Older Runners Retain Youthful Running Economy despite Biomechanical Differences

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ABSTRACT

BECK, O. N., S. KIPP, J. M. ROBY, A. M. GRABOWSKI, R. KRAM, and J. D. ORTEGA. Older Runners Retain Youthful Running Economy despite Biomechanical Differences. *Med. Sci. Sports Exerc.*, Vol. 48, No. 4, pp. 697–704, 2016. **Purpose**: Sixty-five years of age typically marks the onset of impaired walking economy. However, running economy has not been assessed beyond the age of 65 yr. Furthermore, a critical determinant of running economy is the spring-like storage and return of elastic energy from the leg during stance, which is related to leg stiffness. Therefore, we investigated whether runners older than 65 yr retain youthful running economy and/or leg stiffness across running speeds. **Methods**: Fifteen young and 15 older runners ran on a force-instrumented treadmill at 2.01, 2.46, and 2.91 $m \cdot s^{-1}$. We measured their rates of metabolic energy consumption (i.e., metabolic power), ground reaction forces, and stride kinematics. **Results**: There were only small differences in running economy between young and older runners across the range of speeds. Statistically, the older runners consumed 2% to 9% less metabolic energy than the young runners across speeds ($P = 0.012$). Also, the leg stiffness of older runners was 10% to 20% lower than that of young runners across the range of speeds ($P = 0.002$), and in contrast to the younger runners, the leg stiffness of older runners decreased with speed ($P < 0.001$). **Conclusions**: Runners beyond 65 yr of age maintain youthful running economy despite biomechanical differences. It may be that vigorous exercise, such as running, prevents the age related deterioration of muscular efficiency and, therefore, may make everyday activities easier. **Key Words:** AGING, ENERGY EXPENDITURE, LEG STIFFNESS, KINEMATICS

The pursuit of healthy aging and athletic competition are key contributors to the flourishing population of older runners. Over the last 25 yr, the number of runners older than 65 yr in the New York City Marathon increased by more than 4000%, and age group competition among older runners has driven performances to new heights. The current marathon record for men older than 65 yr (2:41:57) would have won a silver medal in the 1924 Olympic Games! Given the increasing participation and improving athletic performances of older runners, we sought to better understand the metabolic demand and biomechanics of running in people older than 65 yr.

Distance-running performance begins to decline around the age of 35 yr (36,50). A prime reason for this decline in performance is the diminution of aerobic capacity ($\dot{V}O_{2max}$) (1,28,48,51). Although it is clear that maximal aerobic capacity is reduced with age, it remains unclear how advanced age affects running economy. Running economy assesses the rate of metabolic energy expenditure and typically refers to the rate of oxygen consumption or metabolic power at specified submaximal running speeds (15). It is well established that walking economy worsens 15% to 20% after the age of 65 yr compared with that of young individuals (38,39,41,44,46). Recent evidence suggests that this worse walking economy may be related to increased coactivation of antagonist leg muscles and/or decreased muscular efficiency (12,41,45). In contrast to the typical age related changes in walking economy, previous studies have revealed that "older" runners exhibit similar running economy as young runners across a range of running speeds (1,48,51). These studies suggest that either the high aerobic demand of running exercise mitigates and/or prevents worsening economy with advanced age, or age-related changes in economy are mode specific such that aging elicits a degradation in walking economy but not running economy. However, the "older" runners examined in the aforementioned studies averaged only 56, 61, and 47 yr of age (1,48,51). Thus, an alternative explanation for the absence of an age effect on running economy may simply be that the subjects in these previous studies were too young to exhibit what might be a normal age-related decline in running economy. Overall, it remains uncertain if running economy declines over the age of 65 yr as is consistently observed in walking.

