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ORIGINAL ARTICLE

Basal body temperature as a biomarker of healthy aging

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Abstract Scattered evidence indicates that a lower basal body temperature may be associated with prolonged health span, yet few studies have directly evaluated this relationship. We examined cross-sectional and longitudinal associations between early morning oral temperature (95.0–98.6 °F) and usual gait speed, endurance walk performance, fatigability, and grip strength in 762 non-frail men (52 %) and women aged 65–89 years participating in the Baltimore Longitudinal Study of Aging. Since excessive adiposity (body mass index ≥35 kg/m^2 or waist-to-height ratio ≥0.62) may alter temperature set point, associations were also examined within adiposity strata. Overall, controlling for age, race, sex, height, exercise, and adiposity, lower temperature was associated with faster gait speed, less time to walk 400 m quickly, and lower perceived exertion following 5-min of walking at 0.67 m/s (all $p \leq 0.02$). In the non-adipose ($N = 662$), these associations were more robust (all $p \leq 0.006$). Direction of association was reversed in the adipose ($N = 100$), but none attained significance (all $p > 0.22$). Over 2.2 years, basal temperature was not associated with functional change in the overall population or non-adipose. Among the adipose, lower baseline temperature was associated with greater decline in endurance walking performance ($p = 0.006$). In longitudinal analyses predicting future functional performance, low temperature in the non-adipose was associated with faster gait speed ($p = 0.021$) and less time to walk 400 m quickly ($p = 0.003$), whereas in the adipose, lower temperature was associated with slower gait speed ($p = 0.05$) and more time to walk 400 m ($p = 0.008$). In older adults, lower basal body temperature appears to be associated with healthy aging in the absence of excessive adiposity.

Keywords Aging · Body temperature · Functional performance · Excessive adiposity

Introduction

Scattered evidence indicates that a lower basal body temperature may correlate with longer health span (Carrillo and Flouris 2011) or analogously a slower rate of aging and delayed emergence of typical aging phenotypes (Soare et al. 2011). Body temperature declines in all species in response to caloric restriction (Roth et al. 2002; Lane et al. 1996; Heilbronn et al. 2006), and studies of transgenic mice indicate that a lower temperature offers longevity benefits independent of caloric restriction (Conti 2008). Observations that a lower resting metabolic rate (RMR) is associated with

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better health and longevity (Schrack et al. 2014; Ruggiero et al. 2008) also support the potential benefit of a lower basal temperature as approximately two thirds of RMR or 40–50 % of total energy expenditure is required for thermoregulation (Landsberg 2012) and a 1 °C rise in temperature translates into a 10–13 % increase in metabolic rate (Du bois 1921 cited in Landsberg 2012).

Body temperature follows a circadian rhythm, lowest in the second half of the nocturnal sleep cycle (Krauchi 2007) with the nadir typically occurring between 5 and 6 a.m. and then gradually rising throughout the day until early evening when it begins to drop (Weinert 2010). Although core temperature is tightly regulated within a narrow set point, it varies across individuals on the order of 1.3 °C (Kelly 2006), and within individuals, it responds acutely to activity level and ambient temperature among other factors. Sources of individual variation are unclear, but limited evidence indicates that the level and variation in amplitude of body temperature decline in late life, possibly due to lower activity, shorter sleep cycle, and/or chronic disease and/or its treatment (Weinert 2010). Studies of active well elderly however do not observe a lower amplitude (Gubin et al. 2006), and sex-related differences may reflect dissimilar physical activity behavior (Gubin et al. 2006). It is thought that the nadir best reflects the basal set point (Kelly 2006) which, in turn, may best reflect health-related attributes as both caloric restriction and athletic conditioning (Shvartz et al. 1974; McLellan 2001; Baum et al. 1976) appear to lower basal temperature.

Little empirical research has addressed the relationship between basal body temperature and health and longevity in humans. One study found that men aged 19–95 years followed for up to 25 years with a body temperature in the lower half of the distribution had better survival than those in the upper half (Roth et al. 2002). Another study of over 18,000 white individuals aged 20–98 years enrolled in a health maintenance organization found that temperature taken during a standardized health appraisal was lower with older age independent of sex, body mass index (BMI), and white blood cell count (Waalen and Buxbaum 2011). These findings were interpreted as evidence of a survival advantage among persons who maintain a lower steady-state body temperature.

