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A Comparison of Treadmill and Overground Walking Effects on Step Cycle Asymmetry in Young and Older Individuals

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Abstract

Although lower limb strength becomes asymmetrical with age, past studies of ageing effects on gait biomechanics have usually analysed only one limb. This experiment measured how ageing and treadmill surface influenced both dominant and non-dominant step parameters in older (Mean 74.0 yr) and young participants (Mean 21.9 yr). Step-cycle parameters were obtained from 3-D position/time data during preferred-speed walking for 40 trials along a 10 m walkway and for 10-minutes of treadmill walking. Walking speed (Young 1.23 m/s, Older 1.24 m/s) and step velocity for the two age groups was similar in overground walking but older adults showed significantly slower walking speed (Young 1.26 m/s, Older 1.05 m/s) and step velocity on the treadmill due to reduced step length and prolonged step time. Older adults had shorter step length than young adults and both groups reduced step length on the treadmill. Step velocity and length of older adults' dominant limb was asymmetrically larger. Older adults increased the proportion of double support in step time when treadmill walking. This adaptation combined with reduced step velocity and length may preserve balance. The results suggest that bilateral analyses should be employed to accurately describe asymmetric features of gait especially for older adults.

Key Words: Ageing, Treadmill Walking, Asymmetry, Gait, Spatio-temporal Parameters

Introduction

There is a worldwide research effort to better understand ageing effects on gait biomechanics with the aim of determining how stability might be compromised and the risk of falling increased.[1] Two fundamental consequences of age-related declines in sensory motor function are evident in walking mechanics. The first is reduced performance, primarily due to loss of muscle strength and associated force production. These changes are reflected in both the kinetic dimensions of gait control[2] and associated spatial and temporal parameters of the step and stride cycle, such as reduced step length, which has been considered the most appropriate spatio-temporal measure of age-related frailty and falls risk.[3, 4] The second major gait-related consequence of ageing is compensatory adaptations that emerge to protect the walker; these effects are reflected in "functional" or adaptive changes to gait cycle variables. The progression toward shorter steps and slower walking as we age, for example, appear to compromise dynamic stability, particularly in the medio-lateral axis.[3, 5-8] Increased step width and prolonged double support in older adults, may therefore emerge as functional responses, in this case maintaining medio-lateral stability. [4, 9] While such ageing-related gait adaptations have been well researched, one characteristic of older adults' gait that has received relatively little attention is the symmetry of step control, as reflected in step length and step time measures sampled from both lower limbs simultaneously.

Previous gait biomechanics investigations have typically described the motion of only one limb and unilateral analysis has, possibly, been employed on the assumption that ageing influences both limbs in the same way. Consequently, traditional averaging of right and left side gait variables would preclude the opportunity to recognise any asymmetry. Adaptive locomotor control is, however, dependent on interactions *between* the lower limbs and kinetic and kinematic variables could be more unequal or "asymmetrical" than previously reported. Sadeghi et al.,[10-12] for example, suggested that asymmetry in spatio-temporal parameters has not only been observed in pathological gait but is also seen in non-impaired individuals, a finding that supports earlier research. [13, 14]

Sadeghi et al.[11] introduced the "functional asymmetry" hypothesis, in which the dominant limb primarily serves forward progression while the non-dominant limb maintains stability but there is no conclusive evidence of 'functional asymmetry' to explain gait asymmetry in healthy young individuals [11, 15] despite the implication of partial support.[12] While previous studies of functional asymmetry have not examined older adults' gait, Perry et al.[2] found that with ageing the dominant limb becomes asymmetrically stronger. It is, therefore, reasonable to hypothesise that spatio-temporal gait parameters also become asymmetrical with ageing. Asymmetry in older individuals has previously been linked to falls risk[2, 16, 17] but there are no previous reports of ageing effects on the symmetry of step cycle parameters.

The aim of this experiment was to investigate ageing effects on step cycle parameters by employing bilateral measurements of individual step cycles, rather than employing the more usual stride cycle analysis that does not separately examine the contribution of the two limbs and therefore masks any asymmetry in spatio-temporal parameters. Accordingly, it was hypothesised that older adults would show greater asymmetry in spatio-temporal parameters (see Figure 1) than young controls. In unconstrained overground walking healthy older adults may be capable of concealing asymmetric features of their gait and use both limbs equally but when encountering a more challenging task they could show increased confidence in their dominant limb. To test whether gait asymmetry is related to the level of challenge in walking we studied gait adaptations when walking at preferred speed overground and also when treadmill walking. Young adults are reported to fully familiarise to treadmill walking[18] whereas in one study, when on a motor driven treadmill older participants were requested to match their overground walking speed, two-thirds were unable to do so without using the safety handrail.[19] Older adults appear, therefore, to be destabilized during treadmill walking and it was of interest to determine whether a challenging treadmill walking condition was reflected in step cycle parameters.