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A critical determinant of running economy is the spring-like storage and return of elastic energy from the leg during stance (32,40). Fundamentally, running is a bouncing gait characterized by a spring–mass model in which the stance leg behaves like a massless linear spring supporting the center of mass (CoM) (4,18). With each step, the elastic tissues of the stance leg are elongated, and store elastic potential energy from foot contact until midstance. Subsequently, the elastic potential energy is converted to kinetic energy from midstance to toe-off. Characteristics of older runners that may indirectly reflect leg stiffness, such as decreased tendon stiffness (30,37), lower active peak vertical ground reaction forces (GRF) (7,30), and greater knee flexion at contact (21,34), suggest that leg spring stiffness decreases with age. Conversely, well-documented decreases in flexibility suggest that "stiffness" may increase with age (23,48). Data on young runners suggest an association between reduced flexibility and enhanced running economy (13,25,52). Yet, only a few investigations have measured the biomechanics of runners older than 65 yr (21,22,34), and none of them report leg stiffness (k_{leg}). Other biomechanical variables have also been correlated with the metabolic cost of running including average vertical ground reaction force (GRF) (33), braking and propulsive GRF (11), contact time (t_{c}) (49), and stride frequency (10). Any attempt to understand the biomechanical basis of running economy should quantify these variables.

The purpose of this study was to determine if runners older than 65 yr exhibit different running economy and/or biomechanics than young runners. Given the conflicting evidence in the literature, we tested the null hypotheses that runners older than 65 yr have similar running economy and leg stiffness as young runners across matched running speeds. To test these hypotheses, we measured metabolic power and GRF, across a range of running speeds in young and older runners. We were also able to quantify the stride kinematics from GRF.

METHODS

Subjects. Fifteen young runners (10 male and 5 female subjects; mean ± SD age, 21.3 ± 2.7 yr; height, 1.77 ± 0.10 m; leg length, 0.94 ± 0.06 m; body mass, 67.1 ± 11.3 kg) and 15 older runners (10 male and 5 female subjects; mean ± SD age, 68.9 ± 4.7 yr; height, 1.70 ± 0.09 m; leg length, 0.89 ± 0.06 m; body mass, 66.7 ± 13.0 kg) volunteered. The standing heights and leg lengths of older runners were, on average, 4.0% (P = 0.041) and 5.3% (P = 0.015) shorter than those of young runners, respectively. Body mass (P = 0.952) and BMI (P = 0.130) were similar between cohorts. All subjects ran for exercise at least three times per week for a minimum of 30 min per session over the last 6 months and were classified as heel strikers, defined by an impact peak in their vertical GRF traces (9). All subjects wore their own typical running shoes. Young and older runners performed a graded exercise $\dot{V}O_{2\max}$ test (modified Balke protocol) to assess aerobic capacity. Aerobic capacity was determined from the highest 30-s period. All subjects were free of neurological, orthopedic, and cardiovascular disorders for a minimum of 6 months before participation. Additionally, we informed the subjects of the risks involved with the study, and they gave written informed consent before participation in accordance with the University of Colorado and Humboldt State University institutional review boards.

Experimental design. All subjects completed a treadmill familiarization session before the experimental session. During the familiarization session, each subject ran on a force-instrumented treadmill (Treadmetrix, Park City, UT) for at least 21 min (7 min at each of the three testing speeds), which exceeded the recommended minimum treadmill habituation time of 10 min (53). After the familiarization session by at least 2 d, subjects ran on the treadmill at three speeds (2.01, 2.46, and 2.91 $\mathrm{m{\cdot}s^{-1}}$). All trials were 5 min in duration, followed by at least 5 min of rest.

Metabolic power. We measured the rates of oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) using open-circuit expired gas analysis (TrueOne 2400, ParvoMedic, Sandy, UT). We calculated the rate of metabolic energy consumption as the average gross metabolic power per kilogram of body mass ($\mathrm{W{\cdot}kg^{-1}}$) using the average $\dot{V}O_2$ ($\mathrm{mL\ O_2{\cdot}s^{-1}}$) and $\dot{V}CO_2$ ($\mathrm{mL\ CO_2{\cdot}s^{-1}}$) from the last minute of each trial when metabolic power had reached steady state (5). Metabolic power is simply the rate of metabolic energy consumption ($\mathrm{J{\cdot}kg^{-1}{\cdot}s^{-1}}$ or $\mathrm{W{\cdot}kg^{-1}}$). Additionally, we monitored the respiratory exchange ratio (RER) throughout each trial to ensure that it remained below 1.0, indicating that oxidative metabolism was the main metabolic pathway.