Much of the previous research on body temperature in humans has hypothesized that a lower basal temperature is energetically efficient and therefore may predispose individuals to obesity (Rising et al. 1992; Landsberg 2012), a major *threat* to health and longevity. However, this theory has received little empirical support. Some studies failed to observe any significant association between body temperature and obesity (Chudecka et al. 2014; Heikens et al. 2011; Savastano et al. 2009), and others found that obese persons tend to have *higher* average temperature (Hoffmann et al. 2012). The only study that found obese persons to have a lower body temperature had a very small sample and found that the lower temperature occurred exclusively during daylight hours (Grimaldi et al. 2015). Alternatively, other researchers have suggested that a lower basal temperature may be an adaptive response to compromised cooling ability associated with excessive adiposity (Chudecka et al. 2014).

To explore the hypothesis that lower basal temperature is a biomarker of healthy aging, we examined the concurrent and predictive association of early morning oral temperature with functional performance and with change over time in functional performance in non-frail older adults. Since adiposity may affect heat dispersion and potentially impact regulation of basal temperature, we also performed analyses stratified by adiposity. The functional performance measures included usual gait speed, endurance walking ability, perceived fatigability, and grip strength. Usual gait speed and endurance walking ability not only assess health age and mortality risk (Studenski et al. 2011; Newman et al. 2006) but also reflect, respectively, energetic efficiency (Schrack et al. 2012) and energetic capacity (Simonsick et al. 2006) for which basal temperature may be especially relevant. Perceived fatigability, the level of exertion experienced while performing a standardized activity (Eldadah 2010), also has an energetic dimension and has recently emerged as an early marker of mobility decline (Simonsick et al. 2016). Grip strength was included as a negative control as it is associated with health and longevity (Rantanen et al. 1999; Rantanen et al. 2012; Metter et al. 2002) but is not itself an energetically demanding task.

Methods

Study participants, eligibility, and selection

The study population consisted of participants in the Baltimore Longitudinal Study of Aging (BLSA) aged

65–89 years who were seen between April 2007 and December 2015. Participants included in this analysis had an early morning oral temperature between 95.0 and 98.6 °F and were free of mobility disability (i.e., did not report having a lot of difficulty or unable to walk 0.25 mile and had a measured gait speed no slower than 0.4 m/s) and able to complete a fast 400-m walk without using a walking aid and had a BMI of at least 21 kg/m^2, as additional assurance that frail individuals were excluded. When multiple visits met these criteria, the first visit in which all criteria were met was selected. We have termed this visit the index visit. A total of 762 participants had at least one eligible visit and constitute the cross-sectional sample. The longitudinal sample consisted of all participants in the cross-sectional sample who had a follow-up clinic or home visit within 1 to 4 years of the index visit in which usual gait speed was assessed. When multiple eligible follow-up visits were available, the visit closest to 2 years from the index visit was used. Of the 762 participants in the cross-sectional sample, 521 (68 %) had an eligible follow-up visit by December 31, 2015 and constitute the longitudinal sample. Of the 241 participants in the cross-sectional but not the longitudinal sample, 8 had a phone follow-up only, and thus, gait speed was not assessed, 40 were outside of the 1 to 4-year follow-up window, 138 were not due or overdue for a follow-up visit, 17 had died, 7 developed dementia or an incapacitating end-stage illness or disability, 16 withdrew, and 15 were lost to follow-up.

The BLSA constitutes a continuous enrollment cohort established in 1958 to study normative aging currently sponsored and conducted by the National Institute on Aging (NIA) Intramural Research Program (IRP). At the time of enrollment, all participants must be free of mobility limitation, cognitive impairment, and chronic conditions except for well-controlled hypertension. Once enrolled, participants are followed on an age-based schedule (approximately every 4 years for persons aged 21–59, biannually for persons aged 60–79, and annually for those 80 years and older) through death. The comprehensive clinical examination takes place at the NIA IRP Clinical Research Unit located in Baltimore, MD, and lasts 3 days on average with the majority of participants staying on the unit throughout testing. Persons unable to attend a clinic visit due to health limitations or caregiving responsibilities are seen in their homes. The current BLSA protocol was approved by the National Institute of Environmental Health Sciences Internal Review Board, and all participants provided written informed consent at all visits.

