Received: 25 January 2020 | Revised: 20 April 2020 | Accepted: 18 May 2020

DOI: 10.1111/sms.13729

ORIGINAL ARTICLE

WILEY

Comparison of balance performance between masters Olympic weightlifters and runners

Bryan L. Riemann | **Mara Mercado** | **Kayleigh Erickson** | **Gregory J. Grosicki**

Biodynamics and Human Performance Center, Georgia Southern University-Armstrong Campus, Savannah, GA, USA

Correspondence
Bryan L. Riemann, Biodynamics and Human Performance Center, Georgia Southern University-Armstrong Campus, 11935 Abercorn Street, Savannah, GA 31419, USA.
Email: briemann@georgiasouthern.edu

Balance disorders are a common problem among older adults that greatly increase susceptibility for falls and fractures. Aerobically trained older (masters) athletes tend to exhibit superior balance abilities compared to that of healthy age-matched counterparts. Olympic weightlifting involves tremendous power production and motor skill coordination throughout the body which may prompt unique sensory information acquisition and integration adaptations. The purpose of this investigation was to compare a modified clinical test of sensory interaction and balance performance between middle-aged (~40-60 years) masters Olympic weightlifters (OWL, n = 48) and runners (RUN, n = 42). Average mediolateral center of pressure velocity (MLCPV) was computed during completion of 2 double leg trials (30-s) completed on firm (FI) and foam (FO) surfaces with eyes open (EO) and eyes closed (EC). While there were no significant differences between the groups for either the EO-FI (P = .143, d = 0.34) or EO-FO (P = .209, d = 0.26), the OWL demonstrated significantly better balance (lower MLCPV) than the RUN for both the EC-FI (P = .009, d = 0.59) and EC-FO (P = .001, d = 0.70). The most salient result of this investigation was the identification of better balance performance by the OWL, particularly when visual inputs were unavailable (ie, EC), compared to the RUN. These results suggest that Olympic weightlifting may provide a superior training stimulus for somatosensory and vestibular function compared to running in middle-aged adults, a benefit that may help to offset archetypal age-related balance deficits.

KEYWORDS
middle age, postural control, somatosensory, vestibular

1 | INTRODUCTION

Beginning in middle age, notable declines in strength,[1-3] balance,[4-7] and functional performance[3,7] begin to occur, leaving older individuals more vulnerable to postural perturbations and at a greater risk of falling. In addition to the undesirable physical consequences of falls (eg, fractures, bruises), older adults who have fallen also exhibit reductions in physiological (eg, morbidity, further functional decline) and mental (eg, depression, loss of self-efficacy) competencies.[8] The benefits of lifelong physical activity and exercise in slowing down the progression of age-related declines in both neurocognitive[9] and physiological[10-12] health, as well as assisting with maintaining functional performance,[13] are well documented. Even if an individual has not been physically active during younger adult years, speculation[14] and direct evidence[15] suggests that initiation of an exercise program in middle age may provide benefits through older age. Moreover, midlife exercise initiation prior to the onset of reductions in phenotypic plasticity that are characteristic of the aging process[16] may help to prophylactically moderate age-related functional decline.

Physical activity and exercise can range from pure participation in strength, cardiovascular, balance, and flexibility training completed solely to reap health benefits, or they can be completed with the additional purpose of training for competitive sport participation. The term masters athlete is typically used to describe individuals older than peak performance age who systematically train and compete in organized sport activities.[17,18] While each specific sport's governing body determines the age at which masters athletes are defined, the majority of masters athletes are over the age of 35 years.[18] As a result of participating in organized competitions, masters athletes may train more regularly and with greater intensity than individuals exercising solely for health benefits, making them a unique group to study the effects of physical activity on successful aging. Not surprisingly, studies comparing former and current masters athletes, most of whom were runners, with age-matched healthy individuals have demonstrated a lower incidence of falls,[19] better balance,[11,17,20] and improved mobility during activities of daily living (walking, sit to stand).[14,20,21]

Maintaining balance is accomplished by the postural control system, which encompasses the collection of sensory sources (somatosensory, vision, and vestibular), the central nervous system to integrate and process the sensory information, and components of the musculoskeletal system to execute preparatory and reactive body segment adjustments. Thus, declines in any of these postural control system components may explain age-related decreases in balance performance. Aside from the obvious deteriorations in the motor components[1,2] contributing to balance, declines in the weighting of the sensory sources contributing to balance have also been demonstrated.[12,22-24] For example, several studies have shown that aging is accompanied by a greater reliance upon visual information for balance.[25-27] More reliance on vision, reflected by poorer balance during completion of eyes closed tasks, suggests possible declines in either vestibular or somatosensory inputs. Indeed, there is direct evidence that somatosensory acuity decreases with age, as evidenced by joint motion threshold and joint position testing[12,28,29] and poorer cortical proprioceptive processing.[30] Furthermore, other studies have reported age-related declines in vestibular function.[22,31] Thus, preventing the functional declines of somatosensory and vestibular input utilization through physical activity and exercise during middle age may be an avenue to preserve balance proficiency and mitigate fall risk in older adults.