Biomechanics. Additionally, we quantified GRF and stride kinematics for 10 strides (20 steps) during minutes 3 to 5 of each trial. We collected GRF data at 1000 Hz, low-pass filtered the data (30 Hz), and calculated GRF characteristics and stride kinematics using a custom MATLAB script (MathWorks Inc, Natick, MA). We calculated the vertical GRF impact loading rate as the average slope of the vertical GRF between 20% and 80% of the period between the initial ground contact and the impact peak (14). Furthermore, we evaluated the peak braking and propulsive GRF. We determined the touchdown and toe-off times from the vertical GRF recordings using a 30-N threshold. This allowed us to calculate stride frequency, stride length, and contact time t_{c}.

We calculated leg stiffness k_{leg} from GRF as per Farley et al (18). Concisely, k_{leg} was determined from the ratio of peak vertical GRF (F_{peak}) and the maximum compression of the leg spring (ΔL).

$$k_{\mathrm{leg}} = \frac{F_{\mathrm{peak}}}{\Delta L} \qquad [1]$$

To calculate ΔL, we measured standing leg length (L_0) from the greater trochanter to the floor using a tape measure and determined the angle of the leg spring at initial ground contact relative to vertical, theta (Θ) using equation 2.

$$\Theta = \sin^{-1}\left(\frac{vt_{\mathrm{c}}}{2L_0}\right) \qquad [2]$$

Theta (Θ) is equal to half the angle swept by the stance leg and was computed using running velocity (v), contact time t_c, and standing leg length L_0. We determined peak vertical displacement of the CoM during stance (Δy) by twice integrating the vertical acceleration of the CoM with respect to time (30). We calculated ΔL using equation 3.

$$\Delta L = \Delta y + L_0(1 - \cos \Theta) \qquad [3]$$

Statistical analyses. To determine the effect of age group (young vs older), speed (2.01, 2.46, and 2.91 m·s^{-1}) and age group by speed interaction on running economy, GRF, and stride kinematics, we used a two-way MANOVA. Significance was set at $P < 0.05$. When warranted, we used *post hoc* repeated measures ANOVAs with Bonferroni corrections to determine the effects of age group and speed on specific dependent variables. In addition, based on the results of the *post hoc* repeated measures ANOVAs, we performed paired *t* test to determine any age-group differences at each speed. Moreover, we compared age-group characteristics of demographic information, anthropometric measurements, standing metabolic power, and maximal oxygen consumption rates between young and older runners using independent samples *t* tests. We performed statistical analyses using SPSS (IBM Corp., Armonk, NY) software.

RESULTS

Running economy. Despite the similar rates of oxygen consumed (mL O$_2$·kg^{-1}·min^{-1}) between groups ($P = 0.050$), older runners consumed metabolic power (W·kg^{-1}) at a slightly slower rate than young runners across the range of speeds ($P = 0.012$) (Table 1 and Fig. 1). The mean elicited metabolic power of older runners was 2% to 9% less than that of young runners across speeds. As expected, faster running speeds increased the magnitudes of $\dot{V}O_2$ and metabolic power for both groups ($P < 0.001$) (Fig. 1). Older runners exhibited 27% lower standing metabolic rates (1.26 vs 1.72 W·kg^{-1}, $P < 0.001$) and 34% lower maximal rates of oxygen consumption ($\dot{V}O_{2max}$) than young runners (37.3 vs 56.1 mL O$_2$·kg^{-1}·min^{-1}, $P < 0.001$). Further analysis revealed that within our older runner cohort, there was no interaction between maximum aerobic capacity ($\dot{V}O_{2max}$) and submaximal rate of oxygen consumed ($P = 0.128$), indicating that individuals with superior maximum aerobic capacities ran at a lower percentage of $\dot{V}O_{2max}$ compared with those with inferior aerobic capacities ($P < 0.001$). The entire cohort of young runners completed all 3 running speeds, but only 14 older runners were able to complete the 2.46 m·s^{-1} trial, and 10 were able to complete the 2.91 m·s^{-1} trial while using primarily aerobic metabolism (RER, <1.0). Therefore, the results of the older runners reflect n = 15, 14, and 10 for 2.01, 2.46, and 2.91 m·s^{-1} trials, respectively.