Measures

Body temperature

Body temperature was measured by using the Welch Allyn SureTemp® (Skaneateles Falls, NY) oral thermometer in early morning around 6:30 a.m. (interquartile range 6:15–6:45 a.m.) with the participant supine and resting in a fasted state. We have labeled this measure basal temperature as it occurs close to the nadir observed in most individuals (Kelly 2006). Oral temperature was also assessed when height, weight, and other anthropometric measures were taken which could occur anytime throughout the multi-day visit. We refer to this temperature as “casual” temperature and include it in one set of analyses for comparison purposes as most cohort studies that assess temperature have only a casual measure available.

Excessive adiposity

We identified persons with excessive adiposity on the basis of BMI and waist-to-height ratio. Participants with level II obesity (BMI ≥ 35 kg/m^2) or a waist-to-height ratio ≥0.62, slightly above the “take action” ratio of 0.6 (Ashwell et al. 2014), were identified as having excessive adiposity. Weight and height were measured to the nearest 0.1 kg and 0.1 cm, respectively. Waist circumference was measured to the nearest 0.1 cm just below the rib cage where the waist tapers. For both height and waist circumference, the average of three measurements was used. Of the 100 participants classified as having excessive adiposity, 88 met the waist-to-height criterion, 40 met the BMI criterion, and 28 met both criteria.

Functional performance

Usual gait speed was measured over 6 m with participants instructed to walk at their “usual walking pace” for two trials. Time was recorded to the hundredth of a second and was divided into six to derive usual gait speed in meters per second (m/s). The faster of the two trials was used in the analyses.

Time to walk 400 m was determined from the long distance corridor walk, a two-stage endurance walk test performed over a 20-m course in an unobstructed tile floor corridor (Simonsick et al. 2006). The first stage consists of a 2.5-min usual pace walk followed immediately by a 400-m walk "done as quickly as possible." Only persons who met none of the following exclusions: severe electrocardiogram abnormalities, systolic or diastolic blood pressure exceeding 199 or 109 mmHg, respectively, or reporting a myocardial infarction, angioplasty, or heart surgery in the prior 3 months or experiencing new or worsening symptoms of chest pain, shortness of breath, or angina and were able to complete the full 400-m walk without using a walking aid at their index visit were included in the study. Time was recorded to the hundredth of a second. Reason for non-completion at the follow-up visit was also recorded.

Perceived fatigability was assessed by administering the Borg Rating of Perceived Exertion which ranges from 6 to 20 (Borg 1990) immediately following performance of a slow paced 5-min walk (1.5 mph; 0.67 m/s) on a treadmill at 0 % grade. This measure of fatigability is strongly associated with physical performance tests such as gait speed (Simonsick et al. 2014) and has been identified as an early marker of functional decline in otherwise healthy older adults (Simonsick et al. 2016). Fatigability assessment was implemented in September 2007 and is thus only available for 647 of the 762 study participants in the cross-sectional and 399 of the 521 participants in the longitudinal analyses.

Grip strength was measured by using a Jamar Hydraulic Hand Dynamometer three times on each hand. The maximum value attained with either hand (kilograms (kg)) was used in the analyses.

Study population descriptors

Age and race were self-reported, and race was dichotomized as black and non-black as very few non-black participants were non-Caucasian. Smoking history was dichotomized as current smoker or former smoker who quit less than 10 years from their index assessment versus never smoker or long-term former smoker. Self-rated health was obtained from the SF-12 questionnaire (Ware et al. 1996). Exercise level was categorized into four levels coded 0 to 3 on the basis of reported time spent in vigorous activities including brisk walking, with 0 corresponding to less than 30 min per week and 3 corresponding to at least 150 min per week (Brach et al. 2004).

Statistical analyses

Participant characteristics were compared across groups (cross-sectional versus longitudinal sample and non-adipose versus adipose) by using chi-squared statistics for categorical measures and Pearson correlation coefficients for continuous variables. Multiple linear regression was used to examine concurrent associations between basal temperature and each functional performance assessment adjusting for age, sex, race, height, exercise level, and adiposity status. Interactions between temperature and sex and race and adiposity were evaluated in separate models. The interaction between body temperature and excessive adiposity was significant for 400-m walk time and borderline significant for fatigability with p values of 0.045 and 0.096, respectively, and supports the a priori decision to conduct parallel analyses stratified by adiposity status. No sex or race interactions were observed (all $p > 0.12$). Associations between basal temperature and change in functional performance were examined by using multiple linear regression with the index value of the functional outcome and length of follow-up included in models with age, sex, race, height, exercise level, and adiposity status. These analyses were conducted by using the overall longitudinal sample and within adiposity strata. To examine whether any observed cross-sectional associations were retained over time, a second set of longitudinal analyses were conducted, excluding the index value of the functional performance measure.

