Effects of sport participation on gait coordination, symmetry and variability in older adults

SHAFIZADEH, Mohsen <http://orcid.org/0000-0002-7524-1058>, BONNER, Stuart, FRASER, Jonathan, PARVINPOUR, Shahab, SHABANI, Mohsen and BARNES, Andrew <http://orcid.org/0000-0001-8262-5132>

Effects of sport participation on gait coordination, symmetry and variability in older adults

Mohsen Shafizadeh[a]*, Stuart Bonner[a], Jonathan Fraser[a], Shahab Parvinpour[b], Mohsen Shabani[c], and Andrew Barnes[a]

[a] *Sheffield Hallam University, Sheffield, UK;* [b] *Kharazmi University, Tehran, Iran and* [c] *Islamic Azad University, Tehran, Iran*

***corresponding author:**

Dr Mohsen Shafizadeh, Academy of Sport and Physical Activity, College of Health, Wellbeing and Life Sciences, Sheffield Hallam University, Sheffield, S10 2BP, United Kingdom.

Email: m.shafizadeh@shu.ac.uk

Running head: *sport participation in older adults*

Abstract

The aim of this study was to compare the interlimb coordination, asymmetry, and variability between older adult who participated in sports (n=25; age=72.6±6.46 years) and sedentary older adults (n=20; age=70.85±3.82 years). The sport participants were selected from tennis and badminton clubs, whereas the sedentary participants were recruited from local community centres. The participants walked at their preferred speed in a 10-meter walkway for 2 minutes. The interlimb coordination was measured by the phase coordination index. Other walking metrics were speed, cadence, swing time, stance time, double-support time, stride time, and swing time asymmetry. The results showed that the sport participants relative to the sedentary group had better interlimb coordination, higher walking speed and cadence, and less swing time variability. Young older adults also had a better interlimb coordination. In conclusion, the findings of this study showed that long-term participation in sports has some anti-ageing benefits on gait coordination and symmetry in older adults.

Keywords: activity, gait declines, ageing, gait metrics, walking.

Introduction

The ageing process is accompanied by changes in the locomotor system. Studying mobility generally and walking gait specifically in older adults is important for two main reasons. First, walking is one of the interesting motor behaviours that is affected by ageing due to its relationship with the cognitive function and executive systems (Tian et al., 2017) and understanding its quality in older adults can provide useful information about ageing biomarkers. For example, age-related changes in gait such as decreased walking speed, cadence, stride length and stride time and increased step width (JudgeRoy, Davis III, & Õunpuu, 1996; Schrager, Kelly, Price, Ferrucci, & Shumway-Cook, 2008) can adversely affect the quality of activities of daily living (ADLs) and increase the risk of chronic disease (Guralnik, Ferrucci, Simonsick, Salive, & Wallace, 1995; Young, 1997) and falls (Maki, 1997; Wang, Patriquin, Vaziri, & Najafi, 2021). Second, walking is a common form of physical activity used by middle-aged and older adults for maintaining physical fitness (Besser & Dannenberg, 2005).

Participation of older adults in moderate to vigorous physical activity such as walking is associated with reduced risk of functional limitations, increased independence (Paterson & Warburton, 2010) and sustained physical function (Edholm, Nilsson, & Kadi, 2019). Some older adults also participate in organised sports to maintain their health and wellbeing (Jenkin, Eime, Westerbeek, O’Sullivan, & van Uffelen, 2017; Stenner, Buckley, & Mosewich, 2020). Sport participation has been reported to offer numerous health benefits including a reduced risk of cardiovascular disease, diabetes and osteoporosis (L. B. Andersen, Schnohr, Schroll, & Hein, 2000; Randers et al., 2010; Sabia et al., 2012). In addition, several sport-specific situations in individual or team sports require quick changes in body direction and postural adjustment (Gréhainge, Richard, & Griffin, 2005) that could improve dynamic balance and walking performance in older adults.

The benefits of physical activity and sports on gait are mainly studied in spatiotemporal parameters. For example, previous studies showed the positive effects of judo (Ciaccioni, Capranica, Forte, Pesce, & Condello, 2020), golf (Kanwar, Moore, Hawkes, & Salem, 2021) and karate (Pliske, Emmermacher, Weinbeer, & Witte, 2016) on walking performance such as step length, speed and cadence in older adults. The spatiotemporal parameters are indicators of overall gait performance, but they do not explain the causes of declines/ improvements in gait (Jordan, Challis, & Newell, 2007). Gait is a complex movement pattern that is formed through dynamic coordination among the limbs and is controlled by the central nervous system (CNS) in the brain and spinal cord (Jahn & Zwergal, 2010; Winter, 1995). Inter-limb coordination, variability and bilateral symmetry are advanced gait parameters that indicate the underlying control mechanisms that are deteriorated by ageing (Gimmon et al., 2018) and also they are unique and are not strongly associated with spatiotemporal gait parameters (Plotnik, Giladi, & Hausdorff, 2007). The flexibility and adaptation in walking for body stability and to meet the requirements of changing environments can be assessed better by advanced gait metrics than overall gait parameters (Reisman, Block, & Bastian, 2005; Woollacott & Tang, 1997), especially in older adults who needs more adaptations in gait to avoid trips and falls (Courtine & Schieppati, 2003). In addition, the importance of advanced gait metrics can be understood from their association with cognitive functions that are responsible for planning, attention and motor control (Bonelli & Cummings, 2022). For example, impaired interlimb coordination was associated with changes in the brain regions such as the supplementary motor area and basal ganglia (Obhi, Haggard, Taylor, & Pascual-Leone, 2002; Plotnik et al., 2007) and a higher temporal and spatial variability in gait was associated with the active cortical involvement and diminished sensorimotor integration in older adults (Tian et al., 2017).