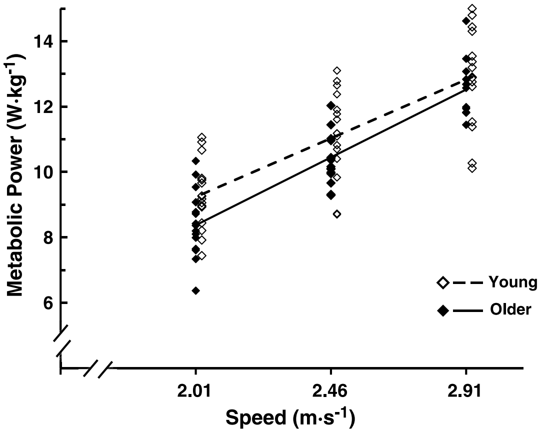

FIGURE 1—Metabolic power (W·kg^{-1}) plotted as a function of running speed (m·s^{-1}) for young (open symbol) and older runners (closed symbol) individually. The dashed and solid lines represents the regression for young and older runners, respectively. Young and older runners were tested at identical speeds, but for clarity, the data are depicted slightly offset from the actual running speeds. The equation of the young runner regression line: metabolic power = 0.85 + 4.15 × speed. The equation of the older runner regression line: metabolic power = 1.33 + 3.65 × speed. The older runners consumed less metabolic power than the young runners across running speeds ($P = 0.012$).

Biomechanics. Across the range of speeds, older runners used 4% to 6% faster stride frequencies compared with young runners ($P < 0.001$; Table 2). That combined with statistically equivalent ground contact times t_c ($P = 0.037$; Bonferroni adjusted significance level set at $P = 0.006$) resulted in 7% to 8% larger duty factors (t_c/t_{stride}) for older versus young runners ($P < 0.001$). Overall, older runners exhibited 13% to 18% greater impact peak vertical GRF magnitudes ($P = 0.004$) but 8% to 11% lower active peak vertical GRF magnitudes ($P < 0.001$) compared with young runners (Fig. 2). Older runners experienced smaller vertical GRF impact loading rates across speeds ($P = 0.002$; Table 2). Overall peak horizontal braking GRF were similar between groups ($P = 0.253$), but the peak horizontal propulsive GRF exerted by older runners were 19% to 33% less in older runners than those of young runners ($P < 0.001$).

Across the range of speeds, older runners had a 10% to 20% lower k_{leg} compared with young runners ($P = 0.002$)

TABLE 1. Metabolic data (mean ± SD).

		2.01 m·s^{-1}	**2.46 m·s^{-1}**	**2.91 m·s^{-1}**	**Effect Size of Age Difference (Partial η^2)**
Metabolic power (W·kg^{-1})	Young	9.28 ± 1.06	11.18 ± 1.36	12.87 ± 1.51	0.08
	Older[a]	8.42 ± 1.07	10.35 ± 0.78	12.57 ± 0.97	
Oxygen consumption (mL O$_2$·kg^{-1}·min^{-1})	Young	26.65 ± 3.25	31.80 ± 3.59	36.57 ± 4.23	0.05
	Older	24.51 ± 3.12[b]	29.95 ± 2.45	36.17 ± 2.86	
Respiratory exchange ratio	Young	0.86 ± 0.07	0.90 ± 0.08	0.91 ± 0.07	0.08
	Older[a]	0.90 ± 0.05	0.92 ± 0.05	0.97 ± 0.04	

[a] Significant group difference across all speeds ($P < 0.05$).

[b] Significant difference between young and older runners ($P < 0.05$).

15, 14, and 10 older runners completed 2.01, 2.46, and 2.91 m·s^{-1}, respectively.

TABLE 2. Biomechanical data (mean ± SD).

