Journal of Research and Practice
on the Musculoskeletal System

Review Article

Effects of aging on biomechanical gait parameters in the healthy elderly and the risk of falling

Pavlos Morfis[1], **Maria Gkaravelli**[2]

[1]Department of Medicine, School of Health Sciences, National and Kapodistrian University of Athens, Athens, Greece;
[2]School of Physical Education and Sport Science, National and Kapodistrian University of Athens, Athens, Greece

Abstract

The biomechanics of walking seems to be affected in the elderly compared to young adults. These adjustments are likely to be associated with an increase in the risk of falling. This review aims to investigate the effect of age on walking ability specifically focusing on studies that have assessed spatiotemporal, kinematics and kinetics variables using three-dimensional (3D) analysis. A systematic review of the research literature was applied until January 2019 across Pubmed electronic database. A targeted search strategy traced full papers that fulfilled the inclusion and exclusion criteria. Eleven of 214 articles met the predetermined inclusion criteria and were included in the review. Differences between older and young adults were found in the most parameters which were evaluated. Changes in the lower-limb walking kinematics in elderly during walking may compromise the quality of gait. However, there is a bibliographic gap, as there are no articles that assess the risk of falling taking into account joint kinematic and kinetic parameters.

Keywords: Falls, Gait disorders, Kinematics, Kinetics, Motion analysis

Introduction

Human gait is one of the most basic movements of the human body[1]. It is the result of a series of rhythmic alternating movements of different segments of the body with the least energy expenditure, which leads to the forward propulsion of human body's center of gravity. It is a mechanism which depends upon closely integrated action of the musculoskeletal, cardiopulmonary and nervous system[2].

The maintenance of walking ability is important for older adults as it provides independence and is necessary to carry out several activities of daily life[3]. Normal aging brings about significant changes in the elderly gait pattern[2,4]. Some researchers use the term "senile gait disorders" when referring to modifications in age-related biomechanical characteristics of gait[5]. The prevalence of walking disorders of the elderly over 70 years is estimated to be 35%[6]. However, 85% of people aged 60-69 years still walk normally, but only 20% of people aged over 85 years do[7].

Age-related changes in biomechanical gait characteristics of elderly have been investigated in several studies, mainly using three dimensional gait analysis[3,8-10]. The majority of these studies present comparable gait characteristics between younger and older age groups[11-15]. Common disorders affecting the gait pattern of elderly are the attenuation of postural reflexes, the poor posture control and the presence of a rigid and less coordinated gait pattern. Also, the poor posture in standing position as becomes more stooped with age displacing foward the body's center of gravity. Displacement of the center of gravity from the midpoint may me lead to a balance lost[2].

Moreover, age-related gait modifications associated with reduced muscle strength and limited lower-limb joint range of motion as a result of physiological and neuromuscular changes[16-23]. In particular, sarcopenia is a well-described effect of aging, which is characterized by a muscle atrophy (a decrease in the cross-sectional area) along with a reduction

The authors have no conflict of interest.

Corresponding author: *Pavlos Morfis, School of Health Sciences, National and Kapodistrian University of Athens, 19 Prasinou Lofou, 14122, Irakleio, Athens, Greece*

E-mail: *paulmorfis@gmail.com*

Edited by: *Konstantinos Stathopoulos*

Accepted *29 September 2020*

in muscle tissue quality due to replacement of muscle fibers with adipose tissue[24]. This process may cause increased joint stiffness[25] whereas muscle mass loss is generally associated with muscle weakness[26]. In addition, studies have shown that in normal aging greater co-activation of muscles is induced during walking in elderly adults[27]. Muscle co-activation although it plays an important role in enhancing joint stabilization during activities such as walking[28-30] is likely to be associated with increased walking energy cost[28].

In walking performance of elderly it is particularly important to take into account changes identified in the joint movement angles[20,31-33]. From the biomechanical analysis of lower extremity activity a reduced hip and ankle range of motion in the sagittal plane has been observed during walking tasks[5,34,35]. This is associated with changes observed in the joints kinetic data. Both the joints moments generated during the movement and the power are disrupted during the gait cycle[3].

Differences were also observed in the spatio-temporal data of elderly walking should be considered[3]. The elderly compensate their reduced physical performance using some protective gait strategies[2,36]. Specifically, the stance and gait base is widened. Elderly adults prefer a step with a 40% wider width than young persons[37], the feet are lifted less high during the swing phase and often shuffling walk is observed. The step length becomes shorter and the walking speed is reduced[4,5].