There is not any study on the effectiveness of sport participation on advanced gait parameters such as interlimb coordination, asymmetry and variability. Previous studies only examined the effects of general physical activity on gait symmetry and variability (Ciprandi et al., 2017; Egerton, Paterson, & Helbostad, 2017). For example, Egerton et al. (2017) did not find any association between gait asymmetry and level of physical activity in older adults. Ciprandi et al. (2017) showed that older women with higher physical activity levels had less step width variability. Thus, the first aim of this study was to compare interlimb coordination, asymmetry, temporal variability, and temporal gait parameters between sedentary older adults and older adults who participated in sports.

Deterioration of coordination, symmetry and variability has been shown in independent older adults (Plotnik et al., 2007; Zadik et al., 2022) and following some chronic diseases (Meijer et al., 2011; Richmond, Swanson, Peterson, & Fling, 2020) regardless of physical activity level. Unlike Plotnik et al. and Zadic, et al. studies that reported coordination deterioration in under 70 years older adults, Gimmon et al. (2018) showed that in healthy older adults it was only evident in very old adults (>85 years) and gait asymmetry also was not related to the ageing. This study examined the mediating role of sport participation on the adverse effects of ageing on coordination, symmetry and variability. The second aim of this study was to examine the interaction of age and group on interlimb coordination, asymmetry, temporal variability, and temporal gait parameters.

Methods

Research design

The type of study was a cross-sectional study that includes 2 variables in terms of sport participation (active/ sedentary) and age groups (young older adults/ old older adults).

Participants

The active group was male (n=12) and female (n=13) older adults who played tennis or badminton at least 3 times per week for more than 20 years. The male (n=15) and female (n=5) sedentary participants were inactive in the last 3 years and were recruited from local community centres. In addition, the participants were classified into 2 age groups: young older adults (65-74 years) and old older adults (75-85 years) for testing the quality of walking metrics between age groups (Ouchi, et al., 2017). The demographic measures of participants are presented in Table 1. Participants received information about the aims of the study and the procedures before taking part and signed the consent form. The ethics committee of college at xxxxxxx University approved the study. The inclusion criteria were injury-free during the testing sessions, no surgery on hip or knee and lack of musculoskeletal, neurological (Parkinson's disease, Multiple Sclerosis, etc.) or any health condition (cardiac problem or heart surgery) that affects their independence. They were informed of their right to withdraw at any stage of the study.

Procedure

The data collection was completed between March and July 2022. Before walking tests, the participants read the information sheet and completed the medical health questionnaire and Trail Making test A. The health questionnaire had information about the participants level of physical activity, musculoskeletal injury and history of diseases. The Trail Making Test-A (TMT-A) is a pen and paper cognitive test (decision-making speed) in which the participant joins 25 circles in ascending order as fast as possible (Corrigan & Hinkeldey, 1987). The TMT-A is a valid and reliable test that assesses executive functions and visual and decision-making skills (Sánchez-Cubillo, et al., 2009). Following this, the participants walked for 3 minutes at their preferred speed to warm up and determine the preferred speed for the actual walking test.

Participants also completed one attempt of the Timed Up and Go test (TUG) to assess their physical condition. They sat on a chair, stood up and walked 3 meters and turned around a cone at their preferred speed, then returned to the same chair. The time to complete the test was measured in seconds and milliseconds (Ng & Hui-Chan, 2005).

In the walking test, the participants walked back and forth along a 10m straight and flat walkway for 2 minutes at their preferred speed. The walkway was marked by 2 cones at the start and end lines. A video analysis system was used to measure the walking performance. A GoPro Hero10 high-speed camera was used to record the walking temporal events. The video recording speed was 120fps, and the resolution was 1080p. One investigator carry the camera that was attached to a handle grip to facilitate the recording. The portable camera was zoomed in within 2-3 meters distance from the legs throughout the walking trial to capture the gait events of each leg including initial contact (the first moment of foot-ground contact) and toe-off (the last moment of foot-ground contact). All tests were carried out by the same investigator. To exclude the effect of environment on walking pace, only the straight-line walking phase was used for analysis and the turning phase was excluded (Plotnik et al., 2007). The strides at beginning of the test were excluded and 50 strides were selected for analysis from each participant.

Data analysis

The gait parameters of this study were walking temporal parameters, temporal variability, phase coordination index (PCI), and gait asymmetry. Three phases of a gait cycle such as stance, swing and double support were determined through video analysis in a special software (Simi motion, German).

Temporal walking parameters

The swing time and stance time of each leg as well as double-support time was calculated and reported as average and coefficient of variation (CV) from successive stride for each participant. The CV values were used as temporal variability metrics in this study. Average walking speed was calculated as the time to complete one 10m distance and the cadence was the number of steps per minute.

Walking asymmetry

Walking asymmetry was measured by comparing the swing time of right and left legs in every gait cycle. This formula was used to quantify the asymmetry (Plotnik et al., 2007):

Walking asymmetry= 100 × |ln (SSwing time / LSwing time)|

SSwing and LSwing time refer to the mean value of swing time for the leg with the short and long mean swing time, respectively. A higher score represents a higher temporal asymmetry between right and left swing.