The majority of the balance studies involving masters athletes have not used assessment methods that partition the contributions of vision, vestibular, and somatosensory sources to balance. Additionally, balance studies involving older athletes have largely only considered aerobically trained athletes such as runners, cyclists, and swimmers; these studies have largely demonstrated enhanced balance abilities in runners compared to healthy age-matched individuals.[11,17] In contrast to aerobic sports which largely involve muscular endurance, Olympic weightlifting is a sport that involves lifting the heaviest possible weight during two events, the snatch and the clean and jerk lifts.[32] Both lifts are explosive movements requiring tremendous power production and motor skill coordination throughout the entire body to raise a barbell from the floor to overhead.[33] Although studies[32-34] have previously examined muscle health in masters-level Olympic weightlifters, these reports have largely neglected to examine possible adaptations in postural control in these unique individuals. Given the task of Olympic weightlifting is associated with high-velocity perturbations to stability and maintaining balance,[35] weightlifters likely experience adaptations in acquiring and integrating sensory information, as well as motor strategies, for maintaining balance. To date, only one study has examined balance abilities of weightlifters.[35] Intriguingly, compared to healthy age-matched controls, elite young (18-30 years) adult weightlifters demonstrated better balance abilities under sensory conditions in which visual inputs were eliminated (ie, eyes closed) and somatosensory inputs were altered (ie, foam support surface). Thus, the purpose of this investigation was to compare modified Clinical Test of Sensory Interaction on Balance (CTSIB) performance between middle-aged (~40-60 years) masters Olympic weightlifters and runners. We hypothesized that the weightlifters would demonstrate better balance than the runners, particularly under assessment conditions with visual inputs unavailable (ie, eyes closed).

2 | MATERIALS AND METHODS

2.1 | Participants

This study included 48 competitors from the 2017 National Masters Olympic Weightlifting Competition and 42 distance runners who were training at least 30 km/wk and regularly competing in races ranging from 10 k to marathons (Table 1). All subjects reported participating in their respective sport at least 6 months and were training at least 3 times per week. After being given an overview of the study procedures, all subjects provided written consent to participate prior to completing demographic and health history questionnaires. All participants were void of any injury or disease that could have affected their balance abilities or ability to train within the last 6 months. This study was approved by the university's institutional review board.

TABLE 1 Descriptive statistics for participant characteristics

	Olympic Weightlifters (n = 48)		Runners (n = 42)	
	Females (n = 22)	Males (n = 26)	Females (n = 17)	Males (n = 25)
Age (y)	45.7 ± 8.1	48.8 ± 9.7	47.5 ± 10.0	47.8 ± 7.5
Mass (kg)*	68.4 ± 14.7	84.1 ± 12.3	58.3 ± 10.5	78.1 ± 11.0
Height (m)**	1.65 ± 0.07	1.74 ± 0.08	1.65 ± 0.09	1.78 ± 0.07
Body mass index (kg/m^2)*	24.3 ± 4.1	27.8 ± 3.5	21.3 ± 2.9	24.4 ± 3.0
Exercise experience (y)*	2.0 (0.5 to 37)	4.0 (1.5 to 33.0)	8.0 (2.0 to 51.0)	7.5 (1.0 to 40.0)
CJ/BM ratio	1.05 ± 0.22	1.26 ± 0.18		
VO_2max (mL/kg/min)			46.2 ± 7.1	56.4 ± 8.0
Weekly distance (km)			44.6 ± 16.3	51.8 ± 20.3

Note: Values presented are mean ± standard deviation, except for exercise experience (median and range).

Abbreviation: CJ/BM ratio, clean and jerk relative to body mass ratio.

*Significant difference between groups ($P < .05$).

