Original Article

Postural stability during standing balance and sit-to-stand in master athlete runners compared with non-athletic old and young adults

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Key Words: ageing, mobility, frailty, sarcopenia, masters athlete

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Abstract

The aim of this study was to compare postural sway during a series of static balancing tasks and during five chair rises between healthy young (mean (SEM) age 26(1) yrs), healthy old (age 67(1) yrs) and master athlete runners (age 67(1) yrs; competing and training for the previous 51(5) yrs) using the Microsoft Kinect One. The healthy old had more sway than young in all balance tasks. The master athletes had similar sway to young during two-leg balancing and one leg standing with eyes open. When balancing on one-leg with eyes closed, both the healthy old and the master athletes had around 17-fold more sway than young. The healthy old and master athletes also had less anterio-posterior movement during chair rising compared with young. These results suggest that masters runners are not spared from the age-associated decline in postural stability and may benefit from specific balance training.

Introduction

Older adults have unstable balance compared with young and the amount of body sway increases with more challenging foot positions that reduce the base of support, and with removal of vision (Gill et al., 2001). The altered posture control in older people is also evident during the gait cycle and transitions from sit-to-stand, which increases the risk of falls (Rubenstein, 2006). The reduced postural control and mobility may occur in part due to the increased tendency for older people to be sedentary (McPhee et al., 2016). Relatively short-term exercise training lasting just a few weeks and including different components of resistance or endurance activities can improve muscle function, mobility and balance (McPhee et al., 2016; Sherrington et al., 2011). It may therefore be expected that very athletic older people (masters athletes) who have been active for the majority of their adult lives would maintain good postural stability when standing and during transition from sit-to-stand, but there is little evidence currently available to this effect. Studying masters athletes may also help to distinguish between effects of ageing per se, and effects occurring due to the combination of sedentary living and ageing (Hawkins et al., 2003). While there is no doubt that masters athletes maintain high physical capability (Rittweger et al., 2009), athletic performance nevertheless declines with advancing age alongside loss of muscle power and cardiopulmonary function (Degens et al., 2013; Michaelis et al., 2008; Runge et al., 2004), so it is possible that balance and performance of common movements such as sit-to-stand transitions in masters athletes also decline with increasing age.

Research into postural control of masters athletes has focused mainly on the ability to recover balance after perturbation. Masters runners with exceptionally high performance (recent world championship competition winners) regained a stable centre of pressure more quickly and required fewer steps to prevent falls compared with non-athletes after moving the standing platform unexpectedly backwards (Brauer et al., 2008). Another study of 173 people attending a mixed-sports event showed that men aged >65 years produced less power during repeated sit-to-stand transitions than those aged 50-64 years (Feland et al., 2005). Postural stability during the movements was not assessed, so it remains unknown whether the older athletes adapted a different rise strategy than healthy old during the sit-to-stand. The older sports participants had similar postural sway to the middle aged when standing upright (Feland et al., 2005), unlike people from the general population where postural sway increases with advancing old age (Gill et al., 2001). However, the sway during standing was assessed for just 5 s immediately following the sit-to-stand transition (Feland et al., 2005), which is more reflective of recovery of stability after whole-body movement than a test of postural sway during quiet standing.

Recent research showed the incidence of falls to be around 10% in athletic older people and associated with shorter time achieved during a single leg stand and slow chair-rise time (Jordre et al., 2016), although postural stability was not measured in this study. Knowing the extent to which athletic older people are unstable during challenging balance tasks and other common movements (such as sit-to-stand) may highlight physiological age-associated declines that are not necessarily halted by specific training of one type (such as running) and instead require targeted intervention. Thus, the aim of this study was to compare postural sway during a series of static balancing tasks and during five chair rises between young, old and master athlete runners.