Interlimb coordination (PCI)

The PCI is an index of the relationship between the right and left legs. The procedure to calculate the PCI can be found in more detail elsewhere (see Plotnik et al. (2007)). Simply, the PCI is a phase difference between the right and left legs at every initial contact. Ideally, this phase difference should be anti-phase and equal to 180˚ (one leg at initial contact and the opposite leg at toe-off). The level of accuracy is the amount of phase difference from 180˚ (ϕ_abs). The level of consistency (ϕ_cv) is calculated by a difference of each phase value from the mean value.

The PCI is the sum of the phase accuracy and phase consistency as below:

PCI= ϕ_cv + PCI_abs

where

PCI_abs= 100 × (ϕ_abs/180)

A higher PCI score represents a higher phase difference between the right and left swing legs, thus poor interlimb coordination.

A 2-way between-subject analysis of variance (group × age) was used to compare the variables between the active and sedentary groups and between young and old older adults. Omega effect size (Cohen, 1988) was used to assess the impact (significance) of independent variables on the walking metrics (small=0.01; medium=0.06; large=0.14). The confidence interval was set at 95%, two-tailed.

Results

Temporal parameters

The main effect of the group on walking speed, cadence, swing times, stance times and double-support time was significant ($p<0.05$). The active group had a faster walking speed and higher cadence than the sedentary group. The active group had a shorter time on all walking phases than the sedentary group (see Table 2).

The old older adults had significantly higher cadence than the young older adults (see Table 2).

The interaction of group and age was not significant ($p>0.05$).

Walking asymmetry

There was not any difference between activity groups, age groups or their interaction on the walking asymmetry index (see Figure 1).

Temporal variability

Only the effect of group on swing time variability was significant. The sedentary group had higher swing time variability than the active group. The old older adults had significantly greater right swing and stride times variability, but less double-support time variability

($p<0.05$) than the young older adults (see Table 2). The interaction of group and age was not significant ($p>0.05$).

Interlimb coordination (PCI)

The interlimb coordination was significantly better ($F_{1,41}=7.65$, $p<0.01$, $\omega^2=0.21$) in the active group (4.07±0.82) than in the sedentary group (4.5±0.71) and in the young older adults (4.19±0.58) than the old older adults (4.47±1.22) groups ($F_{1,41}=2.11$, $p<0.05$, $\omega^2=0.11$). The interaction of group and age was not significant ($p>0.05$).

Discussion

This study aimed to compare interlimb coordination, asymmetry, temporal variability, and temporal walking parameters between sedentary and active older adults and to examine the mediating role of sport participation on ageing. The findings of this study showed that older adults who were active and also participated in sports relative to their sedentary counterparts had a greater walking speed which was mainly due to higher cadence and shorter time on stance, swing and double-support phases. The temporal walking advantages in the active group led to less swing time variability and better interlimb coordination. The mediating role of sport participation was not significant, however, the young older adults group showed better interlimb coordination and less variability and cadence than the old older adults group. The asymmetry was not different among the groups. The temporal walking parameters that were different between active and sedentary groups also had large effect sizes (0.15-0.51) that indicate their high sensitivity to the level of physical activity. Alternatively, the left and right swing time and right swing time variability had the largest effect sizes and sensitivity to ageing.

Interlimb coordination was one of the sensitive advanced gait parameters in this study that was affected by the level of physical activity and ageing. In this study, we showed average PCI values between 4.07 and 4.50 for overground walking at a preferred speed in different groups. Plotnik et al. (2007) in a similar walking protocol (overground, flat walking for 2min) reported an average PCI value of 3.30 in older adults, whereas Gimmon et al. (2018) in a treadmill walking protocol with different speeds reported a PCI value above 7. This difference between 2 walking conditions (overground versus treadmill) on the PCI might be related to the increased adaptations in limb coordination during treadmill walking that is different from everyday walking conditions.

This is the first study that examined the association between physical activity and interlimb coordination in older adults. The positive association between physical activity and specifically sport participation and interlimb coordination can be explained in terms of physical fitness, adaptability and underlying neurophysiological mechanisms. First, because of similarities in motor skills and movements, the transfer of physical activities from organised/ recreational sports to the ADLs is high. The movements in racket sports significantly depend on the physical fitness of lower extremities in terms of leg strength, agility, balance and reactions that are extensively used in daily life situations. The results of participation in other sports also showed improvement in functional mobility skills. For example, previous studies on older sport participants have shown that the stepping skills and agility in boxing and martial arts (Areeudomwong et al., 2019; Lip, Fong, Ng, Liu, & Guo, 2015), foot works in judo (Ciaccioni et al., 2020), using upper-body parts and walking a long distance in golf (Kanwar et al., 2021), using lower and upper-body parts for offensive and defensive performances in volleyball (Allen Hedrick, 2007; Leung, Chung, & Hagger, 2020) and walking football (T. R. Andersen et al., 2014) were related to the improvements in functional tests such as TUG and walking performance. Second, the PCI magnitude requires accuracy and consistency of a coordination pattern between the right and the left legs relative to a target coordination pattern (180˚) in every gait cycle. The ability to keep the anti-phase coordination pattern is an adaptation that can be mediated by practice. For example, Reisman et al. (2005) showed that adults can adapt and store new interlimb coordination patterns after a short bout of training on a split-belt treadmill. This can explain why active older people who practised a variety of locomotor skills for a long period as usual walking or a combination of sport skills can preserve some adaptive qualities to maintain an optimal interlimb coordination pattern despite the adverse effects of ageing on the neuromotor system. Third, the reductions in cognitive and motor plasticity are possible causes of diminished motor skill and performance loss in older adults (Cabeza, 2002; Voelcker-Rehage, 2008) that could be mitigated by some neurophysiological compensations due to practice such as changes in activation pattern, de-differentiation, de-lateralisation (Cabeza, 2002) and less high white matter hypersensitivity burden (Fleischman et al., 2015). The interlimb coordination is associated with structure and activity in the supplementary motor area and basal ganglia (Obhi et al., 2002; Plotnik et al., 2007). Thus, one potential benefit of participating in sports is the ability to maintain the optimal interlimb coordination patterns through preserving/activating perceptual and cognitive skills. Previous studies showed that participation in sports such as karate (Lopes, Oliveira, & Gottlieb, 2019; Witte, Kropf, Darius, Emmermacher, & Böckelmann, 2016), football (Reddy et al., 2017) and golf (Kanwar et al., 2021; Shimada et al., 2018) improved cognitive function, memory and attention in older adults. Because the cognitive and decision-making elements are embedded in the motor skills in sport contexts such as dyads and interpersonal interactions in racket sports (Williams, et al., 2011), it is plausible to expect cognitive-motor improvements following participating in sports in open and dynamic environments. However, these results should be interpreted cautiously because the design of the study was cross-sectional and the main limitation was a lack of any information on the genetic predisposition of the active participants to explain the group differences in terms of genetic, environmental or both.