**Significant differences between genders ($P < .05$).

2.2 | Procedures

Following measurement of height and body mass with a mechanical stadiometer (Detecto), subjects completed two trials of four balance tests consisting of two visual conditions, eyes open (EO) and eyes closed (EC), and two support surfaces, firm (FI) surface and foam (FO) surface (AIREX Balance Pad, Airex AG). Testing was conducted unshod, and participants were cued to stand as "motionless as possible" while maintaining their hands on their hips during the completion of each trial.[36] All balance testing was conducted in a quiet and closed room to avoid noise and visual disturbances. During the EO testing, participants were asked to focus on a target positioned 1.8 m anterior to their testing location and 1.6 m superior to the support surface.[6] The feet were positioned with 7.5 cm separation between the navicular tubercles. Each trial duration was 30 seconds with 30-seconds rest between trials. Prior to commencing the 30-seconds data collection, participants assumed the testing condition for 3 seconds.[6] If a compensatory event or loss of balance occurred during a trial, participants were given one re-test opportunity. All balance testing was conducted on an AMTI force plate (OR6). Force plate data were sampled at 100 Hz by the MotionMonitor acquisition software (The MotionMonitor, IST) and saved for offline analysis. Custom MATLAB based scripts (The Mathworks, Inc.) were used to compute average mediolateral center of pressure (CP) velocity for each trial. CP velocity was selected as the outcome measure based upon the relevance of sway velocity to reflect quiet stance stability.[6] The rationale for considering mediolateral CP velocity was based upon evidence that it is reliable in middle-aged adults,[36] is sensitive to age-related changes in balance performance,[6] and discriminates between fallers and non-fallers,[37,38] as well as predicts future fallers.[39] The average mediolateral CP velocities were averaged across the two trials of each condition.

2.3 | Statistical analysis

Exploratory analysis of the years of training experience and anthropometric characteristics (eg, height, mass, age, body mass index) yielded years of training experience to be positively skewed. Data transformations of years of training experience failed to produce normality; therefore, only non-parametric statistical procedures were used with years of training experience. As expected,[6] exploratory analysis of the mediolateral CP velocities yielded positive skewness. Following a natural logarithm transformation of average mediolateral CP velocities, skewness was eliminated and formal normality tests became non-significant. Two-factor (exercise group by gender) analysis of variance (ANOVA) was conducted on age, height, mass, and body mass index (BMI). The relationship between age, height, mass, and BMI with the transformed mediolateral CP velocities was examined by computing Pearson's correlational coefficients within each exercise group. The relationship between years of training experience and transformed mediolateral CP velocities was examined by computing Spearman's correlational coefficients. Three-factor (exercise group × gender × condition) repeated measures ANOVA was conducted on the transformed mediolateral CP velocities. Bonferroni simple main effect post hoc testing was conducted on significant interactions. Additionally, standardized effects sizes (d) were computed using Hedge's method.[40] All analyses were performed using SPSS (IBM SPSS, Inc 23.0) with an alpha level of .05.

3 | RESULTS

There were no significant (Table 1) age differences between Olympic weightlifters and runners (P = .841) or genders (P = .366). Body mass (P = .003, 95% CI_{diff} = 2.7 to 13.3 kg) and BMI (P < .001, 95% CI_{diff} = 1.7 to 4.7 kg/m^2) of the Olympic weightlifters were significantly greater compared to the runners. The males demonstrated significantly greater mass (P < .001, 95% CI_{diff} = 12.4 to 23.0 kg), height (P < .0001, 95% CI_{diff}=0.08 to 0.14 m), and BMI (P < .001, 95% CI_{diff} = 1.8 to 4.7 kg/m^2) compared to the females. There were no significant exercise group by gender interactions (P > .05) in the participant characteristics. The runners (median = 8 years, range: 1.0-51.0 years) had significantly more years of experience (P < .001) than the Olympic weightlifters (median = 2 years, range: 0.5-37.0 years). There was no significant difference in years of experience (P = .160) between the males (median = 5 years, range: 1.0-40.0 years) and females (median = 4 years, range: 0.5-51.0 years).

Results of the correlational analyses yielded no significant (P > .08) relationships for the Olympic weightlifters between balance performance and age, height, mass, BMI, and experience with coefficients ranging from −0.230 to 0.211 (Table 2). In contrast, for the runners, age was significantly related (P < .043) to balance performance across all four conditions (r = .313 to .360). Additionally, significant relationships between height and EO-FI (r = .309, P = .046) and between experience and EC-FO (r = .544, P < .001) were identified for the runners. There were no significant (P = .069) relationships between mass and BMI with balance performance for the runners.