Methods

Participants and ethical approval

The Local Research Ethics Committee at Manchester Metropolitan University approved the study and all participants provided written, informed consent. The young men and women were recruited from amongst the university student and staff population. The healthy older participants were all living independently and were recruited from the local community, but were excluded if they reported any cognitive, musculoskeletal or cardiovascular disease or other disability that affected their mobility levels. Master runners were recruited as part of ongoing studies (*details added after acceptance*). They were exceptionally physically active for their age, the majority were endurance runners (73%) and the remainder were sprinters (27%). All were free from injury at the time of testing and they had a mean 51.1 (SEM: 5.5) yrs history of competing in athletics. Participants reported training on average 5.5 (SEM: 2.5) hrs per week over the previous 10 yrs and all achieved British Masters Athletics Federation standards for their age group within the past two years. All assessments were completed over a four-month period during 2015 in the research laboratory at (*details added after acceptance)*.

Postural sway and motion analysis data capture

The balance and sit-to-stand assessments (described in more detail below) were selected because they form core parts of the short physical performance test battery commonly used to assess mobility impairments in older people, with additional single-leg stance tests that are well validated and predictive of falls risk (Guralnik et al., 1994; Macrae et al., 1992; Franchignoni et al., 1998). The participant performance was recorded by a Kinect One depth sensor coupled with the Microsoft Windows Software Development Kit (Kinect for Windows Software Development Kit, 2014). The Kinect One accurately tracks human motion and provides temporal-spatial features such as speed, distance travelled and time taken. For example, in Parkinson's disease patients the Kinect One had very low bias and very high accuracy when compared with the gold-standard VICON motion capture system when tracking whole-body movements, such as sit-to-stand (intraclass correlation coefficient = 0.989) (Galna et al., 2014). It is highly accurate and repeatable during standardized balance and sit-to-stand assessments (Clark et al., 2012; Clark et al., 2015; Vernadakis et al., 2014; Ejupi et al., 2015). A detailed description of the data collection techniques and algorithms used in this study has been published previously (*details added after acceptance)*. Briefly, the sensor was fixed horizontally to a tripod at a height of 0.70 metres to synchronise capture of depth and skeleton streams at 30 Hz. Motion capture data (MoCap) was extracted in real time using the technique of Shotton *et al.* (2012). Following validated protocols (Clark et al., 2015; Ejupi et al., 2015; Mentiplay et al., 2015), participants wore tight-fitting shorts and a tight-fitting upper body garment that allowed for unrestricted free movement. The MoCap was composed of 25 joints and the raw axes coordinates (*x*, *y*, *z* orthogonal coordinates) were analysed using purpose-designed algorithms (*Reference details added after acceptance)* that tracked participant movements from over 116,500 frames of skeleton data (Matlab 2014a; MathWorks Inc, USA).

Standing balance

Balance was assessed with arms extended horizontally, parallel to the ground, and participants were given three attempts, separated by rest intervals lasting 30 s, to achieve 10 s without taking any steps or touching external supports in the following foot-placements: 1) side-by-side; 2) semi-tandem; 3) full-tandem; 4) one-leg standing; 5) one-leg standing with eyes closed. Total time was defined as the absolute time taken to perform a test (measured in s). The Centre-of-Mass (CoM) was identified in each frame as the centre of the hip joint, the shoulders and the spine (Gonzalez et al., 2014). The change in position between consecutive frames was considered as the directional change in medio-lateral (ML) and anterio-posterior (AP) movements.

Five-times sit-to-stand

After completing the balance assessments, participants were asked to perform five chair rises as quickly as possible and to keep their arms folded across their chest. A chair with seat height 44 cm and secure back rest, without arm rests, was used and positioned against a wall to prevent it from slipping backwards during the test. The number of chair stands and the estimated time taken to complete each of the five chair stands was determined using spectral analysis techniques (*details added after acceptance)*. For each test, the number of local peaks (i.e. reaching the highest point in the vertical-plane (y-axis) when fully standing) in the data was extracted based on a threshold reached when standing fully upright. It was determined by a minimum distance of 20 frames or greater than the overall sequence mean (the sequence mean occurs at around half-way between sitting and standing). An inversion of this process was undertaken to define the starting and end point of each rise (indicative of a seated position).