		$2.01\ m{\cdot}s^{-1}$	$2.46\ m{\cdot}s^{-1}$	$2.91\ m{\cdot}s^{-1}$	Effect Size of Age Difference (Partial η^2)
Stride frequency (Hz)	Young	1.34 ± 0.06	1.37 ± 0.07	1.40 ± 0.08	0.18
	Older[a]	1.38 ± 0.06	1.45 ± 0.07[b]	1.46 ± 0.05	
Stride length (m)	Young	1.50 ± 0.06	1.80 ± 0.09	2.07 ± 0.12	0.19
	Older[a]	1.46 ± 0.06	1.70 ± 0.08[b]	1.99 ± 0.07	
Contact time (s)	Young	0.30 ± 0.05	0.26 ± 0.03	0.24 ± 0.02	0.06
	Older	0.30 ± 0.03	0.27 ± 0.02	0.25 ± 0.02	
Vertical GRF impact loading rate ($BW{\cdot}s^{-1}$)	Young	42.5 ± 8.6	48.9 ± 9.7	57.3 ± 9.5	0.13
	Older[a]	35.6 ± 9.4	42.8 ± 9.5	48.9 ± 11.4	
Impact vertical GRF peak (BW)	Young	1.01 ± 0.37	1.19 ± 0.23	1.36 ± 0.23	0.10
	Older[a]	1.23 ± 0.32	1.37 ± 0.32	1.59 ± 0.39	
Active vertical GRF peak (BW)	Young	2.06 ± 0.25	2.22 ± 0.25	2.31 ± 0.25	0.22
	Older[a]	1.90 ± 0.18	1.99 ± 0.16[b]	2.06 ± 0.12[b]	
Leg spring ground contact angle (°)	Young	18.4 ± 2.9	19.8 ± 1.9	21.8 ± 1.9	0.33
	Older[a]	20.1 ± 1.5	22.1 ± 1.3[b]	24.5 ± 1.0[b]	
Leg compression (cm)	Young	10.9 ± 1.9	11.7 ± 1.3	12.6 ± 1.5	0.00
	Older	10.6 ± 1.1	11.5 ± 0.9	13.0 ± 1.3	
Leg stiffness ($kN{\cdot}m^{-1}$)	Young	12.59 ± 2.79	12.63 ± 2.83	12.19 ± 2.74	0.13
	Older[a]	11.59 ± 1.80	11.11 ± 1.77	9.68 ± 1.59[b]	

[a]Significant group difference across all speeds ($P < 0.05$).
[b]Significant group difference at referred speed ($P < 0.05$).
15, 14, and 10 older runners completed 2.01, 2.46, and 2.91 $m{\cdot}s^{-1}$, respectively.

(Fig. 3). Although there was no overall interaction effect between age and speed (P = 0.614), while controlling for subjects that could not complete all of the speeds through the use of a linear mixed model, k_{leg} decreased for the older runners by 1.14 $kN{\cdot}m^{-1}$ as running speed increased from 2.01 to 2.91 $m{\cdot}s^{-1}$ ($P < 0.001$). Young runners maintained a constant k_{leg} across the range of speeds (P = 0.077; Table 2 and Fig. 3). Leg spring touchdown angles (Θ) were 8% to 11% more horizontal in older verus young runners (P < 0.001). On the other hand, the maximum compressions of the calculated leg spring during stance (ΔL) were similar between the young and older runners (P = 0.787).

DISCUSSION

Our findings of similar rates of gross oxygen consumption in young and older runners extend previous "older" running studies (1,48,51). However, we reject our first null hypothesis because our older runners consumed statistically lower rates of gross metabolic power than young runners across running speeds (Table 1 and Fig. 1). Metabolic power is the preferred method of measuring aerobic energy expenditure because it takes into account the fuel being oxidized. Depending on the ratio of substrates oxidized (carbohydrates vs fats), the magnitude of energy produced per unit of oxygen consumed varies (5).

Collectively, older runners ran at a higher percentage of $\dot{V}O_{2max}$ than the young runners; thus generating a greater percentage of energy via carbohydrate oxidation due to the increased relative intensity. Gross metabolic power and thus running economy differed between young and older runners because the amount of carbohydrates and fats metabolized varied between groups, resulting in lower overall metabolic power consumption in older runners. Given our running economy results, it is clear that the primary reason for the decline in running performance with advanced age is the decline in $\dot{V}O_{2max}$.

Supporting the notion that running economy does not deteriorate with advanced age, we found that within our older runner cohort, age (65–82 yr) had no effect on the rate of submaximal oxygen consumption (P = 0.551) or metabolic power (P = 0.528). We determined that by using linear mixed models, which assessed the effect of age (yr) on submaximal oxygen consumption and metabolic power while controlling for running speed.