Unlike a previous study that showed deteriorations in interlimb coordination only in the older adults above 85 years (Gimmon et al., 2018), our study showed that people above 75 years old experience such changes and the PCI is a sensitive order parameter that is affected by organismic constraints such as ageing but not mediated by physical activity and sport participation. Maybe one reason is the decline in the speed of decision-making in old older adults in this study as is evident from the Trail Making Test (see Table 1). To understand the effect of ageing on interlimb coordination during walking, more longitudinal studies with larger sample sizes are required in future.

A lack of group differences in the gait asymmetry can indicate a distinct feature of interlimb coordination and swing time asymmetry; the symmetry reflects the similarity in the motor function and activation regarding the leg propulsion, whereas the interlimb coordination is the degrees of association in the rhythmic process of one leg relative to the rhythmic process of another leg in stepping (Plotnik et al., 2007). Only the PCI and gait asymmetry were impaired in stroke hemiplegic patients (Meijer et al., 2011) and in the healthy, independent older adults, gait asymmetry was not strongly correlated with the PCI (Plotnik et al., 2007) or different between young adults, young and old older adults (Gimmon et al., 2018). Altogether, this finding suggests the low sensitivity of the gait asymmetry to functional changes due to ageing or sport participation.

The swing time variability was the only discriminator of active and sedentary groups, and the active group had less variability. Ciprandi et al. (2017) also showed that the very active older adults had less step width variability. Spatiotemporal variability in walking that is measured by linear methods such as standard deviation or the coefficient of variation reflects the magnitude of the variations in a gait measure and naturally, a healthy system requires an optimal variability (not low or high) to give the motor system an acceptable level of adaptability and flexibility to meet the requirements of the tasks and environments

(Stergiou & Decker, 2011). It seems that the benefits of physical activity and sport participation on gait variability can be explained through improvement in the adaptability of the neuromotor system due to practice and perceptual-motor experience to mitigate the active cortical involvement and diminished sensorimotor integration (Tian et al., 2017). The right swing time variability was higher in the old older adults.

The clinical significance of variability (bad or optimal) should be interpreted by its association with risk factors such as frailty, risk of falling and diseases. In previous studies, high variability in stance, swing and stride time (Hausdorff, Edelberg, Mitchell, Goldberger, & Wei, 1997) and step time (Callisaya et al., 2011) were associated with the risks of falls. Because the participants of this study were independent and without any frailty, this amount of temporal variability, despite the group differences, can be classified as optimal.

The fast walking in active older adults resulted in a higher cadence and shorter time on each gait phase. The younger older adults also had faster-walking speed. The fast walking and increased cadence (as an indicator of walking intensity) in active older adults were consequences of good physical fitness and healthy cognitive function that were achieved by long-term participation in sport and physical activities. Walking speed and cadence are important health and ageing biomarkers that should be used as a standard clinical assessment in community-dwelling older adults (Cummings, Studenski, & Ferrucci, 2014) because of their associations with the risk of falls, hospitalisation and subsequent physical and cognitive decline (Peel, Kuys, & Klein, 2013). A recent longitudinal study in older adults showed that low function in walking including walking speed (hazard ratio=1.83) and cadence (hazard ratio=1.60) increased the risk of mortality (Doi, et al., 2021). These findings further support the clinical significance of walking speed (ω^2=0.51) and cadence (ω^2=0.25) as discriminators of active and sedentary groups in this study and advocate the anti-ageing benefits of sport participation and active lifestyle in community-dwelling older adults.

This is one of the few studies that examined the effects of sport participation on advanced walking parameters such as interlimb coordination, asymmetry and variability in community-dwelling older adults. The findings have some implications for national and local governments and policymakers to promote the benefits of sport participation on the preservation of walking performance which is known as a clinical ageing biometric. Establishing gait assessment centres in the sport clubs and community centres for older adults and continuous monitoring of the clinical gait metrics related to frailty, risks of falls and cognitive impairment could help to monitor or prevent some health conditions through proper and timely interventions in modifiable risk factors and reduce the burdens and costs of health systems.

This study had some limitations. We only recruited the participants from racket sports and only through cross-sectional design. Future studies could use other sports and long-term prospective studies on the effects of sport participation on walking performance.