Statistical analysis

Analysis of Kinect data was performed using a customized script in Matlab 2014a (MathWorks Inc, USA) and statistical analysis of the results was completed using

SPSS (IBM Corporation, USA). The ML and AP movements were presented as absolute values (cm). Comparison of results between genders using independent samples t-tests showed no significant differences between men and women for assessments of balance or sit to stand, so results from the two genders were combined for further analyses. Participant group data (young; healthy old and master runners) were compared using one-way ANOVA and where significant differences were detected between groups a tukey's post-hoc test was performed. A two condition (eyes open vs eyes closed) Repeated Measures ANOVA was used to assess within-group differences between the single leg eyes open and the single leg eyes closed balance assessments. Where a significant condition-by-group interaction was found, separate dependent samples t-tests were performed to determine individual group effects. Significance was accepted as $p<0.05$.

Results

The balance and sit to stand results are summarized in Table 1.

Two-leg stance balance tests: During the side-by-side stance, AP movements did not differ between groups ($p=0.667$). The young and master runners had similar ML sway ($p=0.299$), but healthy old had significantly more ML sway than both young ($p=0.001$) and master runners ($p<0.0005$). During the semi-tandem stance, the young and master runners did not differ for ML ($p=0.835$) or AP ($p=0.094$) sway. The healthy old had significantly more ML and AP sway than both the young and master runners (all $p<0.01$). During the tandem stance, ML sway did not differ between groups ($p=0.117$). Master runners had similar AP movements to the young ($p=0.917$) during tandem stance, but the healthy old had more movement than the master runners (p=0.011) and the young (p=0.009).

One-leg stance balance tests: When eyes were open, two young and four healthy old could not achieve the full 10 seconds standing on one leg, but all masters runners completed the test. The postural sway during one-leg standing with eyes open was similar between the young and the master runners, but healthy old had more ML (p=0.001) and more AP sway (p=0.001) than young. When standing on one leg with eyes closed, three young and five master runners could not achieve the full 10 seconds and all of the healthy old failed to reach 10 seconds. Master runners (p=0.048) and healthy old (p<0.0005) were not able to stand on one leg with eyes closed for as long as the young, and healthy old performed worse than master runners (p=0.009). Master runners (p=0.006) and healthy old (p=0.009) had more ML sway than young; there was no difference between master runners and healthy old (p=0.929). Master runners (p=0.045) and healthy old (p=0.012) had more AP sway than young, with no difference between master runners and healthy old (p=0.462).

Comparison of performance during one leg stance with eyes open and eyes closed. When eyes were closed, participants achieved significantly less time (p<0.0005) standing on one leg compared with eyes open. A significant condition-by-group interaction for total time (p<0.0005) was due to the young adults (p=0.193) maintaining similar total balance time with eyes open and eyes closed, while the masters runners (p=0.043) and the healthy old (p<0.0005) had shorter balance time with eyes closed compared with eyes open.

Although all groups had more ML and AP sway (both p<0.0005) during the eyes closed condition compared with eyes open, there were significant condition-by-group interactions for ML (p=0.009) and AP sway (p=0.003). The young showed over 5-fold more ML sway (0.020) and 3.5-fold more AP sway (p=0.005) with eyes closed compared with eyes open. The healthy old showed 3.2-fold more ML sway (0.009) and 4-fold more AP sway (p=0.005) with eyes closed compared with eyes open. The masters runners showed 37-fold more ML sway (0.002) and 8-fold more AP sway (p<0.0005) with eyes closed compared with eyes open.

Five-times chair rise: There was no difference between the groups in the total time taken to perform five chair rises (p=0.361), but the healthy old had higher standard deviation of the time between stands than young (p=0.001) and higher than master runners (p=0.004). There were no significant differences between groups for ML movements of the upper body (p=0.102). Compared with the young, both master runners and healthy old had significantly less AP movements (p<0.0005), but the master runners and healthy old did not differ significantly. The AP movements during the chair rise correlated inversely with both AP and ML sway when balancing with eyes closed (r=-0.327, p=0.045; and r=-0.422, p=0.008, respectively).