These findings show that elderly experience exacerbated declines in the biomechanical parameters of gait associated with their functional worsening[34]. Difficulties in walking can be the precursors of falls, which is the most common cause of serious injuries in older age[7,38]. Nearly one third of older adults aged over 65 fall at least once a year[39,40]. Approximately 10-15% of these falls lead to serious injuries such as brain trauma[41] or hip fractures[7,42] and are associated with repeated hospitalizations and premature death[43].

Gait is a sensitive indicator of overall health status and is closely correlated with life expectancy in elderly adults[44]. Gait abnormalities may lead to loss of autonomy, affect the social interaction, the sense of well-being and reduce quality of life[5,45]. However, gait disturbances and falls are largely underdiagnosed and often receive inadequate assessment[46]. For gait evaluation the spatio-temporal, kinematic and kinetic data collected by the three-dimensional gait analysis is of the utmost importance. The purpose of the present study was to examine through a systematic review of the literature the effect of normal aging on biomechanical parameters of gait which have been evaluated with the three-dimensional gait analysis.

Method

Search strategy

A systematic review of the research literature was applied until January 2019. The literature search was performed in the Pubmed electronic database. The search strategy is presented below: ''aging" OR elderly AND ''gait" OR ''locomotion'' OR ''walking'' OR ''gait disorders'' OR ''falls'' AND ''biomechanics'' OR ''kinematic'' OR ''kinetics'' OR ''three dimensional (3D) analysis''.

Inclusion criteria for selection of the studies were determined a priori: In this systematic review original articles, written in English and referred to healthy elderly subjects were studied. Participants had to be healthy and able to ambulate independently. Studies were required to assess gait characteristics between elderly and young people in terms of spatial-temporal, kinematics and kinetics variables. The gait evaluation should be carried out through the three-dimensional gait analysis system (e.g. camera systems, wearable sensors, electronic walkways, force platforms). Both overground and treadmill walking were deemed acceptable.

Results

Review selection and identification

The initial search yielded 214 citations. Duplicates were then removed and 180 records remained. From titles and abstracts review were selected 18 articles for full text screening, of which 11 met the inclusion criteria and were included.

Of the eleven studies that focused on gait, nine studies compared healthy elderly subjects with healthy young adults[16,20,27,47-52]. Two papers additionally examined age-related differences in gait characteristics between healthy older adults[34,53].

Study characteristics

All papers implied a specific measurement protocol with using 3D motion analysis system (MAS). The number of markers and cameras used was adequately provided in all studies. Seven papers reported the use of AMTI force platforms (Advanced Medical Technology Inc., 151 California Street, Newton)[34,48-53] to determine gait kinetics and two papers reported the assessment of muscle activation during gait through 12-channel desktop direct transmission system sEMG device (Noraxon Inc., Scottsdale, AZ, USA)[27,47]. The majority of studies reported overground walking and a specific gait protocol[20,27,34,47-53] at a self-selected speed during walking. However in a study was selected treadmill walking[16].

Measurement approach - Gait parameters

Eleven studies collected spatial-temporal data, eight studies reported kinematic data, seven studies assessed kinetic variables and two studies used electromyography.

Spatial-temporal variables

Eleven papers reported quantitative gait data, which included gait velocity (n=10), cadence (n=7), step length (n=4), step width (n=5), stride length (n=8), swing time (n=1), stance time (n=3), levels of variability for the stride length and the stride time (n=1).

Gait Velocity - Among articles which reported gait velocity, nine found significant decrease in older persons in comparison with young persons[16,20,27,34,47,50-53], whereas one did not identify significant difference[49].

Cadence - Three paper identified a significant decrease in cadence for older persons[16,27,47], two papers identified significant increase in cadence for older persons[52,53] and in two papers no significant differences were observed[20,50].

Step width - Older adults were observed to increase their step width during walking in tree studies[27,34,47], however Oliveira et al. (2017)[16] observed a decrease in this variable.

Other variables which showed significant differences between older and young persons were that of stride length decreasing[16,20,27,34,47,49,51,53], step length decreasing[20,49,50,52], swing phases percentage decreasing[20], stance phases percentage increasing[20], single support time decreasing[52].

