ± 0.24			
8.8 km/h	0.82 ± 0.23	0.80 ± 0.24			
11.2 km/h	1.02 ± 0.23	1.00 ± 0.21			
13.6 km/h	1.21 ± 0.22	1.17 ± 0.25	0.048	0.0001	0.639
Stance time (% of gait cycle)					
Self-selected speed (km/h)	46.7 ± 8.1	46.7 ± 5.1			
8.8 km/h	46.0 ± 9.5	45.9 ± 7.8			
11.2 km/h	46.5 ± 8.5	46.7 ± 4.5			
13.6 km/h	46.8 ± 8.9	45.4 ± 6.7	0.004	0.0001	0.998

Values are means ± SD.

centre of gravity vertical displacement, step length and stance time. The main effect of age was significant for all variables except for cadence (Wald χ^2 = 2.394; p = 0.122). Main effects for running speed were significant for all temporal spatial variables except for COM displacement (Wald χ^2 = 1.737; p = 0.629).

Figure 1(a–d) displays the mean ankle, knee, hip and pelvis angular displacements in the sagittal plane. Age group by speed interactions were not found to be significant for the ankle, knee and pelvis excursions (all p values >0.05). However, the age by speed interaction term for the hip excursion value was significant (Figure 1(c);p = 0.013). The main effect of running speed achieved significance ($p < 0.0001$), but the main effect of age group did not (Wald χ^2 = 3.552; p = 0.061).

Metabolic and cardiopulmonary measures

Table 3 summarizes the metabolic and cardiopulmonary responses at each speed. No significant age group by speed interactions were revealed in these analyses (all general linear model test results yielded Wald χ^2 values between 0.211 and 1.037; all $p > 0.50$). The main effect of age group was significant for mean HR, percent of maximal HR, mean VO_2 and ventilation rate (all $p < 0.05$). As expected, there was a significant main effect of speed for all metabolic and cardiopulmonary variables in Table 3 (all $p < 0.0001$).

Discussion

This study determined whether or not interactions existed between the age category (younger, masters) and running speed on the biomechanics, metabolic responses and cardiopulmonary responses. Our main findings were that among all the main outcomes, a significant interaction of age group and speed existed for the hip angular

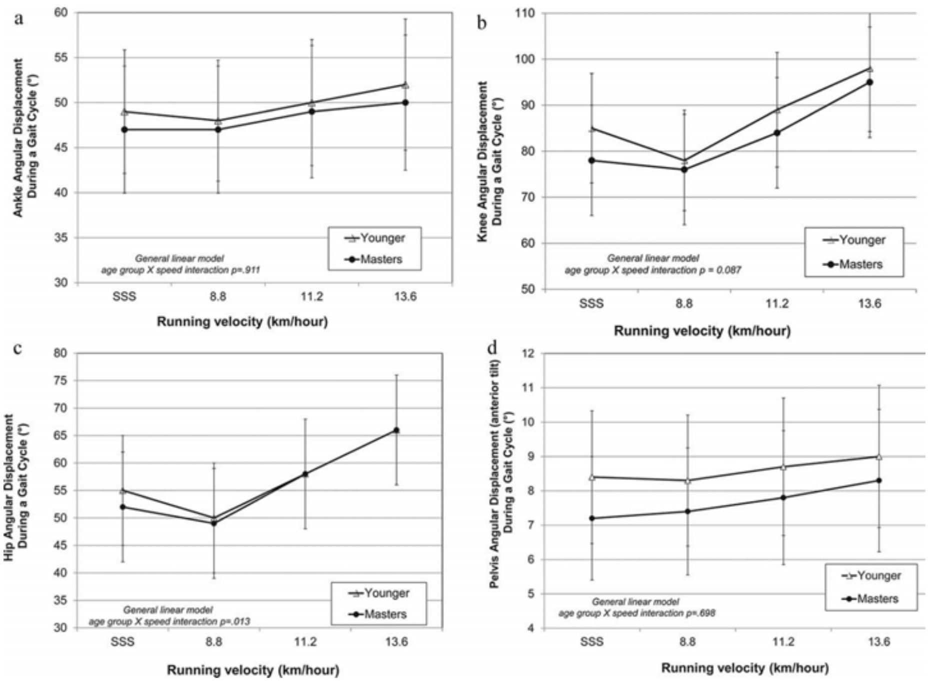

Figure 1. Sagittal plane flexion angular displacement during an average gait cycle in younger and masters runners. Values are expressed in means ± SD. (a) Ankle: the age group by speed interaction term was not significant (Wald χ^2 = 0.537; P = 0.911) (b) Knee: the age group by speed interaction term was not significant (Wald χ^2 = 6.575; P = 0.087) (c) Hip: significance of the age group by speed interaction was achieved (Wald χ^2 = 10.753; P = 0.01). Main effect of speed was significant (Wald χ^2 = 911.001; P < 0.0001) but not age code. (d) Pelvis: the age group by speed interaction term was not significant (Wald χ^2 = 1.430; P = 0.698).

displacement during the gait cycle. Our hypothesis was nearly fully supported by our finding that masters and younger runners would have similar biomechanical responses and metabolic responses to each running speed. Also, masters runners did demonstrate higher relative HRs and ventilation rates during running compared to younger counterparts.