Discussion

There is little doubt that regular physical activity helps to preserve health and physical function into older age and reduce risks of falling, which is the basis of the physical activity recommendations from the UK Chief Medical Officer

(Department of Health, 2011). Our results show that competitive masters runners performed better than non-athletic old and similar to young in moderately challenging balance tasks. However, during more challenging and less familiar conditions when standing on one leg with visual feedback removed, the masters runners were very unstable and they also demonstrated a restricted, possibly more cautious, upper body movement during the chair stand, similar to non-athletic old (Table 1).

Balance Performance

As the balance assessments increased in difficulty, all the participants tended to show more postural sway (Table 1). Masters runners showed similar postural sway to the young during side-by-side stance, semi-tandem, full tandem and one-leg eyes open stance. Conversely, compared to the young, the non-athletic old had around 40% more postural sway during side-by-side, 70% more during semi-tandem, over 4.5-fold more during tandem and over 8-fold more during one-leg standing with eyes open (Table 1). The results from the balance trials that were completed with eyes open suggest some cross-over benefit of regular running training when visual feedback was available. These findings may help to explain why masters athletes have a lower risk of falling than the non-athletic population (Jordre et al., 2016). The results also support those from two previous studies showing that masters athletes recovered balance more quickly after perturbation compared with non-athletic old (Brauer et al., 2008) and old athletes had similar postural sway to middle-aged athletes (Feland et al., 2005). They also add to a large body of evidence suggesting exercise training in old age is beneficial for balance and falls prevention (Orr et al., 2006; Perrin et al., 1999; Glenn et al., 2015; Sherrington et al., 2011).

During balance trials performed on one leg with eyes closed, the extent of underlying age-related deterioration was clearly apparent both in the old and the masters runners. A previous study of masters cyclists showed that they were often unable to balance on one leg with eyes closed for more than ten seconds (Pollock et al., 2015), which is similar to the performance we previously reported for non-athletic older people and substantially worse than younger adults (*details added after acceptance)*, again indicating poor postural control in older athletes. Running and cycling both require the majority of work to be completed by the legs, but the loads and eccentric contractions during cycling are lower than when running (Millet et al., 2009). Any comparison of balance performance between these two modes of training is beyond the scope of this study.

Results in Table 1 indicate that the young had around 4-fold more sway (5-fold ML and 3.5-fold AP) when standing on one leg with eyes closed compared to one-leg with eyes open. Master runners showed 17-fold more sway (37-fold ML and 8-fold AP) when standing on one-leg with eyes closed compared with one-leg with eyes open, going from reasonable stability with their eyes open to finding the task very difficult and performing almost as badly as the non-athletic old with their eyes closed. The non-athletic old showed around 3.5-fold more sway (3.2-fold ML and 4-fold AP) with eyes closed compared with eyes open. This value might seem modest compared to the 17-fold change for master runners, but the old were already very unstable on one leg with their eyes open. Indeed, when eyes were closed, all of the old and around a third of the master runners failed to stand on one leg for 10 sec.

Overall, our results indicate that long-term, regular intense running is associated with better balance during standing tasks completed with the eyes open compared with age-matched non-athletic old. However, long-term training did not attenuate the declines in postural sway during static balancing with eyes closed. These results might appear to conflict with advice that training can improve balance in older people (Sherrington et al., 2011), but the available evidence shows that the training-induced improvements to balance are most pronounced for 'vulnerable' populations at high risk of falling and they rarely or never return to levels seen in young (Sherrington et al., 2011). Our methodology cannot elucidate the sensory-motor control mechanisms differentially affecting balance performance with eyes open compared with eyes closed. Removing the visual feedback increases reliance upon the nervous-system components of motor control including central processing, vestibular function, proprioception and efferent motor-unit recruitment. Age-related declines in these systems are well documented (Campbell et al., 1973; Piasecki et al., 2016; Li et al., 2014; Lopez et al., 1997; Wiesmeier et al., 2015) although few previous studies included master athletes. The poor balance of masters runners with their eyes closed suggests that even competitive masters athletes might benefit from regular balance training.