In conclusion, the findings of this study showed that long-term participation in sports has some anti-ageing benefits on advanced walking parameters, coordination and variability, and health-related walking parameters, speed and cadence, in older adults. The old older adults also had poor coordination and a higher swing time variability.

Declaration of interest

No conflict of interest to report.

References

Allen Hedrick, M. (2007). Training for high level performance in women's collegiate volleyball: Part I training requirements. *Strength and Conditioning Journal, 29*(6), 50.

Andersen, L. B., Schnohr, P., Schroll, M., & Hein, H. O. (2000). All-cause mortality associated with physical activity during leisure time, work, sports, and cycling to work. *Archives of internal medicine, 160*(11), 1621-1628.

Andersen, T. R., Schmidt, J., Nielsen, J., Randers, M., Sundstrup, E., Jakobsen, M., . . .

Bangsbo, J. (2014). Effect of football or strength training on functional ability and physical performance in untrained old men. *Scandinavian journal of medicine & science in sports, 24*, 76-85.

Areeudomwong, P., Saysalum, S., Phuttanurattana, N., Sripoom, P., Buttagat, V., & Keawduangdee, P. (2019). Balance and functional fitness benefits of a Thai boxing dance program among community-dwelling older adults at risk of falling: A randomized controlled study. *Archives of gerontology and geriatrics, 83*, 231-238.

Besser, L. M., & Dannenberg, A. L. (2005). Walking to public transit: steps to help meet physical activity recommendations. *American journal of preventive medicine, 29*(4), 273-280.

Bonelli, R. M., & Cummings, J. L. (2022). Frontal-subcortical circuitry and behavior. *Dialogues in clinical neuroscience*.

Cabeza, R. (2002). Hemispheric asymmetry reduction in older adults: the HAROLD model. *Psychology and aging, 17*(1), 85.

Callisaya, M. L., Blizzard, L., Schmidt, M. D., Martin, K. L., McGinley, J. L., Sanders, L. M., & Srikanth, V. K. (2011). Gait, gait variability and the risk of multiple incident falls in older people: a population-based study. *Age and ageing, 40*(4), 481-487.

Ciaccioni, S., Capranica, L., Forte, R., Pesce, C., & Condello, G. (2020). Effects of a 4-month judo program on gait performance in older adults. *The Journal of Sports Medicine and Physical Fitness, 60*(5), 685-692.

Ciprandi, D., Bertozzi, F., Zago, M., Ferreira, C. L. P., Boari, G., Sforza, C., & Galvani, C. (2017). Study of the association between gait variability and physical activity. *European review of aging and physical activity, 14*(1), 1-10.

Corrigan, J. D., & Hinkeldey, N. S. (1987). Relationships between parts A and B of the Trail Making Test. *Journal of clinical psychology, 43*(4), 402-409.

Courtine, G., & Schieppati, M. (2003). Human walking along a curved path. I. Body trajectory, segment orientation and the effect of vision. *European Journal of Neuroscience, 18*(1), 177-190.

Cummings, S. R., Studenski, S., & Ferrucci, L. (2014). A diagnosis of dismobility—giving mobility clinical visibility: a Mobility Working Group recommendation. *Jama, 311*(20), 2061-2062.

Edholm, P., Nilsson, A., & Kadi, F. (2019). Physical function in older adults: impacts of past and present physical activity behaviors. *Scandinavian journal of medicine & science in sports, 29*(3), 415-421.

Egerton, T., Paterson, K., & Helbostad, J. L. (2017). The association between gait characteristics and ambulatory physical activity in older people: a cross-sectional and longitudinal observational study using generation 100 data. *Journal of Aging and Physical Activity, 25*(1), 10-19.

Fleischman, D. A., Yang, J., Arfanakis, K., Arvanitakis, Z., Leurgans, S. E., Turner, A. D., . . . Buchman, A. S. (2015). Physical activity, motor function, and white matter hyperintensity burden in healthy older adults. *Neurology, 84*(13), 1294-1300.

Gimmon, Y., Rashad, H., Kurz, I., Plotnik, M., Riemer, R., Debi, R., . . . Melzer, I. (2018). Gait coordination deteriorates in independent old-old adults. *Journal of Aging and Physical Activity, 26*(3), 382-389.

Gréhainge, J., Richard, J., & Griffin, L. (2005). Teaching and learning team sports and games. Abingdon: Routledge Falmer: Taylor & Francis Group.

Guralnik, J. M., Ferrucci, L., Simonsick, E. M., Salive, M. E., & Wallace, R. B. (1995). Lower-extremity function in persons over the age of 70 years as a predictor of subsequent disability. *New England Journal of Medicine, 332*(9), 556-562.

Hausdorff, J. M., Edelberg, H. K., Mitchell, S. L., Goldberger, A. L., & Wei, J. Y. (1997).

Increased gait unsteadiness in community-dwelling elderly fallers. *Archives of physical medicine and rehabilitation, 78*(3), 278-283.

Jahn, K., & Zwergal, A. (2010). Imaging supraspinal locomotor control in balance disorders. *Restorative neurology and neuroscience, 28*(1), 105-114.

Jenkin, C. R., Eime, R. M., Westerbeek, H., O'Sullivan, G., & van Uffelen, J. G. (2017). Are they 'worth their weight in gold'? Sport for older adults: benefits and barriers of their participation for sporting organisations *Sport, Physical Activity and Public Health* (pp. 131-148): Routledge.

Jordan, K., Challis, J. H., & Newell, K. M. (2007). Walking speed influences on gait cycle variability. *Gait & posture, 26*(1), 128-134.