The two exercise groups demonstrated different balance proficiency (Figure 1) depending upon the vision/support surface condition ($F_{3,258} = 3.6$, $P = .015$, $\eta^2_p = 0.04$). For both the Olympic weightlifters and runners, with each increasing testing condition difficulty (EO-FI < EC-FI < EO-FO < EC-FO), there were significant decrements (higher mediolateral CP velocities) in balance (P < .001). While there were no significant differences between the groups for either the EO-FI (P = .143, d = 0.34) or EO-FO (P = .209, d = 0.26), the Olympic weightlifters demonstrated significantly better balance (lower mediolateral CP velocities) than the runners for both the EC-FI (P = .009, d = 0.59) and EC-FO (P = .001, d = 0.70). There were no significant differences related to gender (P > .05).

4 | DISCUSSION

The purpose of this investigation was to compare balance performance, with an emphasis on using a balance assessment approach that altered the sensory sources essential to maintaining balance, between middle-aged masters Olympic weightlifters and runners. With positive adaptations in balance ability already being demonstrated in runners compared to age-matched healthy controls,[11,17] the novelty of this investigation was the comparison of balance performance between runners and Olympic weightlifters, a form of weightlifting that is different from the traditional form of weightlifting completed for strength training. Consistent with our hypothesis, the most salient result of this investigation was the identification of better balance performance by the weightlifters, particularly when visual inputs were unavailable (ie, eyes closed), compared to the runners. This would suggest the weightlifters had an enhanced ability to utilize vestibular and somatosensory inputs to compensate for the

TABLE 2 Correlational coefficients (P values) between balance performance and participant characteristics

	Firm surface		Foam surface	
	Eyes open	**Eyes closed**	**Eyes open**	**Eyes closed**
Weightlifters				
Age	−0.230 (0.133)	−0.107 (0.491)	0.211 (0.170)	0.172 (0.265)
Height	0.150 (0.308)	0.204 (0.164)	0.172 (0.243)	0.255 (0.080)
Mass	0.022 (0.888)	0.099 (0.522)	0.131 (0.398)	0.157 (0.309)
BMI	−0.001 (0.995)	0.027 (0.805)	0.032 (0.758)	−0.113 (0.300)
Experience[a]	0.009 (0.952)	0.139 (0.368)	0.117 (0.449)	0.031 (0.840)
Runners				
Age	0.353 (0.022)	0.318 (0.040)	0.360 (0.019)	0.313 (0.043)
Height	0.309 (0.046)	0.172 (0.276)	−0.080 (0.615)	−0.172 (0.276)
Mass	0.284 (0.069)	0.202 (0.200)	−0.004 (0.978)	−0.091 (0.568)
BMI	0.162 (0.305)	0.149 (0.347)	0.022 (0.888)	−0.005 (0.975)
Experience[a]	0.215 (0.173)	0.228 (0.146)	0.256 (0.102)	0.544 (<0.001)

Abbreviation: BMI, body mass index.

[a]Spearman's correlational coefficient.

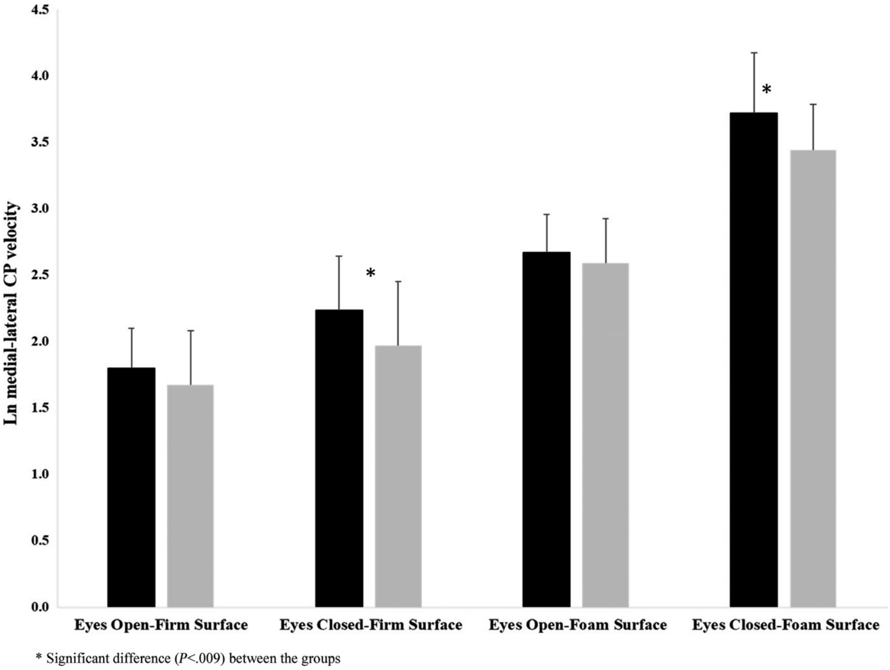

FIGURE 1 Balance performance (natural logarithm-transformed mediolateral center of pressure velocity) across the four testing conditions. For both the runners (black bars) and weightlifters (gray bars), there were significant ($P < .001$) increases (less stability) in center of pressure velocity with each more difficult testing condition. Additionally, the runners demonstrated significantly ($P < .009$) higher center of pressure velocity for the eyes closed-firm surface and eyes closed-foam surface conditions. Error bars are standard deviations