Five times sit-to-stand

The five times sit to stand is a commonly used test of physical function in older people and patient groups and a part of the Short Physical Performance Battery (Guralnik et al., 1994). Recently, Ejupi *et al.* (2015) used the Kinect One to detect differences between older fallers compared with non-fallers in the five-times-sit-to-stand in the laboratory and the unsupervised home setting. In the present study, similar methodology with the Kinect One was used to show that young, healthy old and athletic old complete five chair rises in similar overall time. However, both the athletic and non-athletic old had less AP movement of the upper body throughout the task, which was principally due to the older adults and masters runners restricting the forwards lean of the upper body in the early stages of the sit-to-stand transition. The healthy old had more variability in time taken between chair rises due to slowing of movements during the task. The inverse correlation between AP movement during the chair stand test and sway during balancing with eyes closed might reflect an awareness of limitations of postural stability during functional tasks, causing older people to be more cautious, or less confident, during the transition from sit-to-stand. This caution when standing is thought to protect against leaning the centre of gravity too far forward and consequently losing balance (Binda et al., 2003).

Limitations and further work

The main limitation of using the Kinect One to track movements is that the data collection area is restricted to within 4m of the depth sensor. This is sufficient for analysis of sit-to-stand and static balance and although we have previously shown that spatio-temporal characteristics of gait can be analysed (*details added after acceptance)*, we considered 4m to be too limiting to compare gait results between groups. Future studies could consider using a treadmill during analysis of gait with the Kinect One. In this study we recruited masters runners to complete the assessments as a model of active ageing. It is possible that masters athletes competing in different weight-bearing events that have a greater emphasis on balance control, agility or strength, or indeed non-weight-bearing activities (such as swimming or cycling), may produce different results. All of the assessments were completed in a research laboratory and it will be important to determine how the differences that we identified between groups translate to mobility in a real-world setting.

Summary and conclusion

These results indicate that masters runners display greater postural stability than non-athletic old when balancing with visual feedback intact. However, during the more challenging condition when visual feedback was removed while standing on one leg, the masters runners were just as unstable as non-athletes, both being considerably less stable than young adults. The masters runners and healthy old restricted their upper body forwards lean during transitions from sit to stand, which was associated with the higher postural sway when balancing with eyes closed. These results suggest that masters runners are not spared from the age-associated decline in postural stability and are likely to benefit from the inclusion of specific challenging balance exercises into their weekly training programme to try to halt any further decline and reduce the risks of injurious falls.

Conflict of interest

None declared.

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References

Binda, S. M., Culham, E. G. and Brouwer, B. (2003) 'Balance, muscle strength, and fear of falling in older adults.' *Exp Aging Res*, 29(2), Apr-Jun, pp. 205-219.

Brauer, S. G., Neros, C. and Woollacott, M. (2008) 'Balance control in the elderly: do Masters athletes show more efficient balance responses than healthy older adults?' *Aging Clin Exp Res*, 20(5), Oct, pp. 406-411.

Campbell, M. J., McComas, A. J. and Petito, F. (1973) 'Physiological changes in ageing muscles.' *J Neurol Neurosurg Psychiatry*, 36(2), Apr, pp. 174-182.

Clark, R. A., Pua, Y. H., Fortin, K., Ritchie, C., Webster, K. E., Denehy, L. and Bryant, A. L. (2012) 'Validity of the Microsoft Kinect for assessment of postural control.' *Gait Posture*, 36(3), Jul, pp. 372-377.

Clark, R. A., Pua, Y. H., Oliveira, C. C., Bower, K. J., Thilarajah, S., McGaw, R., Hasanki, K. and Mentiplay, B. F. (2015) 'Reliability and concurrent validity of the Microsoft Xbox One Kinect for assessment of standing balance and postural control.' *Gait Posture*, 42(2), Jul, pp. 210-213.