Consistent with most of the previous research, we found that at matched speeds, older runners used 4% to 6% faster stride frequencies and shorter stride lengths compared with young runners (P < 0.001) (7,21,30,31,34). In contrast, Quinn and colleagues (48) reported similar stride frequencies between young and older runners. These discrepancies in young versus older runner comparisons may be explained by differences between group leg lengths. Our young and older runners used similar normalized stride lengths (stride length per leg length) across speeds (P = 0.478). Because previous studies that reported age-related difference in stride lengths did not provide normalized stride length data (7,21,30,31,34), it is uncertain if their older runners took smaller strides due to shorter leg lengths or because of age-related adaptation.

The peak impact vertical GRF for our older runners were greater than those of young runners and consistent with previous reports (7,21). At first glance, that suggested that aging inhibits the ability to mitigate the magnitude of ground forces upon landing, which may have implication for overuse injury rates (42). However, our older runners had reduced vertical GRF loading rates. It is not yet clear which impact loading variable most predisposes a runner to injury (54).

DeVita and Hortobagyi (17) reported that compared with young individuals, older individuals exhibit a distal-to-proximal shift of joint powers in walking via greater hip extensor power use and lower ankle plantar flexor power generation. Recently, the same distal-to-proximal shift of joint powers

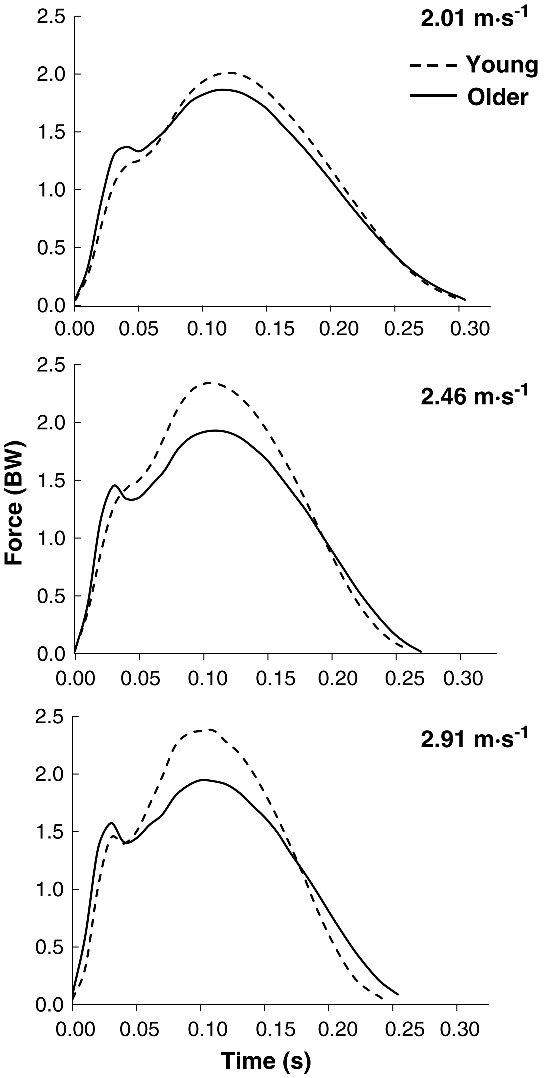

FIGURE 2—Mean vertical ground reaction force per body weight (BW) for young versus older runners over time (s) and across running speeds. Traces are the averages for all young and old subjects. All young and old runners exhibited distinct impact peaks; however, the peaks were attenuated by the averaging process.

was reported in running in older individuals (16,34). It would seem that the elevated peak impact vertical GRF evident in our older runners might arise from an impaired ability to absorb energy at the ankle upon ground contact (34), but again, our older runners had lower vertical GRF loading rates. Later in the contact phase, the active peak vertical GRF were lower for older versus young runners. Reduced force and power generation from ankle plantar flexors may explain the decreased peak active vertical GRF in older runners. Kulmala et al. (34) reported that older runners generated 41% less power via ankle plantarflexion but compensated by producing 41% more power from hip extensors compared with young runners at a matched speed, yet knee extensor power was similar between groups (34). Overall, the differences between young and older runners in terms of both the impact and active vertical GRF peaks indicate decreased ankle plantar flexor muscle function in the older runners.