Kinematic variables

There are considerable kinematic differences observed in various studies between older and young adults. Particularly with respect to changes in kinematic data, the elderly subjects walked with a greater anterior tilt of the pelvis[51,52]. Age also appears to alter hip joint kinematics. Three paper identified a significant increase at mean values for the hip flexion at toe off[16] as well as higher percent of the gait cycle for hip flexion[34,52]. In addition, the elderly had reduced hip extension[50,51]. An increase in knee flexion is observed at the initial contact in older adults walking[16,50]. Between-group comparisons of joint ankle kinematics there are also significantly reduced mean values for the ankle dorsi flexion at heel strike[16] and for the ankle plantar flexion during late stance and at toe off[16,50-52]. Afiah et al. (2016)[20] found that in older adults the peak extension timing of the hip, peak flexion timing of the knee and peak plantar flexion timing of the ankle joint were significantly later. Should also be mentioned that in two studies there were no significant differences observed relative to the joint angle parameters between two groups[48,20].

Kinetic variables

From the literature review it was observed that there are significant differences in the findings between the kinetic variables.

Hip: Kim and colleagues[50] noted a lower hip extension moment with reduced hip extensors power at the loading phase in elderly but no statistical differences in the hip flexion moment. Kerrigan and colleagues[51] report lower hip flexion moment stance of elderly. Judge et al.[52] also reported that if the analysis was adjusted for differences in step length, older subjects developed 16% more hip flexor power than younger subjects. Older age was also associated with higher peak joint power in the adduction and abduction movements of the hip and knee[53].

Knee: Kerrigan et al. (1998)[51] observed reduction in knee extension moment at initial contact, in knee flexion moment at midstance and in knee flexion moment at preswing. Also, identified significant decrease in knee power absorption at loading response, knee power generation at midstance and knee power absorption at preswing.

Ankle: A study by Kim et al. (2014)[50] noted that the ankle plantar flexion moment and the ankle plantar flexion power burst of elderly was slightly smaller than younger subjects. Ko et al. (2009)[53] reported that elderly have lower peak joint power in plantar flexion and dorsi flexion movements. Judge et al. (1996)[52] recorded that elderly subjects developed 17% lower peak ankle plantar flexor power than young subjects.

Discussion

The aim of the present systematic review was to provide a comprehensive overview of studies that investigate the effect of normal aging on biomechanical parameters of gait which have been evaluated with the three-dimensional gait analysis. Overall, the results of the systematic review provides sound evidence that aging has a substantial impact on specific spatiotemporal, kinematics and kinetics variables.

An activity such as walking is an overall result of several movement parameters, and may be fairly representative of the individual's performance[3]. Documented changes in some walking parameters may be the most indicative gait adaptations selected by elderly and not the result of age-specific impairments[3].

Reduced walking speed is the most consistent change associated with age[5]. Spontaneous walking speed is usually reduced by 1% per year from the age of 60 years onwards.[54,55]. Walking speed of less than 0.8 m/s are associated with limited ambulatory capability and walking speed equal to or less than 0.4 m/s is related with an inability to respond to daily life activities[5,56]. It is important to mention that decrease in walking speed was associated with a 7% increased risk for falls[6]. It is considered a simple measure to detect changes in mobility[5] and it is a good indicator of health and survival in older adults, especially after age 75[2,57].

The results regarding the walking cadence are not clear. Some studies reported a decrease and some increase in this variable. In addition, some studies have indicated that the elderly maintain a normal cadence during walking[3,23,58,59]. Cadence maintenance are considered to be the result of generally high physical activity levels in older adults. When older participants have moderate physical activity, they also have better walking capacity[59]. Consequently, it might be difficult to notice any significant difference in the cadence of the older adults.

From the review of the literature was observed smallest stride length in elderly. The average stride length in healthy adults ranges between 150 and 170 cm. Shorter stride length in very elderly is correlated with the short stature [59]. This observation is also consistent with the results of previous studies[32,58,60] in which/where it was observed that height are significantly associated with stride length and walking speed. Moreover, elderly prefer a 40% wider step width than young persons (average step width in elderly women about 8 cm and in elderly men 10 cm)[37]. According to Maki (1997)[36] and contrary to common expectation, a wider stride does not necessarily increase stability but instead seems to predict an increased likelihood of experiencing falls.