Degens, H., Maden-Wilkinson, T. M., Ireland, A., Korhonen, M. T., Suominen, H., Heinonen, A., Radak, Z., McPhee, J. S. and Rittweger, J. (2013) 'Relationship between ventilatory function and age in master athletes and a sedentary reference population.' *Age*, 35(3), Jun, pp. 1007-1015.

Department of Health, U. (2011) 'Start Active, Stay Active: UK Physical Activity Guidelines.' *Department of Health, UK*, http://www.dh.gov.uk/health/category/publications/, 11 July, 2011,

Ejupi, A., Brodie, M., Gschwind, Y. J., Lord, S. R., Zagler, W. L. and Delbaere, K. (2015) 'Kinect-Based Five-Times-Sit-to-Stand Test for Clinical and In-Home Assessment of Fall Risk in Older People.' *Gerontology*, 62(1) pp. 118-124.

Feland, J. B., Hager, R. and Merrill, R. M. (2005) 'Sit to stand transfer: performance in rising power, transfer time and sway by age and sex in senior athletes.' *Br J Sports Med*, 39(11), Nov, p. e39.

Franchignoni, F., Tesio, L., Martino, M. T. and Ricupero, C. (1998) 'Reliability of four simple, quantitative tests of balance and mobility in healthy elderly females.' *Aging (Milano)*, 10(1), Feb, pp. 26-31.

Galna, B., Barry, G., Jackson, D., Mhiripiri, D., Olivier, P. and Rochester, L. (2014) 'Accuracy of the Microsoft Kinect sensor for measuring movement in people with Parkinson's disease.' *Gait Posture*, 39(4), Apr, pp. 1062-1068.

Gill, J., Allum, J. H., Carpenter, M. G., Held-Ziolkowska, M., Adkin, A. L., Honegger, F. and Pierchala, K. (2001) 'Trunk sway measures of postural stability during clinical balance tests: effects of age.' *J Gerontol A Biol Sci Med Sci*, 56(7), Jul, pp. M438-447.

Glenn, J. M., Gray, M. and Binns, A. (2015) 'The effects of loaded and unloaded high-velocity resistance training on functional fitness among community-dwelling older adults.' *Age Ageing*, 44(6), Nov, pp. 926-931.

Gonzalez, A., Hayashibe, M., Bonnet, V. and Fraisse, P. (2014) 'Whole body center of mass estimation with portable sensors: using the statically equivalent serial chain and a Kinect.' *Sensors (Basel)*, 14(9) pp. 16955-16971.

Guralnik, J. M., Simonsick, E. M., Ferrucci, L., Glynn, R. J., Berkman, L. F., Blazer, D. G., Scherr, P. A. and Wallace, R. B. (1994) 'A short physical performance battery assessing lower extremity function: association with self-reported disability and prediction of mortality and nursing home admission.' *J Gerontol*, 49(2), Mar, pp. M85-94.

Hawkins, S. A., Wiswell, R. A. and Marcell, T. J. (2003) 'Exercise and the master athlete--a model of successful aging?' *J Gerontol A Biol Sci Med Sci*, 58(11), Nov, pp. 1009-1011.

Jordre, B., Schweinle, W., Oetjen, S., Dybsetter, N. and Braun, M. (2016) 'Fall History and Associated Physical Performance Measures in Competitive Senior Athletes.' *Topics in Geriatric Rehabilitation*, 32(1) pp. 1-16.

Kinect for Windows Software Development Kit (2014) 'http//http://www.microsoft.com/en-us/kinectforwindows.'

Li, C., Beaumont, J. L., Rine, R. M., Slotkin, J. and Schubert, M. C. (2014) 'Normative Scores for the NIH Toolbox Dynamic Visual Acuity Test from 3 to 85 Years.' *Front Neurol*, 5 p. 223.

Lopez, I., Honrubia, V. and Baloh, R. W. (1997) 'Aging and the human vestibular nucleus.' *J Vestib Res*, 7(1), Jan-Feb, pp. 77-85.