JudgeRoy, J. O., Davis III, B., & Õunpuu, S. (1996). Step length reductions in advanced age: the role of ankle and hip kinetics. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 51*(6), M303-M312.

Kanwar, K. D., Moore, J. L., Hawkes, R., & Salem, G. J. (2021). Golf as a physical activity to improve walking speed and cognition in older adults: A non-randomized, pre-post, pilot study. *Mental Health and Physical Activity, 21*, 100410.

Leung, K.-M., Chung, P.-K., & Hagger, M. S. (2020). The effects of light volleyball intervention programme in improving selected physical and psychological attributes of older adults in Hong Kong. *International Journal of Sport and Exercise Psychology, 18*(1), 1-12.

Lip, R. W., Fong, S. S., Ng, S. S., Liu, K. P., & Guo, X. (2015). Effects of Ving Tsun Chinese martial art training on musculoskeletal health, balance performance, and self-efficacy in community-dwelling older adults. *Journal of Physical Therapy Science, 27*(3), 667-672.

Lopes, B. J. P., Oliveira, C. R. d., & Gottlieb, M. G. V. (2019). Effects of karate-dŌ training in older adults cognition: Randomized controlled trial. *Journal of Physical Education, 30*.

Maki, B. E. (1997). Gait changes in older adults: predictors of falls or indicators of fear? *Journal of the American geriatrics society, 45*(3), 313-320.

Meijer, R., Plotnik, M., Zwaaftink, E. G., van Lummel, R. C., Ainsworth, E., Martina, J. D., & Hausdorff, J. M. (2011). Markedly impaired bilateral coordination of gait in post-stroke patients: Is this deficit distinct from asymmetry? A cohort study. *Journal of neuroengineering and rehabilitation, 8*(1), 1-8.

Ng, S. S., & Hui-Chan, C. W. (2005). The timed up & go test: its reliability and association with lower-limb impairments and locomotor capacities in people with chronic stroke. *Archives of physical medicine and rehabilitation, 86*(8), 1641-1647.

Obhi, S. S., Haggard, P., Taylor, J., & Pascual-Leone, A. (2002). rTMS to the supplementary motor area disrupts bimanual coordination. *Motor control, 6*(4), 319-332.

Ouchi, Y., Rakugi, H., Arai, H., Akishita, M., Ito, H., Toba, K., Kai, I., & Joint Committee of Japan Gerontological Society (JGLS) and Japan Geriatrics Society (JGS) on the definition and classification of the elderly (2017). Redefining the elderly as aged 75 years and older: Proposal from the Joint Committee of Japan Gerontological Society and the Japan Geriatrics Society. *Geriatrics & gerontology international, 17(7)*, 1045–1047.

Paterson, D. H., & Warburton, D. E. (2010). Physical activity and functional limitations in older adults: a systematic review related to Canada's Physical Activity Guidelines. *International Journal of Behavioral Nutrition and Physical Activity, 7*(1), 1-22.

Peel, N. M., Kuys, S. S., & Klein, K. (2013). Gait speed as a measure in geriatric assessment in clinical settings: a systematic review. *The Journals of Gerontology: Series A, 68*(1), 39-46.

Pliske, G., Emmermacher, P., Weinbeer, V., & Witte, K. (2016). Changes in dual-task performance after 5 months of karate and fitness training for older adults to enhance fall prevention. *Aging clinical and experimental research, 28*(6), 1179-1186.

Plotnik, M., Giladi, N., & Hausdorff, J. M. (2007). A new measure for quantifying the bilateral coordination of human gait: effects of aging and Parkinson's disease. *Experimental brain research, 181*(4), 561-570.

Randers, M., Nybo, L., Petersen, J., Nielsen, J. J., Christiansen, L., Bendiksen, M., . . . Krustrup, P. (2010). Activity profile and physiological response to football training for untrained males and females, elderly and youngsters: influence of the number of players. *Scandinavian journal of medicine & science in sports, 20*, 14-23.

Reddy, P., Dias, I., Holland, C., Campbell, N., Nagar, I., Connolly, L., . . . Hubball, H. (2017). Walking football as sustainable exercise for older adults–A pilot investigation. *European journal of sport science, 17*(5), 638-645.

Reisman, D. S., Block, H. J., & Bastian, A. J. (2005). Interlimb coordination during locomotion: what can be adapted and stored? *Journal of neurophysiology, 94*(4), 2403-2415.

Richmond, S. B., Swanson, C. W., Peterson, D. S., & Fling, B. W. (2020). A temporal analysis of bilateral gait coordination in people with multiple sclerosis. *Multiple sclerosis and related disorders, 45*, 102445.

Sabia, S., Dugravot, A., Kivimaki, M., Brunner, E., Shipley, M. J., & Singh-Manoux, A. (2012). Effect of intensity and type of physical activity on mortality: results from the Whitehall II cohort study. *American journal of public health, 102*(4), 698-704.

Sánchez-Cubillo, I., Periáñez, J. A., Adrover-Roig, D., Rodríguez-Sánchez, J. M., Ríos-Lago, M., Tirapu, J., & Barceló, F. (2009). Construct validity of the Trail Making Test: role of task-switching, working memory, inhibition/interference control, and visuomotor abilities. *Journal of the International Neuropsychological Society*, *15(3)*, 438–450.

Schrager, M. A., Kelly, V. E., Price, R., Ferrucci, L., & Shumway-Cook, A. (2008). The effects of age on medio-lateral stability during normal and narrow base walking. *Gait & posture, 28*(3), 466-471.