absence of visual information. Further evidence suggesting that Olympic weightlifting may be beneficial in slowing aging-related balance declines was evident in the correlational analyses. While age was associated with poorer balance performance in the runners across all four balance testing conditions, there were no significant relationships between age and balance performance in the weightlifters. This finding contrasts all of the previous research demonstrating decreases in balance performance with increasing age.[4,6,26,27] Collectively, these results suggest that Olympic weightlifting may attenuate age-related declines in balance performance, thereby mitigating fall risk in older adults.

As described previously, with aging comes a heavier reliance on visual information for balance,[25-27] which may be explained by documented declines in vestibular[22,31] and somatosensory[12,28-30] inputs. Thus, when seeking to understand potential age-related changes in balance performance, comparing the decrement in balance performance between EC compared to EO is a means to determine the importance of visual inputs to the postural control system, as well as the ability of vestibular and somatosensory inputs to compensate for the absence of visual information. Consequentially, it was not surprising that both groups of participants in the current study demonstrated significant decreases in balance performance (ie, higher CP velocity) during EC compared to EO on both the FI and FO support surfaces. Most remarkable was that removing vision on the firm and foam surfaces had a more pronounced effect for the runners compared to the weightlifters, suggesting the weightlifters had a heightened ability to utilize compensatory sensory information stemming from either vestibular or somatosensory sources. This result is consistent with a previous study comparing young adult (18-30 years) national level competitive Olympic and power weightlifters to a healthy group of untrained individuals.[35] Specifically, during a limits of stability task under EO/EC visual conditions and FI/FO surfaces, Bryanton and Bilodeau[35] reported that the weightlifters were less affected by changing sensory conditions than the untrained participants. Taken together, these findings suggest Olympic weightlifting may promote a heighted ability to use vestibular and/or somatosensory sources for balance, although the underlying mechanisms for this phenomenon remain to be explored.

Previous research demonstrates that older adults who are not physically active have a higher reliance on vision during balance testing than older adults who participate in either low energy physical activities (eg, yoga, "soft" gymnastics) or aerobic activities (eg, running, cycling, swimming).[41] Interestingly, the low energy group seemed to be less reliant on vision during the balance testing than those participating in aerobic exercise.[41] We observed superior postural control in Olympic weightlifters versus the runners. Similar to yoga and "soft" gymnastics, Olympic weightlifting involves whole-body movements which may promote greater vestibular and somatosensory stimulation. In contrast, during aerobic activities such as running, cycling, and swimming, while the vestibular otolith organs would be subjected to greater linear acceleration compared to that experienced during activities of daily living, the semicircular canals would not experience maximal stimulation because the orientation of the head with respect to gravity largely remains constant. Additionally, similar to both yoga and "soft" gymnastics, during Olympic weightlifting the body segments undergo large ranges of motion, thereby exaggerating stimulation of the mechanoreceptors responsible for proprioception. In contrast, aerobic activities typically involve cyclical body segment displacements through more limited ranges of motion. Movement velocity is also quite discrepant when comparing Olympic weightlifters and runners. Olympic weightlifting involves explosive power-focused movements that likely promote greater stimulation of both the vestibular and proprioceptive receptors. Moreover, stimulation of plantar cutaneous mechanoreceptors during changes in vertical project of the total body center of mass with Olympic weightlifting may further benefit proprioceptive feedback. Providing direct evidence of the above speculation regarding potential adaptations from various exercise and physical activities through direct vestibular and proprioception testing is recommended for future research.

The foam surface condition diminishes the precision of the sensory information provided to the postural control system by the plantar cutaneous mechanoreceptors. Furthermore, in contrast to standing on a firm surface during which head and ankle movements are largely harmonious, while standing on a foam surface, the movement about the ankles many be incongruent with head acceleration. Therefore, during the EC-FO condition, the adequacy of proprioceptive and vestibular inputs is critical for the postural control system to maintain stability. Superior balance exhibited by the Olympic weightlifters during the FO surface provides further evidence of enhanced vestibular and proprioceptive utilization.