Interestingly, all of the older runners in our study were heel strikers, although we did not prescreen the older runners for foot-strike pattern. Our percentage of older runners that were heel-strikers (100%) contrasts reports in the literature suggesting that 75%–89% of all runners are heel-strikers (27,35). For this reason, we specifically recruited only heel-striking young runners to mitigate confounding variables (foot-strike pattern) that may have hindered our ability to investigate age-related adaptations. Previous studies with older runners either did not specify foot-strike pattern or reported that all subjects were heel-strikers. It may be that the ability of older runners to effectively land with a mid-foot or fore-foot strike during sustained running is compromised with advanced age.

We also reject our second null hypothesis because of the overall decrease in k_{leg} of older versus young runners (Table 2 and Fig. 3). The lower k_{leg} values resulted from lower active peak vertical GRF yet similar ΔL. One possible contributor to the reduced k_{leg} of older runners is the association between lower tendon stiffness and advanced age (30,37). Alternatively, future assessments of joint stiffness may explain the decreased k_{leg} in older runners. Previous studies indicate that alterations in ankle and knee (but not hip) joint stiffness influence k_{leg} (19,20,43). Joint torsional stiffness (k_{joint}) is calculated via the quotient of the change in magnitude of the net joint moment (ΔM_{joint}) and the joint angle ($\Delta\Theta_{\text{joint}}$) in the sagittal plane from initial ground contact to mid-stance (19,20,43).

$$k_{\text{joint}} = \frac{\Delta M_{\text{joint}}}{\Delta\Theta_{\text{joint}}} \qquad [4]$$

No studies have reported k_{joint} for older runners; however, Kulmala et al. (34) provide data on both ΔM_{joint} and $\Delta\Theta_{\text{joint}}$

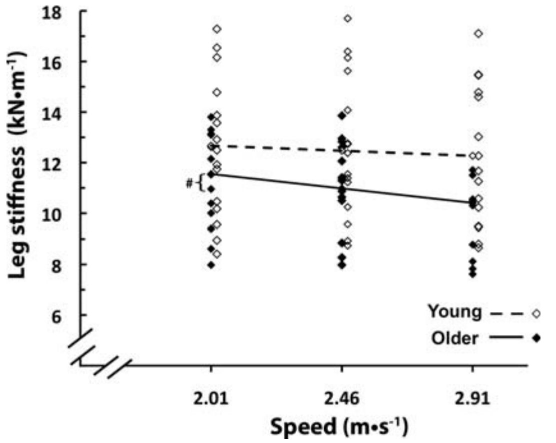

FIGURE 3—Leg stiffness (kN·m^{-1}) plotted as a function of running speed (m·s^{-1}) for young (open symbol) and older runners (closed symbol) individually. The dashed and solid lines represents the regression for young and older runners, respectively. Young and older runners were tested at identical speeds, but for clarity, the data are depicted slightly offset from the actual running speeds. The pound symbol indicates speed effect. The equation of the young runner regression line: leg stiffness = 13.56 – 0.44 × speed. The equation of the older runner regression line: leg stiffness = 14.10 – 1.27 × speed. Across the range of speeds, older runners had lower k_{leg} compared with young runners (P = 0.002).

for older runners. They found that older runners use lower magnitudes of ΔM_{ankle} while maintaining similar $\Delta\Theta_{\text{ankle}}$ compared with young runners at a matched speed (4.0 $\text{m}\cdot\text{s}^{-1}$), indicating that older runners have lower k_{ankle}. Previous research supports the findings of lower magnitudes of ΔM_{ankle} (31) and similar $\Delta\Theta_{\text{ankle}}$ (7,21) during ground contact in older versus young runners. In regard to knee mechanics, the older runners in the study by Kulmala et al exhibited similar ΔM_{knee} and nondifferent $\Delta\Theta_{\text{knee}}$ versus young runners, inferring no difference in k_{knee} between groups (34). Although k_{leg} was not reported, the older runners in the study by Kulmala et al likely ran with lower k_{leg} compared with their young runners via lower k_{ankle} and similar k_{knee}. In contrast to reported knee mechanics by Kulmala et al, previous studies found reduced $\Delta\Theta_{\text{knee}}$ magnitudes in older runners versus young runners (7,21). Future research should quantify the relationship between k_{leg} and k_{joint} in older individuals across running speeds.