Smaller percentages of swing phase observed in older adults may be the result of reductions in swing limb advancement as well as muscle power. The higher percentages of the support phase could be due to the decrease in the stability of trunk and lower extremities. Furthermore, increasing the percentage of the support phase propose that more time is required after the limb advancement so that older adults maintain weight-bearing stability[59]. The aforementioned findings are supported by the results of previous studies[61,62] showing/which indicate that elderly adopt a slower walking pattern.

For the elderly in gait analysis should also take into account kinematic and kinetic parameters. It has been found that many of the joints movements are typical for the gait patterns for the gait patterns of older adults[58,59]. Kerrigan et al. (1998)[51] and Judge et al. (1996)[52] reported an increased anterior pelvic tilt, while Ko et al. (2010)[34] recorded reductions in the range of motion in the joints of hip, knee and ankle. Another important finding was that hip extension was significantly reduced. A decrease in hip extension has been recorded by Oliveira et al. (2017)[16], Kim et al. (2014)[50] and Kerrigan et al. (1998)[51] while Ko et al. (2010)[34] and Judge et al. (1996)[52] found that the percent of the gait cycle for hip flexion were higher. A reduction in hip extension may imply a functional tightness that would be preventing the full extension of the hip mainly in the toe-off[16].

Moreover, Afiah et al., (2014)[20,59] in their study provides new information about the motion of the hip joint, more specific about the peak extension timing of the joint throughout the gait cycle. According to studies conducted by Kerrigan et al. (1998)[51]; Alcock et al. (2013)[63] and Anderson and Madigan (2014)[64], the delay in the maximum extent of the hip joint may be related to various parameters. As already mentioned, there is a decrease in the range of hip extension. Also, the weakness of the hip flexor muscles affects the individual's effort to change the joint position while poor hip flexor power affects/influences the push-off.

Although the moments have been used to characterize the gait of older people, in most studies either limited to a flat analysis or when was performed a three-dimensional (3D) analysis information was provided only for the sagittal level[3]. Kerrigan et al. (1998)[51] noted that during walking, there were significant reductions in peak hip flexion moment at stance in elderly. Judge and colleagues (1996)[52] in their study noticed that when the analysis was adjusted for differences in step length, older subjects developed 16% more hip flexor power than younger subjects. Kim et al. (2014)[50] report that the hip extension moment as well as the hip power exerted by the hip extensors at the loading phase was reduced in elderly compared to that of young persons. Also, the hip flexor power burst of elderly was smaller. Information about knee movement is not clear. There is a disagreement in researchers' findings and no statistical significant differences.

According to other alterations observed in the walking pattern of elderly, they indicate decreased plantar flexion peak ankle in late stance compared to young participants[52]. This condition is likely to contribute to older person's shorter step length. This finding is in agreement with previous studies[16,50,51] and provide novel information about the effect of aging on kinematic angular parameters. Elderly individuals appear to have restricted range of movement at the knee[33,52] and also demonstrate limited capacity in limb advancement during the push-off period due to reduced plantar flexor moments[34].

Some previous studies have determined the kinetic characteristics of ankle joint in elderly. According to Judge et al. (1996)[52] there was significant difference in joint power between old and young subjects in peak ankle plantar flexor power. Older subjects developed 17% lower power than young subjects. Kim et al. (2014)[50] noticed that the elderly showed smaller ankle plantar flexor power burst. This adaptation seems to be a compensatory mechanism to the reduction in hip extension. There are no significant differences identified in joint angle parameters between two groups from Kulmala et al. 2017[48] and Afiah et al. 2016[20].

A number of parameters showed significant differences between older and young adults. The necessary adjustments that may have taken place for weight acceptance and body propulsion during the walking from elderly may contribute to age-related differences in gait biomechanics. Progressive age-related deterioration in neuromuscular and neurophysiological function causes declines in sensory systems, sarcopenia, slower movement and central processing, all linked to deficits in gait[65]. It is important to mention, that most gait studies of elderly people focus on the risk of falling during gait in clinical populations and often are limited to the evaluation of spatiotemporal parameters. There is a bibliographic gap, as there are no articles that assess the risk of falling taking into account joint kinematic and kinetic data. Joint kinematic and kinetic parameters are essential to understanding age-related changes in gait. Changes in gait are generally directly involved in fall mechanisms and are robust prediction factors. Further research aiming at a holistic approach to the gait disturbances that may lead to falling is necessary.