Comparative kinematic studies

Ageing is associated with some modifications to running mechanics and temporal spatial parameters (Bus, 2003; Conoboy & Dyson, 2006; Fukuchi & Duarte, 2008) such as reductions in lower extremity joint angular displacement, preferred running speed, stride length and longer stance time (Conoboy & Dyson, 2006; Fukuchi et al., 2014). Our masters runners demonstrated less joint excursion during the gait cycle at all joints measured. Masters runners did not have different cadence, stride length or stance time values than younger runners. This finding is discrepant to previous works likely because of methodological differences. For example, some studies were conducted while runners ran on an over-ground force plate (Lilley et al., 2011). Conoboy and Dyson (2006)

Table 3. Metabolic and cardiopulmonary responses of young and masters runners.

	Young	Masters	p (sig) Age	Speed	Interaction
Mean heart rate					
Self-selected speed	146 ± 28	140 ± 22			
8.8 km/h	150 ± 27	141 ± 26			
11.2 km/h	153 ± 32	143 ± 30			
13.6 km/h	158 ± 32	153 ± 32	0.0001	0.0001	0.792
Percent of maximal heart rate					
Self-selected speed	76.9 ± 14.7	82.5 ± 13.6			
8.8 km/h	78.4 ± 14.1	83.1 ± 16.0			
11.2 km/h	79.9 ± 16.7	84.5 ± 18.4			
13.6 km/h	82.5 ± 16.7	89.3 ± 19.2	0.0001	0.0001	0.913
Mean VO_2 (mL/kg × min)					
Self-selected speed	35.0 ± 6.5	33.6 ± 5.6			
8.8 km/h	34.8 ± 6.5	32.8 ± 7.4			
11.2 km/h	36.4 ± 6.0	34.8 ± 8.0			
13.6 km/h	39.1 ± 6.5	37.1 ± 8.6	0.001	0.0001	0.976
Ventilation (L/min)					
Self-selected speed	68.4 ± 14.7	70.9 ± 14.0			
8.8 km/h	68.9 ± 15.2	72.1 ± 15.3			
11.2 km/h	73.7 ± 14.9	78.7 ± 17.7			
13.6 km/h	83.5 ± 15.7	89.1 ± 16.0	0.0001	0.0001	0.741
Rate of energy expenditure (J/min)					
Self-selected speed	49.4 ± 12.5	47.6 ± 10.9			
8.8 km/h	48.9 ± 12.5	46.8 ± 12.6			
11.2 km/h	51.0 ± 11.7	50.2 ± 13.3			
13.6 km/h	56.1 ± 12.5	54.4 ± 13.8	0.122	0.0001	0.891
Fat use (% of total energy used)					
Self-selected speed	21.7 ± 19.9	22.3 ± 24.4			
8.8 km/h	24.2 ± 25.1	24.2 ± 26.5			
11.2 km/h	23.6 ± 25.6	20.8 ± 26.1			
13.6 km/h	14.3 ± 20.9	12.7 ± 23.7	0.568	0.0001	0.912
Carbohydrate use (% of total energy used)					
Self-selected speed	78.1 ± 19.6	77.0 ± 24.0			
8.8 km/h	74.3 ± 24.2	75.7 ± 26.8			
11.2 km/h	76.5 ± 25.4	78.8 ± 25.9			
13.6 km/h	85.6 ± 20.5	87.0 ± 23.7	0.584	0.0001	0.912

Values are means ± SD.

captured kinematics in the field after seven miles of outdoor running, and measurements were obtained using a camera tripod system from one camera. Comparative evidence on the COM displacement are relatively scarce, but older adult runners had a lower vertical COM compared to younger adult runners while running on a track at 9.7 km/h (Karamanidis & Arampatzis, 2007).

At the three standardized, non-preferred running speeds, our masters runners employed a “hip-dominant” movement strategy where the hip angular excursion increased similar to that of the younger runners while maintaining the same COM vertical displacement. Similarly, hip function has been shown to be preserved with ageing in runners (DeVita et al., 2016). Three interpretations exist: (1) less collective angular displacement at the ankle, knee and pelvis may contribute to the lower COM displacement (Fukuchi et al., 2014); (2) adopting a hip-dominant motion may minimize the COM displacement, maintain stability and mitigate the expected increase in ground reaction forces at faster speeds or (3) other compensatory frontal or transverse plane motions may offset vertical COM displacement with non-preferred speed. For example, masters runners have greater peak ankle eversion angles and more internal knee rotation than younger comparators which may contribute to motion but not vertical displacement (Lilley et al., 2011). Overall, the combination of both sagittal and other plane adaptations when running at faster unaccustomed paces could help minimize vertical COM displacement and keep acute joint loads below a threshold that could induce joint pain. At the higher standardized speeds, the hip flexion angular displacement is increased, which can either create femoacetabular discomfort (Loudon & Reiman, 2014) or place higher tensile stresses on the hamstrings, one of the top three sites of injury in masters runners (McKean et al., 2006). Lower hip strength values, flexibility and power in masters runners (Brisswalter & Nosaka, 2013; Quinn et al., 2011) or strength imbalances in the quadriceps and hamstrings may contribute to overuse injuries (McKean et al., 2006). This may be especially true when coupled with the relatively high hip joint excursions at higher running speeds. Increasing running speeds also increases the flexion–extension forces acting at the ankle and knee (Petersen et al., 2014). The Achilles is a major injury site for masters runners (McKean et al., 2006). Step length increases with greater angular displacement of the lower extremity joints. Compared to self-selected speed, speeds greater than 11.2 km/h injury risk could potentially increase stresses at the Achilles tendon by lengthening the steps and fostering overreaching. Emphasis on hip flexion–extension and adduction–abduction strengthening and cadence training (Schubert et al., 2014) to control step length may be useful to help masters runners reduce injury risk while running at different speeds.