Methods

Participants

Ten young adults (18 – 35 years, 6 males/4 females, age 21.9 ± 3.30 years) and ten older adults (> 65 years, 6 males/4 females, age 74.0 ± 7.63 years) participated; their height, body mass and limb dominance characteristics were as follows: Young: Height (1.67 ± 0.10 m), Weight (68.4 ± 12.21 kg), Limb dominance (n = right/left: 8/2) Older: Height (1.69 ± 0.11 m), Weight (73.1 ± 9.06 kg); Limb dominance (n = right/left: 8/2). The limb used to kick a ball was classified as the dominant limb, as previously used.[15] All older adults lived independently, were able to perform routine daily activities, free of any known cognitive, orthopaedic or neurological abnormalities and able to walk for at least 20 minutes continuously. Older volunteers were also excluded if they exceeded 12 seconds on a 'timed up and go test', scored less than 20 on a visual contrast sensitivity test ('Melbourne Edge Test') and reported at least one fall within the previous two years. None of the participants were regular treadmill users. All participants provided informed consent using procedures approved and mandated by the Victoria University Human Research Ethics Committee.

Experimental Protocol

Overground walking was performed at each participant's preferred speed along a ten meter overground walkway for 40 trials. Two force platforms (AMTI, Watertown, MA, USA) located in the middle of the walkway flush with the floor recorded foot-ground contact at 1200 Hz for consecutive steps. An Optotrak® optoelectric motion capture system (Northern Digital Inc., Canada) with two camera towers tracked the 3D position of eight markers (light-emitting diodes) on each foot at 240 Hz. Post-test processing of the overground walkthrough trials allowed the calculation of average preferred walking speed. A 10-minutes rest was provided for each participant before proceeding to treadmill walking to minimise the effect of fatigue on their gait.

The treadmill condition included a 10 minute warm up and familiarity phase during which preferred treadmill walking speed was determined by beginning at the average of overground walking speed and then decreasing by 0.3km/h every 10 strides until participants reported that it was uncomfortable to maintain normal walking. Speed was then decreased a further 0.3km/h and then increased systematically by 0.3km/h until reported as being uncomfortably fast. This procedure was repeated three times with the average of the six reported speeds taken as preferred walking speed on the treadmill. This protocol for determining treadmill walking speed has been applied in previous research.[20-22] After a suitable rest participants walked at their determined speed for 10 minutes and 3-D motion data were continuously collected throughout the treadmill walking test for analysis. All participants wore a safety harness when treadmill walking and their own flat, rubber soled, walking shoes.

Insert Figure 1 about here

Data Acquisition and Analysis

Using an established procedure[23] the distal end of most anterior toe part of a shoe and the proximal inferior surface of the shoe out-sole (i.e. heel) were reconstructed to represent toe and heel motion, respectively. Raw data of the markers and analogue data were low-pass filtered with a 4th order zero-lag Butterworth Filter with a cut-off frequency of 15 Hz (e.g. Mathie et al.[24]). Average overground preferred walking speed was calculated from all valid walkthrough trials using the heel contact events. To identify heel contact and toe off in both walking surface conditions we applied a foot velocity algorithm similar to that proposed by O’Connor et al.[25] The validity of the method was also supported by our own comparisons of kinematic and force plate data from the overground walking trials. The dependent variables were the analysed spatio-temporal step parameters: step velocity, step length, step width, and step time (including swing and double support). The independent variables were walking surface (overground and treadmill), limb (dominant and non-dominant), and age (young and older). Step velocity was calculated as step length divided by step time for the two limbs separately. Displacement between successive contralateral heel contacts in the anterior-posterior direction defined step length and in the medio-lateral direction, step width. Step time was the time taken to complete one step. Each step parameter was measured separately for the dominant and non-dominant limbs except step width. Step time comprises swing time and double support time (Figure 1). As commonly employed in gait cycle analysis the swing phase was the interval between ipsilateral toe off and heel contact, while double support was the interval between contralateral heel contact and ipsilateral toe off. Swing time and double support time were also normalised to a percentage of step time. A similar algorithm to that proposed by O'Connor et al.[25] was applied to obtain the timing of heel contact and toe off

A 2 X 2 X 2 (age x surface x limb) repeated measures mixed model Analysis of Variance (ANOVA) design was applied to all spatial-temporal dependent variables. Age was the between subject factor with surface and limb the within subject factors. F-ratios were accepted as significant when computed *p* values were .05 or less (using SPSS 16.0, SPSS Inc., Chicago, IL, USA). Post-hoc comparisons between means for significant interactions were analysed using Tukey's procedure.