References

1. Paróczai R, Bejek Z, Illyés Á. Kinematic and kinetic parameters of healthy elderly people. Periodica Polytechnica Mechanical Engineering 2005;49(1):63-70.

2. Pirker W, Katzenschlager R. Gait disorders in adults and the elderly: A clinical guide. Wien KlinWochenschr 2017;129(3-4):81-95.
3. Watelain E, Barbier F, Allard P, Thevenon, A, Angué JC. Gait pattern classification of healthy elderly men based on biomechanical data. Archives of Physical Medicine and Rehabilitation 2000;81(5):579-586.
4. Beijersbergen CM, Granacher U, Vandervoort AA, DeVita P, Hortobágyi T. The biomechanical mechanism of how strength and power training improves walking speed in old adults remains unknown. Ageing Res Rev 2013;12(2):618-27.
5. Cruz-Jimenez M. Normal Changes in Gait and Mobility Problems in the Elderly. Phys Med Rehabil Clin N Am 2017;28(4):713-725
6. Verghese J, Levalley A, Hall CB, et al. Epidemiology of gait disorders in community-residing older adults. J Am Geriatr Soc 2006;54:255-61.
7. Sudarsky, L. Gait disorders: prevalence, morbidity, and etiology. Advances in Neurology2001; 87:111-117.
8. Arif M, Ohtaki Y, Ishihara T, Inooka H. Walking gait stability in young and elderly people and improvement of walking stability using optimal cadence. In: MHS 2002 - Proceedings of 2002 international symposium micromechatronics human science, pp 245-251.
9. Callisaya ML, Blizzard L, Schmidt MD et al . Sex modifes the relationship between age and gait: a population-based study of older adults. J Gerontol A Biol Sci Med Sci 2008;63:165-170.
10. Lord S, Galna B, Verghese J et al. Independent domains of gait in older adults and associated motor and nonmotor attributes: validation of a factor analysis approach. J Gerontol A Biol Sci Med Sci 2013;68(7):820-827.
11. Mills PM, Barrett RS Swing phase mechanics of healthy young and elderly men. Hum Mov Sci 2001;20:427-446.
12. Grabiner PC, Biswas ST, Grabiner MD. Age-related changes in spatial and temporal gait variables. Arch Phys Med Rehabil 2001;82:31-35.
13. Moyer BE, Chambers JA, Redfern MS, Cham R. Gait parameters as predictors of slip severity in younger and older adults. Ergonomics 2006;49:329-343.
14. Schulz BW. Healthy younger and older adults control foot placement to avoid small obstacles during gait primarily by modulating step width. J Neuroeng Rehabil 2012;9:69.
15. Vieira ER, Lim H-H, Brunt D et al. Temporo-spatial gait parameters during street crossing conditions: a comparison between younger and older adults. Gait Posture 2015;41:510-515.
16. Oliveira CF, Vieira ER, Machado Sousa FM, Vilas-Boas JP. Kinematic Changes during Prolonged Fast-Walking in Old and Young Adults. 2017;4:207.
17. Kang HG, Dingwell JB. Effects of walking speed, strength and range of motion on gait stability in healthy older adults. J Biomech 2008;41(14): 2899-905.
18. Faulkner JA, Larkin LM, Cla flin DR, Brooks SV. Age-related changes in the structure and function of skeletal muscles. Clin Exp Pharmacol Physiol 2007;34(11):1091-6.
19. Fan Y, Li Z, Han S, Lv C, Zhang B. Te in fluence of gait speed on the stability of walking among the elderly. Gait Posture 2016;47:31-6.
20. Afiah IN, Nakashima H, Muraki S. An exploratory investigation of changes in gait parameters with age in elderly Japanese women. Springerplus 2016;5(1):1069.
21. Guralnik JM, Ferrucci L, Simonsick EM et al. Lower-extremity function in persons over the age of 70 years as a predictor of subsequent disability. N Engl J Med 1995;332:556-561.
22. Winegard KJ, Hicks AL, Sale DG, Vandervoort AA. A 12-year followup study of ankle muscle function in older adults. J Gerontol Biol Sci 1996;51:B202-B207.