Despite the current study utilizing a balance assessment approach which largely centered on stressing the various sensory systems involved with balance, it is also plausible that adaptations in the efferent (eg, motor) components may also partly explain the group differences identified. Previous studies examining balance in middle and older-aged adults have partially attributed better balance performance to strength and/or rate of torque differences in those who are either masters athletes or physically active compared to healthy non-active individuals.[15,17,20] Several studies examining the effects of age on master Olympic weightlifter performance have demonstrated that while the weightlifters maintain higher levels of muscle function, muscle performance declines at similar rates as healthy controls.[32-34] As we did not evaluate muscle performance in the current study, we can only speculate that the Olympic weightlifters likely possessed greater muscle strength and power. It is recommended that future balance research involving masters Olympic weightlifters include measures of strength.

One limitation of the current study was the cross-sectional design comparing the two exercise groups without a group of healthy aged-matched controls. The decision to not recruit healthy aged-matched controls was based on the number of studies showing masters athletes, particularly runners, demonstrating better balance abilities compared to healthy controls.[11,15,17,41] Additionally, aside from sensory and motor adaptations secondary to physical activity differences, masters athletes are likely be more competitive than non-athletes[17] and thus may be in a higher state of arousal which could confound group comparison interpretation. Based on demographic and anthropometric factors influencing balance performance,[6] we compared the groups with regard to gender, age, height, body mass, and body mass index. While age and gender did not differ between the groups, body mass and body mass index were both significantly greater in the Olympic weightlifters. Interestingly, neither body mass nor body mass index were revealed to be significantly related to balance performance; therefore, these factors were not included as covariates. An additional potential confounding factor was years of experience our participants participated in either running or Olympic weightlifting. Unfortunately, the years of experience for both groups were severely positively skewed, even after exploring several data transformations, so this variable could not be included as a covariate. Nonetheless, it is noteworthy that the runners trended toward greater years of training experience based on the median being 5 years greater, as well as the minimum and maximum years of experience being longer compared to the weightlifters. Moreover, we did not evaluate muscle quality and function so the degree to which differences in muscle performance may have influenced the enhanced balance abilities in the Olympic weightlifters is unknown. Future research involving these cohorts should include comparisons of muscle quality and function. To elucidate whether the superior balance in the Olympic weightlifters was due to the unique, high-velocity Olympic weightlifting stimulus or was simply a product of greater lean mass observed in this cohort,[42] future research is recommended to compare Olympic weightlifters to other competitive resistance-trained masters athletes (eg, powerlifters).

This study was specifically designed to assess contributions and integration of the three sensory sources involved with balance and therefore used the CTSIB evaluation approach. The CTSIB requires bilateral stance testing on both FI and FO surfaces under EO and EC visual conditions to determine the relative reliance of each sensory system to balance. As Olympic weightlifting is a bilateral stance activity, the Olympic weightlifters may have had an advantage over the runners because our balance testing methodology used bilateral stance. However, the stance width used for testing was much narrower than the stance width used for Olympic weightlifting. Thus, there was some novelty in the testing methodology that was not specific to either weightlifting or running. It is worthy to note that although the CTSIB has many strengths, criticisms of this well-accepted assessment modality include its lack of consideration for balance performance during dynamic tasks or under single leg support, which may have greater translational significance. Though neither Olympic weightlifting nor distance running would be anticipated to impart unique unilateral stance advantages, future research may be advised to consider the effects of various training modes (eg, running vs. weightlifting) on balance using more novel stance positions, such as tandem stance, or perturbation responses and other more dynamic balance tasks.

5 | PERSPECTIVE

Preventing functional declines of proprioceptive and vestibular input utilization through physical activity and exercise during middle age may be an avenue to preserve balance proficiency and mitigate fall risk in older individuals. Positive adaptations in balance abilities have been previously demonstrated in aerobically trained masters athletes, such as runners. Olympic weightlifting involves high-velocity whole-body movements with both the upper and lower extremities and axial region moving through large angular displacements, including changes in head orientation. The current study demonstrated better balance performance in middle-aged masters Olympic weightlifters compared to runners, particularly when visual inputs were unavailable. Our results suggest that Olympic weightlifting may provide a superior training stimulus compared to running in preventing the age-related declines in somatosensory and vestibular function; however, it still remains to be determined if these adaptations would transfer to functional activities, recovery from perturbations, and fall prevention. Future studies should consider direct measurement of vestibular and somatosensory acuity, measures of muscle quality and function, and more dynamic balance testing involving perturbation recovery responses as well as the translation of these adaptations to real-life functional tasks. Moreover, since many older adults will not likely commence Olympic weight training, evaluation of the efficacy of physical activity interventions incorporating dynamic, high velocity, total body movement patterns as a means to improve balance performance in older individuals is of interest.