To determine if there was a sex effect on running economy or any biomechanical parameter, we reran the MANOVA while testing the interaction of sex as a covariate. Subsequent to the Bonferroni correction, running economy was not influenced by sex ($P \geq 0.035$); however, stride frequency, stride length, and k_{leg} were each different between male and female runners ($P < 0.001$). Consistent with the differences in stride frequencies and stride lengths between young and older runner groups, when scaled to leg length, differences between male and female runners dropped out ($P = 0.618$). Runners with shorter legs generally take relatively shorter strides regardless of age or sex, but the correlation is weak (8). Also, female runners in our study adopted k_{leg} values that were 14% to 19% lower than that of male runners across speeds ($P < 0.001$). This is consistent with previous work showing that female runners produce lower vertical stiffness during two-legged hopping as compared with male runners (47). Furthermore, Gabriel et al (24) found lower normalized k_{ankle} during the push-off phase of walking in female runners compared with male runners. Conceivably, k_{ankle} during running could also be reduced in female runners, thus contributing to lower k_{leg}. Despite the significant sex effects on some specific biomechanical parameters, these findings did not compromise the validity of our results because of the equal number of male and female runners in each runner group (young and older).

A reasonable limitation of our study was the cross-sectional design. It is possible that our older runners were more economical when they were younger, yet a 40-yr-long longitudinal design is not practical. Impressively, Trappe et al (51) measured the running economy of runners over a 22-yr period and reported no changes in subjects who continued to run for exercise over the experimental duration (51). Conversely, the subjects in the study by Trappe et al ceased running for exercise since their baseline measurements consumed significantly higher submaximal rates of oxygen consumption per kilogram of body mass as they grew older. Collectively, the present study, other cross-sectional studies (1,48), and a longitudinal study (51) indicate that advanced age *per se* does not substantially degrade running economy if people maintain regular vigorous aerobic exercise.

Unlike the results of the present study on running, previous research has shown that sedentary older adults consume more energy to walk than young adults (38,39,41,44,46). Proposed age-related physiological changes that are associated with greater metabolic energy expenditure in walking include the following: increased coactivation of agonist/antagonist leg muscles and decreased muscular efficiency (12,41,45). Recently, our group reported that the metabolic power consumption during walking in older runners is lower than that of older sedentary adults and older walkers (who walk for exercise ≥3 times per week for ≥30 min per bout) and is similar to that of young adults (44). It is possible that running for exercise mitigates increases in coactivation of opposing leg muscles, thereby maintaining both youthful walking and running economy. Previously, Häkkinen et al. (18) showed that older adults who implemented a lower limb strength training regimen reduced leg muscle coactivation by 5% to 10%. The neuromuscular adaptations of strength training, which lead to reduced muscular coactivation may also be elicited via running exercise (26). Our findings of lower k_{leg} values from the older runners further suggest that running exercise reduces muscular coactivation in older individuals (3,29). Future work investigating the electromyography recordings of older adults (runners and nonrunners) while walking and running will improve our knowledge on the effects that aging and physical exercise have on muscular (co)activation.

Advanced age is also associated with a decline of muscular efficiency (2,41). However, Conley et al (12) reported that aerobic exercise possibly maintains youthful muscular efficiency regardless of advanced age. This hypothesis is supported by new evidence demonstrating that aerobically trained older adults have a higher mitochondrial volume density and function, in addition to better cycling efficiency, compared with older sedentary adults (6). These findings (6,12) coupled with our group's previous report of better walking economy in older runners versus older walkers (44) suggests that vigorous aerobic exercise reduces the deterioration of muscular efficiency and therefore retains/improves the metabolic demand of locomotion.

CONCLUSIONS

Runners older than 65 yr maintain youthful running economy. The youthful running economy of older runners is not a byproduct of identical biomechanics because the elicited ground reaction forces and stride kinematics of older runners differ from those of young runners. Together with our previous study (44), we conclude that running exercise seemingly protects against the worsening of both walking and running economy with advanced age. It may be that vigorous exercise, such as running, prevents the age related deterioration of muscular efficiency in general and, therefore, may make everyday activities easier.

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