Results

Participant characteristics including functional performance are provided in Table 1 separately for those with and without excessive adiposity for both the cross-sectional and longitudinal samples. Overall, the cross-sectional sample included 48 % women and 25 % black with mean age of 74 years and basal oral body temperature of 97.7 °F. The study population was generally healthy and well-functioning with only 3 % smoking currently or within the past 10 years, upwards of 79 % reporting very good to excellent health, and nearly 40 % meeting physical activity guidelines relative to less than 3 % in the general population aged 60 years and older (Troiano et al. 2008). Functional performance was also consistent with above average health (Simonsick et al. 2014). The overall cross-sectional and longitudinal

Table 1 Participant characteristics in the cross-sectional and longitudinal samples by adiposity status[a]

	Cross-sectional sample		Longitudinal sample	
Number	No excess adiposity 662	Excess adiposity 100	No excess adiposity 462	Excess adiposity 59
Age, mean (SD), years	74.1 (6.8)	71.7 (6.1)	74.5 (6.8)	72.1 (6.4)
Women, %	49.7	43.0	48.5	40.7
Black, %	23.0	28.0	23.6	32.2
Core body temperature, mean (SD), °F	97.7 (0.5)	97.7 (0.4)	97.7 (0.5)	97.8 (0.4)
Casual temperature, mean (SD), °F	97.4 (0.6)	97.6 (0.7)	97.4 (0.6)	97.6 (0.8)
BMI, mean (SD), kg/m^2	26.1 (3.1)	34.2 (3.9)	26.1 (3.1)	34.0 (3.9)
Waist-height ratio, mean (SD)	0.53 (0.05)	0.65 (0.04)	0.53 (0.05)	0.65 (0.4)
Health status and behaviors				
Current or recent smoker, %	2.4	8.0	2.4	6.8
Fair to poor self-rated health, %	0.8	3.0	0.9	3.5
Very good to excellent self-rated health, %	80.1	66.7	78.9	75.9
Sedentary (active <30 min/week), %	29.9	51.0	29.9	50.9
Physically active ≥150 min/week), %	41.8	25.0	40.7	20.3
Functional performance				
Usual gait speed, mean (SD), m/s	1.15 (0.22)	1.07 (0.19)	1.14 (0.21)	1.07 (0.20)
400-m time, mean (SD), s	277 (52)	302 (50)	278 (52)	301 (46)
Perceived fatigability, mean (SD), RPE[b]	8.6 (2.1)	9.4 (2.4)	8.6 (2.1)	9.5 (2.2)
Grip strength, mean (SD), kg[c]	31.1 (10.2)	32.9 (9.2)	31.3 (10.2)	32.2 (9.2)

BMI body mass index, RPE rating of perceived exertion

[a] Excessive adiposity defined as BMI ≥ 35 kg/m^2 or waist/height ratio ≥0.62

[b] Overall *N* for the cross-sectional sample was 649 with 75 classified as having excess adiposity; the respective *N* for the longitudinal sample was 399 and 37

[c] Overall *N* for the cross-sectional sample was 747 with 97 classified as having excess adiposity; the respective *N* for the longitudinal sample was 498 and 57

samples did not differ on any of the sociodemographic and health-related and function-related parameters examined. Persons with excessive adiposity were slightly younger and more likely to be men and black and exhibit slightly less favorable health and functional profiles with the exception of grip strength than those without excessive adiposity.

Results from the cross-sectional analyses are provided in Table 2. In the overall sample, lower temperature was associated with faster usual gait speed, less time to walk 400 m, and lower fatigability. In analyses stratified by adiposity, the same associations were observed in the non-adipose and appear stronger and more robust. In the excessive adiposity subgroup, no significant associations were observed, but notably, the beta coefficients associated with temperature were in the opposite direction for usual gait speed, 400-m walk time, and fatigability than those in the non-adipose. No associations were observed for grip strength in the overall sample or excessive adiposity subgroup. Supplemental Table 2A reports similar cross-sectional associations in the subset of participants comprising the longitudinal sample.