ORCID

Bryan L. Riemann https://orcid.org/0000-0003-1850-0372

REFERENCES

1. Faulkner JA, Larkin LM, Claflin DR, Brooks SV. Age-related changes in the structure and function of skeletal muscles. *Clin Exp Pharmacol Physiol*. 2007;34(11):1091-1096.
2. Piasecki M, Ireland A, Stashuk D, Hamilton-Wright A, Jones DA, McPhee JS. Age-related neuromuscular changes affecting human vastus lateralis. *J Physiol*. 2016;594(16):4525-4536.
3. Wu F, Callisaya M, Wills K, Laslett LL, Jones G, Winzenberg T. Both baseline and change in lower limb muscle strength in younger women are independent predictors of balance in middle age: a 12-year population-based prospective study. *J Bone Miner Res*. 2017;32(6):1201-1208.
4. Choy NL, Brauer S, Nitz J. Changes in postural stability in women aged 20 to 80 years. *J Gerontol A Biol Sci Med Sci*. 2003;58(6):525-530.
5. Isles RC, Choy NL, Steer M, Nitz JC. Normal values of balance tests in women aged 20–80. *J Am Geriatr Soc*. 2004;52(8):1367-1372.
6. Riemann BL, Lininger M, Kirkland MK, Petrizzo J. Age related changes in balance performance during self-selected and narrow stance testing. *Arch Gerontol Geriatr*. 2018;75:65-69.
7. Wu F, Callisaya M, Laslett LL, et al. Lower limb muscle strength is associated with poor balance in middle-aged women: linear and nonlinear analyses. *Osteoporos Int*. 2016;27(7):2241-2248.
8. Terroso M, Rosa N, Torres Marques A, Simoes R. Physical consequences of falls in the elderly: a literature review from 1995 to 2010. *Eur Rev Aging Phys Act*. 2014;11(1):51-59.
9. Zhao E, Tranovich MJ, DeAngelo R, Kontos AP, Wright VJ. Chronic exercise preserves brain function in masters athletes when compared to sedentary counterparts. *Phys Sportsmed*. 2016;44(1):8-13.
10. Hawkins SA, Wiswell RA, Marcell TJ. Exercise and the master athlete–a model of successful aging? *J Gerontol A Biol Sci Med Sci*. 2003;58(11):1009-1011.
11. Leightley D, Yap MH, Coulson J, et al. Postural stability during standing balance and sit-to-stand in master athlete runners compared with nonathletic old and young adults. *J Aging Phys Act*. 2017;25(3):345-350.
12. Ribeiro F, Oliveira J. Aging effects on joint proprioception: the role of physical activity in proprioception preservation. *Eur Rev Aging Phys Act*. 2007;4(2):71-76.
13. Ringsberg KA, Gardsell P, Johnell O, Josefsson PO, Obrant KJ. The impact of long-term moderate physical activity on functional performance, bone mineral density and fracture incidence in elderly women. *Gerontology*. 2001;47(1):15-20.
14. Glenn JM, Vincenzo J, Canella CK, Binns A, Gray M. Habitual and maximal dual-task gait speeds among sedentary, recreationally active, and masters athlete late middle-aged adults. *J Aging Phys Act*. 2015;23(3):433-437.
15. Perrin PP, Gauchard GC, Perrot C, Jeandel C. Effects of physical and sporting activities on balance control in elderly people. *Br J Sports Med*. 1999;33(2):121-126.
16. Haran PH, Rivas DA, Fielding RA. Role and potential mechanisms of anabolic resistance in sarcopenia. *J Cachexia Sarcopenia Muscle*. 2012;3(3):157-162.
17. Brauer SG, Neros C, Woollacott M. Balance control in the elderly: do Masters athletes show more efficient balance responses than healthy older adults? *Aging Clin Exp Res*. 2008;20(5):406-411.
18. Reaburn P, Dascombe B. Endurance performance in masters athletes. *Eur Rev Aging Phys Act*. 2008;5(1):31-42.
19. Jordre B, Schweinle W, Oetjen S, Dybsetter N, Braun M. Fall history and associated physical performance measures in competitive senior athletes. *Top Geriatr Rehabil*. 2016;32:1-16.
20. Raty HP, Impivaara O, Karppi SL. Dynamic balance in former elite male athletes and in community control subjects. *Scand J Med Sci Sports*. 2002;12(2):111-116.
21. Feland JB, Hager R, Merrill RM. Sit to stand transfer: performance in rising power, transfer time and sway by age and sex in senior athletes. *Br J Sports Med*. 2005;39(11):e39.