Shimada, H., Lee, S., Akishita, M., Kozaki, K., Iijima, K., Nagai, K., . . . Tanaka, T. (2018). Effects of golf training on cognition in older adults: a randomised controlled trial. *J Epidemiol Community Health, 72*(10), 944-950.

Stenner, B. J., Buckley, J. D., & Mosewich, A. D. (2020). Reasons why older adults play sport: A systematic review. *Journal of sport and health science, 9*(6), 530-541.

Stergiou, N., & Decker, L. M. (2011). Human movement variability, nonlinear dynamics, and pathology: is there a connection? *Human movement science, 30*(5), 869-888.

Tian, Q., Chastan, N., Bair, W.-N., Resnick, S. M., Ferrucci, L., & Studenski, S. A. (2017). The brain map of gait variability in aging, cognitive impairment and dementia—a systematic review. *Neuroscience & Biobehavioral Reviews, 74*, 149-162.

Voelcker-Rehage, C. (2008). Motor-skill learning in older adults—a review of studies on age-related differences. *European review of aging and physical activity, 5*(1), 5-16.

Wang, C., Patriquin, M., Vaziri, A., & Najafi, B. (2021). Mobility performance in community-dwelling older adults: potential digital biomarkers of concern about falling. *Gerontology, 67*(3), 365-373.

Williams, A. M., Ford, P. R., Eccles, D. W., & Ward, P. (2011). Perceptual-cognitive expertise in sport and its acquisition: Implications for applied cognitive psychology. *Applied Cognitive Psychology, 25*(3), 432-442.

Winter, D. A. (1995). Human balance and posture control during standing and walking. *Gait & posture, 3*(4), 193-214.

Witte, K., Kropf, S., Darius, S., Emmermacher, P., & Böckelmann, I. (2016). Comparing the effectiveness of karate and fitness training on cognitive functioning in older adults—a randomized controlled trial. *Journal of sport and health science, 5*(4), 484-490.

Woollacott, M. H., & Tang, P.-F. (1997). Balance control during walking in the older adult: research and its implications. *Physical therapy, 77*(6), 646-660.

Young, A. (1997). Ageing and physiological functions. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, 352*(1363), 1837-1843.

Zadik, S., Benady, A., Gutwillig, S., Florentine, M. M., Solymani, R. E., & Plotnik, M. (2022). Age related changes in gait variability, asymmetry, and bilateral coordination–When does deterioration starts? *Gait & posture, 96*, 87-92.

Table 1- Demographic measures and physical and cognitive function of different groups

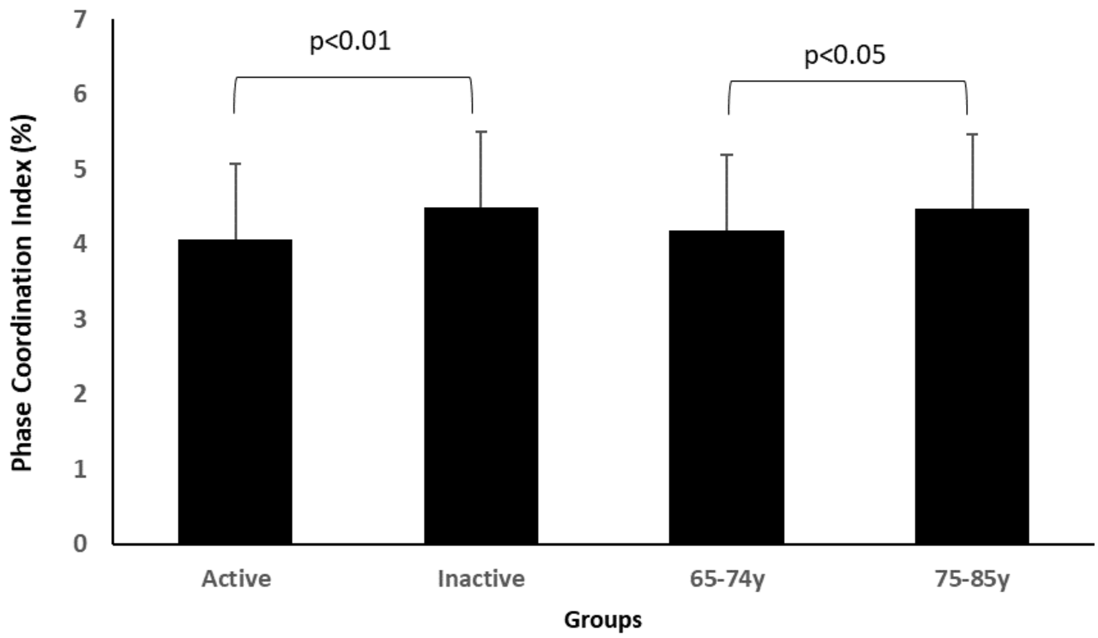
	Active (n=25)	**Inactive (n=20)**	**65-74y (n=33)**	**75-85y (n=12)**
Age (year)	72.52 (7.4)	70.85 (3.8)	68.78 (2.9)	80 (4.6)
Height (cm)	173.32 (6.5)	163.95 (5.5)	167.27 (7.2)	174.33 (6.5)
Body Mass (Kg)	70.32 (13.1)	67.70 (9.2)	69.13 (11.8)	69.2 (11.21)
Trail Making Time (sec)	31.24 (10.7)	24.8 (3.4)	25.92 (5.1)	35.12 (1)
Timed Up and Go (sec)	7.31 (1.2)	8.22 (1.2)	7.62 (1.1)	7.98 (1.7)

Table 2- The ANOVA results and effect sizes of sport participation and age in different gait parameters.