Results from the cross-sectional analyses in which casual temperature replaced early morning or basal temperature are detailed in Supplemental Table 2B. Casual temperature ranged from 95.5 to 101.2 °F and was moderately correlated with early morning temperature $r = 0.38$ ($p < 0.001$). No associations were observed between casual temperature and functional performance in the overall sample. In the non-adipose, associations were borderline significant with p values of 0.065 and

Table 2 Cross-sectional associations[a] between core body temperature and functional performance

No.	Overall 762 β (SE) p value	No excess adiposity 662 β (SE) p value	Excess adiposity 100 β (SE) p value
		Usual gait speed (m/s)	
Body temperature (°F)	−0.044 (0.014) 0.002	−0.050 (0.015) <0.001	0.014 (0.044) 0.743
Age (years)	−0.011 (0.001) <0.001	−0.012 (0.001) <0.001	−0.008 (0.004) 0.033
Excess adiposity	−0.081 (0.021) <0.001		
		400-m walk time (s)	
Body temperature (°F)	9.38 (3.14) 0.003	11.63 (3.29) <0.001	−12.61 (10.35) 0.226
Age (years)	3.31 (0.25) <0.001	3.42 (0.26) <0.001	2.44 (0.88) 0.007
Excess adiposity	27.1 (4.76) <0.001		
		Fatigability (RPE)[b]	
Body temperature (°F)	0.374 (0.156) 0.017	0.443 (0.159) 0.006	−0.278 (0.667) 0.678
Age (years)	0.088 (0.012) <0.001	0.087 (0.013) <0.001	0.103 (0.054) 0.062
Excess adiposity	0.789 (0.253) 0.002		
		Grip strength (kg)[c]	
Body temperature (°F)	−0.430 (0.457) 0.347	−0.369 (0.482) 0.444	−0.861 (1.51) 0.569
Age (years)	−0.327 (0.037) <0.001	−0.326 (0.038) <0.001	−0.332 (0.128) 0.011
Excess adiposity	0.544 (0.699) 0.437		

Units for body temperature are degrees above 95.0 °F, and units for age are years above 65

[a] Adjusted for age, adiposity status (BMI ≥ 35 kg/m^2 or waist-height ratio ≥0.62), sex, race, height, and exercise level

[b] Overall N is 649 with 75 classified as having excess adiposity

[c] Overall N is 747 with 97 classified as having excess adiposity

0.058, respectively, for usual gait speed and 400-m walk time with beta coefficients associated with a 1 °F increment of −0.024 and 5.45 in comparison to betas of over twice the magnitude of −0.062 ($p < 0.001$) and 13.6 ($p < 0.001$) associated with early morning or basal temperature.

Findings from the longitudinal analyses of functional performance change over an average follow-up of 2.2 years are displayed in Table 3. Basal temperature was not associated with change in any functional performance measure in the overall sample or in the non-adipose. In contrast, in those with excessive adiposity, lower body temperature was associated with more time needed to walk 400 m ($p = 0.006$). Analyses of whether cross-sectional associations were retained over time (Supplemental Table 3A) found in the non-adipose that lower temperature continued to be associated with faster usual gait speed ($B = -0.042$; $p = 0.028$) and less time to walk 400 m quickly ($B = 14.5$, $p = 0.004$). Whereas, in those with excessive adiposity, lower temperature which was not associated cross-sectionally with functional performance predicted slower gait speed ($B = 0.111$; $p = 0.050$) and more time to walk 400 m ($B = -40.5$; $p = 0.008$), an average of 2.2 years later. No longitudinal associations were observed between basal temperature and fatigability or grip strength overall or within adiposity strata.