22. Lopez I, Honrubia V, Baloh RW. Aging and the human vestibular nucleus. *J Vestib Res*. 1997;7(1):77-85.
23. Pasma JH, Engelhart D, Maier AB, Schouten AC, van der Kooij H, Meskers CGM. Changes in sensory reweighting of proprioceptive information during standing balance with age and disease. *J Neurophysiol*. 2015;114(6):3220-3233.
24. Wiesmeier IK, Dalin D, Maurer C. Elderly use proprioception rather than visual and vestibular cues for postural motor control. *Front Aging Neurosci*. 2015;7:97.
25. Perrin PP, Jeandel C, Perrin CA, Bene MC. Influence of visual control, conduction, and central integration on static and dynamic balance in healthy older adults. *Gerontology*. 1997;43(4):223-231.
26. Roman-Liu D. Age-related changes in the range and velocity of postural sway. *Arch Gerontol Geriatr*. 2018;77:68-80.
27. Tanaka H, Uetake T. Characteristics of postural sway in older adults standing on a soft surface. *J Hum Ergol (Tokyo)*. 2005;34(1–2):35-40.
28. Deshpande N, Simonsick E, Metter EJ, Ko S, Ferrucci L, Studenski S. Ankle proprioceptive acuity is associated with objective as well as self-report measures of balance, mobility, and physical function. *Age (Dordr)*. 2016;38(3):53.
29. Skinner HB, Barrack RL, Cook SD. Age-related decline in proprioception. *Clin Orthop Relat Res*. 1984;184:208-211.
30. Piitulainen H, Seipäjärvi S, Avela J, Parviainen T, Walker S. Cortical proprioceptive processing is altered by aging. *Front Aging Neurosci*. 2018;10:147.
31. Alcock L, O'Brien TD, Vanicek N. Association between somatosensory, visual and vestibular contributions to postural control, reactive balance capacity and healthy ageing in older women. *Health Care Women Int*. 2018;39(12):1366-1380.
32. The DJ, Ploutz-Snyder L. Age, body mass, and gender as predictors of masters olympic weightlifting performance. *Med Sci Sports Exerc*. 2003;35(7):1216-1224.
33. Pearson SJ, Young A, Macaluso A, et al. Muscle function in elite master weightlifters. *Med Sci Sports Exerc*. 2002;34(7):1199-1206.
34. Anton MM, Spirduso WW, Tanaka H. Age-related declines in anaerobic muscular performance: weightlifting and powerlifting. *Med Sci Sports Exerc*. 2004;36(1):143-147.
35. Bryanton MA, Bilodeau M. The effect of vision and surface compliance on balance in untrained and strength athletes. *J Mot Behav*. 2018;51(1):75-82.
36. Riemann BL, Piersol K. Intersession reliability of self-selected and narrow stance balance testing in older adults. *Aging Clin Exp Res*. 2017;29(5):1045-1048.
37. Bigelow KE, Berme N. Development of a protocol for improving the clinical utility of posturography as a fall-risk screening tool. *J Gerontol A Biol Sci Med Sci*. 2011;66(2):228-233.
38. Melzer I, Benjuya N, Kaplanski J. Postural stability in the elderly: a comparison between fallers and non-fallers. *Age Ageing*. 2004;33(6):602-607.
39. Maki BE, Holliday PJ, Topper AK. A prospective study of postural balance and risk of falling in an ambulatory and independent elderly population. *J Gerontol*. 1994;49(2):M72-M84.
40. Kline R. *Beyond Significance Testing: Statistical Reform in the Behaviorial Sciences*, 2nd edn. Washington, DC: American Psychological Association; 2013.
41. Gauchard GC, Jeandel C, Perrin PP. Physical and sporting activities improve vestibular afferent usage and balance in elderly human subjects. *Gerontology*. 2001;47(5):263-270.
42. Erickson KR, Grosicki GJ, Mercardo M, Riemann BL. Bone mineral density and muscle mass in masters Olympic weightlifters and runners. *J Aging Phys Act*. 2020. 1-7. https://doi.org/10.1123/japa.2019-0426

How to cite this article: Riemann BL, Mercado M, Erickson K, Grosicki GJ. Comparison of balance performance between masters Olympic weightlifters and runners. *Scand J Med Sci Sports*. 2020;30:1586–1593. https://doi.org/10.1111/sms.13729