23. Silder A, Heiderscheit B, Thelen DG. Active and passive contributions to joint kinetics during walking in older adults. J Biomech 2008; 41:1520-1527.
24. Ryall JG, Schertzer JD, Lynch GS. Cellular and molecular mechanisms underlying age-related skeletal muscle wasting and weakness. Biogerontology (Review) 2008;9(4):213-28.
25. Whittington B, Silder A, Heiderscheit B, Thelen DG. The contribution of passive-elastic mechanisms to lower extremity joint kinetics during human walking. Gait Posture 2008;27:628-34.
26. Visser M, Kritchevsky SB, Goodpaster BH, Newman AB, Nevitt M, Stamm E, Harris TB. Leg muscle mass and composition in relation to lower extremity performance in men and women aged 70 to 79: the health, aging and body composition study. J Am Geriatr Soc 2002;50:897-904.
27. Lee HJ, Chang WH, Hwang SH, Choi BO, Ryu GH, Kim YH. Age-related differences in muscle co-activation during locomotion and their relationship with gait speed: a pilot study. BMC Geriatr. 2017;17:44.
28. Hortobagyi T, Solnik S, Gruber A, Rider P, Steinweg K, Helseth J, DeVita P. Interaction between age and gait velocity in the amplitude and timing of antagonist muscle coactivation. Gait Posture 2009; 29:558-64.
29. Peterson DS, Martin PE. Effects of age and walking speed on coactivation and cost of walking in healthy adults. Gait Posture 2010;31:355-9.
30. Larsen AH, Puggaard L, Hamalainen U, Aagaard P. Comparison of ground reaction forces and antagonist muscle coactivation during stair walking with ageing. J Electromyogr Kinesiol 2008;18:568-80.
31. Savelberg HHCM, Meijer K. The effect of age and joint angle on the proportionality of extensor and flexor strength at the knee joint. J Gerontol A Biol Sci Med Sci 2004;59:1120-1128.
32. Kimura T, Kobayashi H, Nakayama E, Hanaoka M. Effects of aging on gait patterns in the healthy elderly. Anthropol Sci 2007;115:67-72
33. Kirkwood R, Gomes H, Sampaio R et al. Biomechanical analysis of hip and knee joints during gait in elderly subjects. Acta Ortopédica Bras 2007;15:267-271.
34. Ko SU, Hausdorff JM, Ferrucci L. Age-associated differences in the gait pattern changes of older adults during fast-speed and fatigue conditions: results from the Baltimore longitudinal study of ageing. Age Ageing 2010;39:688-94.
35. Owings TM, Grabiner MD. Variability of step kinematics in young and older adults. Gait Posture 2004;20:26-9.
36. Maki BE. Gait changes in older adults: predictors of falls or indicators of fear. J Am Geriatr Soc 1997;45:313-20.
37. Aboutorabi A, Arazpour M, Bahramizadeh M, Hutchins SW, Fadayevatan R. The effect of aging on gait parameters in able-bodied older subjects: a literature review. Aging Clinical and Experimental Research 2016;28(3):393-405.
38. Stolze H, Klebe S, Zechlin C, Baecker C, Friege L, Deuschl G. Falls in frequent neurological diseases - prevalence, risk factors and aetiology. Journal of Neurology 2004; 251(1):79-84.
39. Campbell AJ, Reinken J, Allan BC, Martinez GS. Falls in old age: a study of frequency and related clinical factors. Age Ageing 1981;10(4):264-70.
40. Tinetti ME, Speechley M, Ginter SF. Risk factors for falls among elderly persons living in the community. N Engl J Med 1988; 319(26):1701-7.
41. Jager TE, Weiss HB, Coben JH, Pepe PE. Traumatic brain injuries evaluated in U.S. emergency departments, 1992-1994. Acad Emerg Med. 2000;7(2):134-40.
42. Hayes WC, Myers ER, Morris JN, Gerhart TN, Yett HS, Lipsitz LA. Impact near the hip dominates fracture risk in elderly nursing home residents who fall. Calcif Tissue Int 1993;52:192-198.