Macrae, P. G., Lacourse, M. and Moldavon, R. (1992) 'Physical performance measures that predict faller status in community-dwelling older adults.' *J Orthop Sports Phys Ther*, 16(3) pp. 123-128.

McPhee, J. S., French, D. P., Jackson, D., Nazroo, J., Pendleton, N. and Degens, H. (2016) 'Physical activity in older age: perspectives for healthy ageing and frailty.' *Biogerontology*, 17(3), Jun, pp. 567-580.

Mentiplay, B. F., Perraton, L. G., Bower, K. J., Pua, Y. H., McGaw, R., Heywood, S. and Clark, R. A. (2015) 'Gait assessment using the Microsoft Xbox One Kinect: Concurrent validity and inter-day reliability of spatiotemporal and kinematic variables.' *J Biomech*, 48(10), Jul 16, pp. 2166-2170.

Michaelis, I., Kwiet, A., Gast, U., Boshof, A., Antvorskov, T., Jung, T., Rittweger, J. and Felsenberg, D. (2008) 'Decline of specific peak jumping power with age in master runners.' *J Musculoskelet Neuronal Interact*, 8(1), Jan-Mar, pp. 64-70.

Millet, G. P., Vleck, V. E. and Bentley, D. J. (2009) 'Physiological differences between cycling and running: lessons from triathletes.' *Sports Med*, 39(3) pp. 179-206.

Orr, R., de Vos, N. J., Singh, N. A., Ross, D. A., Stavrinos, T. M. and Fiatarone-Singh, M. A. (2006) 'Power training improves balance in healthy older adults.' *The journals of gerontology. Series A, Biological sciences and medical sciences*, 61(1), Jan, pp. 78-85.

Perrin, P. P., Gauchard, G. C., Perrot, C. and Jeandel, C. (1999) 'Effects of physical and sporting activities on balance control in elderly people.' *Br J Sports Med*, 33(2), Apr, pp. 121-126.

Piasecki, M., Ireland, A., Stashuk, D., Hamilton-Wright, A., Jones, D. A. and McPhee, J. S. (2016) 'Age-related neuromuscular changes affecting human vastus lateralis.' *J Physiol*, 594(16), Aug 15, pp. 4525-4536.

Pollock, R. D., Carter, S., Velloso, C. P., Duggal, N. A., Lord, J. M., Lazarus, N. R. and Harridge, S. D. (2015) 'An investigation into the relationship between age and physiological function in highly active older adults.' *J Physiol*, 593(3), Feb 1, pp. 657-680; discussion 680.

Rittweger, J., di Prampero, P. E., Maffulli, N. and Narici, M. V. (2009) 'Sprint and endurance power and ageing: an analysis of master athletic world records.' *Proceedings. Biological sciences / The Royal Society*, 276(1657), Feb 22, pp. 683-689.

Rubenstein, L. Z. (2006) 'Falls in older people: epidemiology, risk factors and strategies for prevention.' *Age Ageing*, 35 Suppl 2, Sep, pp. ii37-ii41.

Runge, M., Rittweger, J., Russo, C. R., Schiessl, H. and Felsenberg, D. (2004) 'Is muscle power output a key factor in the age-related decline in physical performance? A comparison of muscle cross section, chair-rising test and jumping power.' *Clinical physiology and functional imaging*, 24(6), Nov, pp. 335-340.

Sherrington, C., Tiedemann, A., Fairhall, N., Close, J. C. and Lord, S. R. (2011) 'Exercise to prevent falls in older adults: an updated meta-analysis and best practice recommendations.' *New South Wales public health bulletin*, 22(3-4), Jun, pp. 78-83.