	Active (n=25)	Inactive (n=20)	F	ω^2	65-74y (n=33)	75-85y (n=12)	F	ω^2
Walking Performance								
Cadence (step/min)	113.88 (7.9)	96.15 (15.5)	9.35**	0.25^L	103.9 (15.6)	111.75 (10.2)	1.6	0.02^S
Speed (m/sec)	1.32 (0.1)	0.9 (0.2)	28**	0.51^L	1.12 (0.3)	1.15 (0.2)	0.47	0
Temporal Variability								
R Swing time (CV%)	5.05 (0.8)	6.7 (1.8)	26.3**	0.5^L	5.67 (1.1)	6.11 (2.4)	7.83**	0.21^L
L Swing time (CV%)	4.79 (0.9)	6.82 (2.9)	5.45*	0.15^L	5.82 (2.5)	5.34 (1.4)	0.003	0
R Stance time (CV%)	9.87 (1.9)	7.77 (2.1)	0.5	0	6.72 (1.9)	15.03 (28)	1.16	0
L Stance time (CV%)	10.03 (2)	8.17 (2.8)	0.41	0	6.98 (2.5)	15.3 (28)	1.13	0
R Stride time (CV%)	5.25 (13.4)	4.68 (1.7)	0.18	0	3.53 (1.7)	9.02 (19)	1.24	0.01^S
L Stride time (CV%)	5.65 (13.4)	4.98 (2.1)	0.25	0	3.86 (2)	9.44 (19)	1.21	0
Double-support time (CV%)	14.05 (2.7)	14.51 (4.6)	0.17	0	14.68 (3.8)	13.08 (2.8)	2.19	0.04^S
Walking Time								
R Swing time (sec)	0.417 (0.02)	0.491 (0.05)	10**	0.26^L	0.462 (0.06)	0.417 (0.03)	5.18*	0.13^L
L Swing time (sec)	0.418 (0.02)	0.483 (0.06)	7.68**	0.23^L	0.458 (0.06)	0.415 (0.03)	4*	0.11^L
R Stance time (sec)	0.627 (0.05)	0.797 (0.1)	14.7**	0.36^L	0.718 (0.1)	0.662 (0.06)	1.01	0
L Stance time (sec)	0.624 (0.05)	0.803 (0.1)	14.7**	0.36^L	0.724 (0.1)	0.668 (0.06)	1.12	0
R Stride time (sec)	1.046 (0.07)	1.28 (0.1)	14.15**	0.34^L	1.18 (0.1)	1.08 (0.08)	2.17	0.04^S
L Stride time (sec)	1.05 (0.07)	1.28 (0.1)	13.52**	0.33^L	1.18 (0.2)	1.08 (0.08)	2.11	0
Double-support time (sec)	0.106 (0.01)	0.156 (0.03)	20.15**	0.32^L	0.131 (0.03)	0.121 (0.02)	0.021	0

*significant at 0.05 S: small effect size; M: medium effect size; L: large effect size

**significant at 0.01



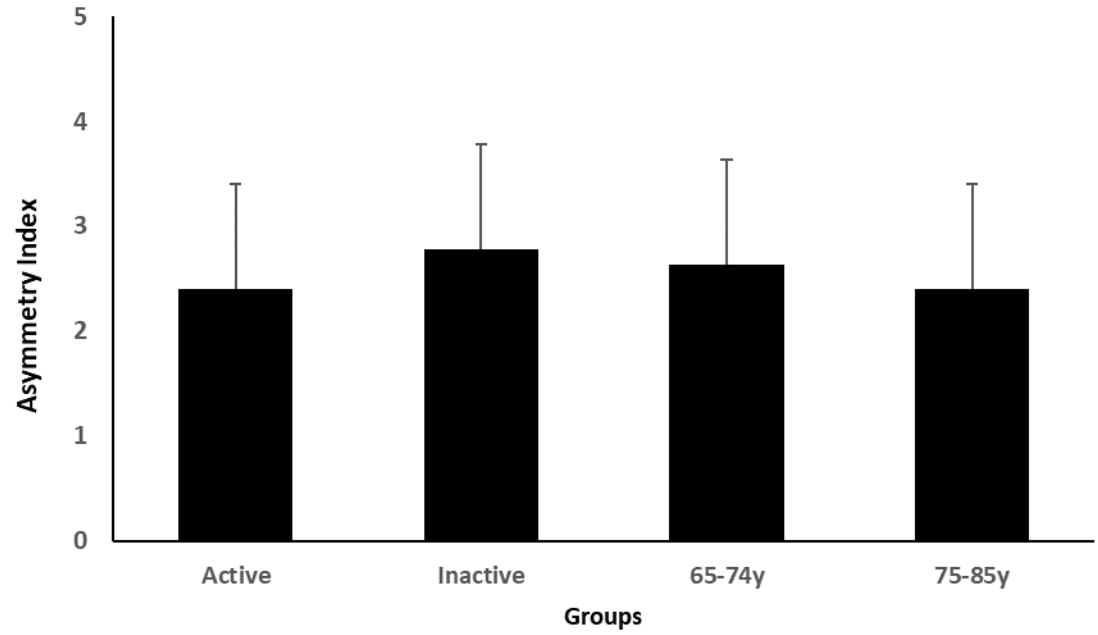


Figure 1- Means (SD) of PCI and asymmetry index scores in different groups.