43. Auvinet B, Touzard C, Montestruc F, Delafond A, Goeb V. Gait disorders in the elderly and dual task gait analysis: a new approach for identifying motor phenotypes. J Neuroeng Rehabil 2017;14:7.
44. Studenski S, Perera S, Patel K, Rosano C, Faulkner K, Inzitari M et al. Gait speed and survival in older adults. JAMA 2001;305(1):50-58.
45. Mahlknecht P, Kiechl S, Bloem BR, Willeit J, Scherfler C, Gasperi A et al. Prevalence and burden of gait disorders in elderly men and women aged 60-97 years: a population-based study PLoS One 2013;8(7):e69627.
46. Rubenstein LZ, Solomon DH, Roth CP, Young RT, Shekelle PG, Chang JT et al. Detection andmanagement of fallsand instability in vulnerable elders by community physicians. Journal of the American Geriatrics Society 2004;52(9):1527-1531.
47. Lee HJ, Chang WH, Hwang SH, Choi BO, Ryu GH, Kim YH. Age-Related Locomotion Characteristics in Association with Balance Function in Young, Middle-Aged, and Older Adults. J Aging Phys Act 2017;25(2):247-253.
48. Kulmala JP, Korhonen MT, Kuitunen S, Suominen H, Heinonen A, Mikkola A, et al. (2017). Whole body frontal plane mechanics across walking, running, and sprinting in young and older adults. Scand J Med Sci Sports 2017;27(9):956-963.
49. Hortobágyi T, Rider P, Gruber AH, DeVita P. Age and muscle strength mediate the age-related biomechanical plasticity of gait. Eur J Appl Physiol 2016;116(4):805-14.
50. Kim WS, Kim EY. Comparing self-selected speed walking of the elderly with self-selected slow, moderate, and fast speed walking of young adults. Ann Rehabil Med 2014;38(1):101-8.
51. Kerrigan DC, Todd MK, Della Croce U et al. Biomechanical gait alterations independent of speed in the healthy elderly: evidence for specifc limiting impairments. Arch Phys Med Rehabil 1998; 79:317-322.
52. Judge JO, Davis RB, Ounpuu S. Step length reductions in advanced age: the role of ankle and hip kinetics. J Gerontol A Biol Sci Med Sci 1996;51(6):303-12.
53. Ko S, Ling SM, Winters J, Ferrucci L. Age-related mechanical work expenditure during normal walking: the Baltimore Longitudinal Study of Aging. J Biomech 2009;42(12):1834-9.
54. Ashton-Miller JA. Age-associated changes in the biomechanics of gait and gaitrelated falls in older adults. In: Hausdorff JM, Alexander NB, editors. Gait disorders: evaluation and management. Boca Raton (FL): Taylor & Francis; 2005. p. 63-100.
55. Brach JS, Perera S, VanSwearingen JM, et al. Challenging gait conditions predict 1-year decline in gait speed in older adults with apparently normal gait. Phys Ther 2011;91(12):1857-64.
56. Fritz S, Lusardi M. White paper: “Walking speed: the sixth vital sign”. J Geriatr Phys Ther 2009;32(2):46-9.
57. Mielke MM, Roberts RO, Savica R, Cha R, Drubach DI, Christianson T, et al. Assessing the temporal relationship between cognition and gait: slow gait predicts cognitive decline in the Mayo Clinic Study of Aging. J Gerontol A Biol SciMedSci. 2013;68(8):929-37.
58. Winter DA (1991) The biomechanics and motor control of human gait: Normal, elderly and pathological, 2nd Editio. Waterlo Press, Canada.
59. Afiah IN, Nakashima H, Muraki S. (2014). Age-related changes in walking motion of Japanese females : basic analysis of gait motion. In: Proceeding of the 1st Asian conference on ergonomics and design, pp 1-5.
60. Bendall M, Bassey E, Pearson M. Factors affecting walking speed of elderly people. Age Ageing 1989;18:327-332.
61. Whittle MW (2007) Gait analysis: An introduction, 4th edn. Butterworth Heinemann Elsevier, UK.
62. Perry J, Burnfeld JM (2010) Gait analysis: Normal and pathological function, 2nd edn. SLACK Incorporated, USA.
63. Alcock L, Vanicek N, O’Brien TD. Alterations in gait speed and age do not fully explain the changes in gait mechanics associated with healthy older women. Gait Posture 2013;37:586-592.
64. Anderson DE, Madigan ML. Healthy older adults have insufcient hip range of motion and plantar flexor strength to walk like healthy young adults. J Biomech 2014; 47:1104-1109.
65. Papegaaij S, Taube W, Baudry S, Otten E, Hortobagyi T. Aging causes a reorganization of cortical and spinal control of posture. Front Aging Neurosci. 2014;6: 28.