Shotton, J., Girshick, R., Fitzgibbon, A., Sharp, T., Cook, M., Finocchio, M., Moore, R., Kohli, P., Criminisi, A., Kipman, A. and Blake, A. (2012) 'Efficient Human Pose

Estimation from Single Depth Images.' *IEEE Trans Pattern Anal Mach Intell*, Oct 26,

Vernadakis, N., Derri, V., Tsitskari, E. and Antoniou, P. (2014) 'The effect of Xbox Kinect intervention on balance ability for previously injured young competitive male athletes: a preliminary study.' *Phys Ther Sport*, 15(3), Aug, pp. 148-155.

Wiesmeier, I. K., Dalin, D. and Maurer, C. (2015) 'Elderly Use Proprioception Rather than Visual and Vestibular Cues for Postural Motor Control.' *Front Aging Neurosci*, 7 p. 97.

Tables

Measurement	Young	Healthy Old	Masters runners	p-value
Participant Characteristics				
N (% male)	15 (68)	13 (65)	15 (47)	
Age (years)	25.5 (6.4) [b,c]	67.6 (3.9)	67.2 (5.2)	0.000
Height	173.2 (8.5)	170.9 (6.1)	165.7 (10.1)	0.058
Body mass	77.1 (16.3)	77.5 (17.0)	61.0 (9.5) [a,b]	0.005
BMI	25.0 (5.2)	26.4 (5.8)	22.1 (2.2)	0.051
Two-leg (Open Eyes)				
ML-CoM Sway (cm)	0.27 (0.11)	0.44 (0.15)[a,c]	0.22 (0.09)	0.001
AP-CoM Sway (cm)	0.32 (0.2)	0.36 (0.21)	0.38 (0.17)	0.667
Semi Tandem (Open Eyes)				
ML-CoM Sway (cm)	0.29 (0.08)	0.49 (0.16) [a,c]	0.29 (0.11)	0.001
AP-CoM Sway (cm)	0.21 (0.07)	0.36 (0.14) [a,c]	0.28 (0.14)	0.009
Tandem (Open Eyes)				
ML-CoM Sway (cm)	0.41 (0.2)	1.87 (3.86) [a,c]	0.30 (0.12)	0.117
AP-CoM Sway (cm)	0.27 (0.11)	1.33 (1.86) [a,c]	0.30 (0.16)	0.016
One Leg (Open Eyes)				
Total Time (s)	9.74 (0.72)	8.47 (2.42)	10.00 (0.00)	0.165
ML-CoM Sway (cm)	0.28 (0.09)	3.85 (4.62) [a]	0.32 (0.12)	0.001
AP-CoM Sway (cm)	0.41 (0.21)	1.78 (2.13) [a]	0.68 (0.46)	0.012
One Leg (Closed Eyes)				
Total Time (s)	9.47 (1.24)	5.09 (1.70) [a,c]	8.12 (2.96) [a,b]	0.001
ML-CoM Sway (cm)	1.5 (1.78)	12.66 (9.1) [a]	11.93 (14.86) [a]	0.010
AP-CoM Sway (cm)	1.47 (1.16)	7.07 (5.57) [a]	5.48 (7.68) [a]	0.036
Chair Stand				
Total Time (s)	9.42 (1.94)	10.09 (1.64)	9.38 (1.75)	0.597
ML CoM Sway (cm)	1.35 (0.58)	1.67 (0.90)	1.15 (0.3)	0.102
AP CoM Sway (cm)	17.07 (4.6)	10.83 (3.57) [a]	8.97 (3.08) [a]	0.001
Time Rise (s)	1.43 (0.27)	1.55 (0.27)	1.54 (0.23)	0.361
Time Rise SD (s)	0.53 (0.11)	0.79 (0.16) [a,c]	0.58 (0.42)	0.002

Table 1. Comparison between young, master athletes and old for balance and chair rise performance. ML: Medial Lateral; AP: Anterior-Posterior; CoM: Centre-of-Mass. Data shown as mean (SD). The p-value represents the main effect of group from the ANOVA. Results from the post-hoc between-groups comparisons are indicated as [a]: significantly different from Young; [b]: significantly different from healthy old; [c]: significantly different from masters runners (actual p-values are reported in the main text).