Discussion

In well-functioning, non-excessively adipose persons aged 65 to 89 years, a lower basal oral temperature was associated with better performance of energetically oriented assessments such as usual gait speed, walking endurance, and fatigability which are also hallmarks of healthy aging (Studenski et al. 2011; Newman et al. 2006; Simonsick et al. 2016). Although lower temperature was not associated with a lower rate of decline in functional performance over an average 2.2 years, it did predict sustained superior performance in gait speed and endurance walk time. These protective associations were not observed in persons with excessive adiposity, however. If anything, the opposite relationship was

Table 3 Longitudinal associations[a] between body temperature and functional performance

No.	Overall 521 β (SE) *p* value	No excess adiposity 462 β (SE) *p* value	Excess adiposity 59 β (SE) *p* value
		Follow-up usual gait speed (m/s)	
Usual gait speed (m/s)	0.575 (0.039) <0.001	0.578 (0.043) <0.001	0.496 (0.089) <0.001
Body temperature (°F)	−0.001 (0.015) 0.963	−0.007 (0.017) 0.665	0.065 (0.045) 0.151
Age (years)	−0.008 (0.001) <0.001	−0.008 (0.001) <0.001	−0.007 (0.003) 0.041
Excess adiposity	−0.024 (0.024) 0.324		
		Follow-up 400-m walk time (s)[b]	
400-m walk time (s)	1.03 (0.038) <0.001	1.01 (0.039) <0.001	0.88 (0.133) <0.001
Body temperature (°F)	−1.27 (3.01) 0.672	2.17 (3.12) 0.486	−30.3 (10.4) 0.006
Age (years)	0.79 (0.27) 0.003	0.81 (0.28) 0.004	1.43 (0.96) 0.144
Excess adiposity	0.14 (4.92) 0.966		
		Follow-up fatigability (RPE)[c]	
Fatigability (RPE)	0.560 (0.043) <0.001	0.555 (0.045) <0.001	0.682 (0.176) 0.001
Body temperature (°F)	−0.175 (0.167) 0.295	−0.194 (0.171) 0.257	0.093 (0.836) 0.912
Age (years)	0.053 (0.014) <0.001	0.059 (0.014) <0.001	−0.058 (0.071) 0.423
Excess adiposity	0.012 (0.295) 0.968		
		Follow-up grip strength (kg)[d]	
Grip strength (kg)	0.694 (0.030) <0.001	0.688 (0.032) <0.001	0.735 (0.091) <0.001
Body temperature (°F)	0.619 (0.390) 0.114	0.635 (0.407) 0.119	0.660 (1.52) 0.665
Age (years)	−0.152 (0.032) <0.001	−0.162 (0.034) <0.001	−0.090 (0.121) 0.462
Excess adiposity	−0.233 (0.609) 0.702		

Units for body temperature are degrees above 95.0 °F

[a] Adjusted for age, sex, race, height, exercise level, and functional performance at the index visit and follow-up time in days in all models and excess adiposity status at the index visit in the overall sample. For 400-m walk time, use of a walking aid during testing was also accounted for

[b] Due to 400-m walk test exclusion, failure, or home visit status at follow-up, the overall sample size is 481 of which 52 have excess adiposity

[c] The overall follow-up sample size is 399 and of which 37 have excess adiposity

[d] The overall follow-up sample size is 498 of which 57 have excess adiposity

detected with a lower temperature predicting worse walking endurance and greater decline 2.2 years later. The lack of any associations with grip strength suggests that the lower temperature-better function relationship is restricted to energetically demanding health status indicators and supports the notion that a lower temperature set point facilitates better walking performance through enhanced energetic efficiency (Schrack et al. 2012).

Findings are consistent with the limited research on body temperature and health in humans (Roth et al. 2002; Waalen and Buxbaum 2011) and extend the purported beneficial associations of lower temperature from longer survival to more optimal gait speed, endurance, and fatigability. Study results partially support the hypothesis that persons with a lower basal temperature or "cooler engine" experience a slower rate of aging. Evidence that a lower temperature confers a sustained functional advantage provides further support, yet the absence of an association with rate of change (i.e., slower decline) somewhat diminishes enthusiasm for the slower aging hypothesis. The average follow-up was only 2.2 years, however, which may be insufficient to distinguish differential rates of decline. Further, the reduction in rate of aging associated with a lower temperature is likely to be small and subtle (Roth et al. 2002).

Casual temperature, despite a high correlation with early morning or basal temperature, exhibited generally weak and no more than borderline significant associations with gait speed and endurance walk time. This suggests that temperature set point or nadir is the more informative parameter and that early morning temperature taken in a fasted and resting state may provide a good approximation of a true nadir. Since temperature follows a circadian pattern and responds to environmental factors, body temperature taken at random time points under uncontrolled conditions may poorly reflect the set point. Unfortunately, most observational studies of aging have not measured early morning temperature.