Metabolic responses to running at different speeds

There were no significant interactions of age group by running speed for cardiopulmonary and metabolic outcomes. However, the ventilation and relative HR values were higher in masters runners compared to younger runners at all speeds. The lack of differences in VO_2 values despite the relatively high HR may be partly explained by cardiovascular efficiency adaptations such as increased stroke volume and improvements in oxygen extraction in our masters runners (Sagiv, Goldhammer, Ben-Sira, & Amir, 2007). Our data agree with studies which fail to find age-related differences in exercise economy (Tanaka & Seals, 2008), but disagree with some which show that trained masters runners demonstrate lower running efficiency and at set speeds (Peiffer et al., 2016; Sultana et al., 2012). It is possible that at longer running distances or time, masters runners may experience greater HRs and, when coupled with muscle fatigue, could increase energy cost. Our testing duration may not have been sufficiently long enough to diverge these metabolic responses in our two age groups. While this study did not measure running patterns in the field, masters runners can achieve short bursts of faster speeds similar to younger runners, but prefer to maintain a slower speed that may be more “comfortable” from the cardiac perspective. Quinn et al. (2011) showed that runners over 40 years of age could keep pace across a range of speeds up to 14.5 km/h for short 5 min intervals (Quinn et al., 2011). But, in a comparative study of soccer officials who run at slow and fast speeds during a longer duration of a match, the older officials maintained HR workload as younger officials by reducing the amount of sprinting and total distance during the event (Weston, Castagna, Impellizzeri, Rampinini, & Breivik, 2010). Despite the physical capacity to run at both low and high speeds, these older officials self-restricted their participation in running at the speeds that were least comfortable.

This study is among the first that we are aware of that estimated fat and carbohydrate use during running in young and masters runners. Regular participation in running exercise may maintain the metabolic capacity of skeletal muscle during ageing. Masters runners may maintain their aerobic and glycolytic systems with run training. In older endurance-trained persons, mitochondrial volume and density and metabolic protein synthesis may be increased (Broskey et al., 2014), sufficient to maintain substrate oxidation patterns at given workloads similar to that of younger runners. Only maximal respiratory exchange ratio values at maximal exercise intensity have been compared among male and female older and younger runners. Specifically, men older than 70 years have previously shown lower respiratory exchange ratio values compared to younger men.(Hawkins, Marcell, Victoria Jaque, & Wiswell, 2001) The relevance of maintaining metabolic abilities is to attenuate and delay fatigue-induced biomechanics, such as ground reaction forces, COM vertical displacement and stance times (Giovanelli et al., 2016). Thus, the ability of our trained masters runners to achieve similar metabolic responses as younger runners may indirectly help maintain better biomechanics during longer running bouts.

Limitations and strengths

A limitation of this study included the use of specific instrumentation for differences in outcome variables, such as the COSMed device. We did detect small significant differences in VO_2 values in one speed (8.8 km/h) which fell within the range of the standard error of measurement of the COSMed device. This cross-sectional analysis used a simple stratification of two age brackets. Our participant pool did not contain enough older runners to create more age brackets that could reveal an age threshold at which differences may occur. We did not capture muscle activity patterns to determine whether differences in the activation patterns of the lower extremity or pelvis could explain the results we obtained in this study. The use of electromyography could address this issue. We used relatively short durations of each running speed, and longer durations may represent a more realistic response to that stimulus and reveal age-differences that were not detected. Strengths of this study include the large sample size and inclusion of runners of different training backgrounds, sex, shoe wear and training goals. Moreover, the two running groups were very well-matched in the characteristics that may have contributed to discrepant findings in other studies. As such, we contend that the results are generalizable to the average runner.

Conclusions

Masters runners increase the angular displacement of the ankle, knee and pelvis and metabolic and cardiopulmonary responses similar to younger runners during running at non-preferred running speeds. These findings suggest that masters runners use motion strategies to help offset joint loading and control metabolic cost of running. Masters runners adopt a hip-dominant strategy, increase step length and do not change COM vertical displacement when increasing running speed. Training at higher speeds may place greater mechanical stresses on soft and bony tissues of the lower extremity, particularly the hamstrings, Achilles and hip in masters runners. Improving hip flexion/ extension strength and cadence in masters runners may help reduce injury risk in this population.

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