Factors that impact individual differences in temperature set point have not been widely studied (Weinert 2010). In the cross-sectional sample, a regression model with age, sex, race, weight, height, waist circumference, exercise category, and time temperature was measured explained only 2.1 % of the variance in early morning temperature with black race and time of measurement showing positive yet weak associations ($B = 0.093$; $p = 0.037$ and $B = 0.002$; $p = 0.014$, respectively). The same model (absence of the time temperature was taken since it was not recorded) explained 2.1 % of the variance in casual temperature with age having a weak negative association ($B = -0.009$; $p = 0.016$), which is consistent with previous work (Weinert 2010; Waalen and Buxbaum 2011). Additionally, as basal temperature did not differ between those with and without excess adiposity and none of the body composition parameters were associated with either basal or casual temperature, findings do not support the argument that lower temperature connotes a metabolic handicap that contributes to obesity through lower caloric needs (Grimaldi et al. 2015; Landsberg 2012).

The absence of cross-sectional and possible converse longitudinal associations between basal temperature and usual gait speed and endurance walking ability in those with excess adiposity warrants comment. It has been suggested that lower body temperature in the excessively obese may be an adaptation to reduced ability to dissipate heat (Chudecka et al. 2014) to provide a buffer from incurring an excessively high temperature when ambient temperature is high and/or during physical exertion not unlike the adaptive response observed in heat trained athletes (Shvartz et al. 1974). Under this scenario, a lower temperature could indicate more severe obesity and/or compromised cooling ability which, in turn, may threaten endurance performance and promote faster decline. Alternatively, the observed deleterious association between lower temperature and functional performance in those with excessive adiposity may indicate that lower temperature reflects more severe underlying illness or other obesity-related factors such as sleep apnea which has been found associated with lower energy expenditure during sleep (Hins et al. 2006) which may reflect lower basal temperature. Similar "reversals" or converse relationships have been observed with other health indicators and risk factors. For example, low total cholesterol while typically protective, in the presence of cancer, frailty, or declining health, low cholesterol signifies more severe morbidity (Schupf et al. 2005).

This study has some limitations. As noted previously, the current follow-up may be too short to distinguish differential rates of functional decline with respect to temperature. We restricted the follow-up to no more than 4 years because few study eligible participants (i.e., 40) had been followed beyond 4 years, but since the BLSA is ongoing, we can revisit longitudinal associations in future analyses. Second, we used early morning oral temperature as an indirect measure of basal core temperature. Although oral temperature is typically lower than core temperature, it follows the identical circadian pattern and is more reliable than tympanic or axillary temperature and more acceptable to study participants than rectal assessment (Kelly 2006). Lastly, we defined excess adiposity by using dichotomous cutpoints for BMI and waist-to-height ratio. These cutpoints were intended to be illustrative and not definitive. Future work should consider body mass and fatness as well as regional or central fat distribution to better understand the obesity-body temperature-functional performance relationship.

In this study, we sought to evaluate whether a lower basal temperature is a biomarker of healthy aging. What we discovered is somewhat of a cautionary tale—not necessarily unique to temperature. Our findings generally support basal temperature as a biomarker, but not without qualifications. First, basal temperature is not a valid biomarker of healthy aging in the presence of poor or declining health as serious illness has been found to lower temperature set point (Weinert 2010) which is why the current study was largely restricted to persons in good to excellent health. Second, as the findings clearly demonstrate, excessive adiposity also invalidates lower basal temperature as a healthy aging biomarker. Both declining health and excessive adiposity have amorphous boundaries and are somewhat transitional states which pose challenges for defining the applicable population for any biomarker and for following the relationships between candidate biomarkers and health age over time. A lower basal temperature may indeed support or reflect a slower rate of aging, but this association may disintegrate when disease happens. Recognizing these threats to validity may be invaluable in the search for biomarkers of the rate of aging.

In sum, in overtly healthy non-excessively obese older men and women, basal oral temperature appears to be a biomarker of healthy aging as persons with lower temperatures demonstrate superior gait speed, walking endurance, and fatigability, all hallmarks of healthy aging.

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