Results

Mean walking speeds were; *Overground*, Young 1.23 m/s, Older 1.24 m/s and for *Treadmill Walking* Young 1.26 m/s and Older 1.05 m/s. There were no main effects on walking speed for either age or surface but an age x surface interaction (F (1, 18) = 5.0, p=.038) supported the above observation that the older participants selected an equivalent preferred speed overground but were significantly slower on the treadmill. Consistent with the walking speed data, young adults' step velocity was relatively constant across walking surfaces for both limbs and, as expected from the walking speed analysis, an age x surface interaction was again obtained (F (1, 18) = 5.0, p = .038) indicating that older adults' step velocity was significantly lower in treadmill walking than overground (Figure 2).

There was a limb effect on step velocity (F (1, 18) = 8.1, p = .011) but again, an age x limb interaction (F (1, 18) = 11.6, p = .003) was obtained, such that older adults' non-dominant step velocity was significantly lower than their dominant limb in both the overground and treadmill walking tasks.

Step length was longer in the young (F (1, 18) = 9.8, p = .006) and significantly shorter when treadmill walking in both age groups (F (1, 18) = 8.8, p = .008). There was also a significant difference between the limbs (F (1, 18) = 13.4, p = .002) due to shorter non-dominant steps but this was observed only in the older group as revealed by a significant age x limb interaction (F (1, 18) = 15.9, p = .001). Step width was larger in the older adults for the both walking conditions (Figure 2). The comparison between overground and treadmill walking of the older adults showed the marked increase, but the difference did not achieve statistical significance (F (1, 18) = 4.3, p = .053).

Step time analysis found an age x surface interaction (F (1, 18) = 5.5, p = .031) with young adults reducing step time while the older participants increased step time when treadmill walking. Examination of the step cycle sub-components revealed age x surface interactions for double support (F (1, 18) = 4.7, p = .044) and swing (F (1, 18) = 4.6, p = .047). Thus, increased absolute step time in treadmill walking as a function of age was due to both support time and swing time being extended. In addition, the *proportion* of double support in step time also increased significantly in the older groups' treadmill condition (age x surface, F (1, 18) = 5.6, p = .030) while as a consequence percentage swing time decreased (Figure 3).

Insert Figures 2 and 3 about here

Discussion

In this experiment both age groups walked at the same speed overground and with the same overground step velocity. In contrast, Whittle[4] and others[8, 26] reported lower average walking speeds in older adults but older persons in their upper range walked faster than the mean for young adults. The older participants in this study were healthy and physically active while other studies may have had greater diversity within their selected ‘healthy’ older adult sample. The results here suggest that when walking for a short duration at preferred speed on an unobstructed level surface, the effect of ageing alone in the absence of gait pathology may not significantly reduce walking speed relative to young controls.

When, in this study, the dominant and non-dominant step velocities were analysed separately, older adults showed asymmetrically greater step velocity and step length in the dominant limb. This result is consistent with previous work indicating that with age the dominant limb becomes asymmetrically stronger despite an overall reduction in absolute strength (e.g., Perry et al.[2]). Slower step velocity and shorter step length in the non-dominant limb may, therefore, be due to age-specific asymmetry in lower limb kinetics. The accentuated asymmetry revealed in significantly faster step velocity and longer step length in the older sample’s dominant limb could be interpreted as evidence of an increased propulsive role consistent with the “functional asymmetry” hypothesis discussed earlier. Confirming the non-dominant limb’s role in support is more problematic in that both step width and double support potentially comprise a contribution from either limb or both limbs. One limitation of the current study is that a limited number of step cycle parameters were investigated and a more detailed account of gait cycle kinematics may be required to determine more conclusively the non-dominant limb’s role in supporting gait. Further information to complement the findings reported here would, therefore, be required to more strongly support the hypothesised functional contribution by the non-dominant limb. It is, however, also possible that the dominant limb could play the larger supporting role if it becomes stronger with ageing[27] and in that case the ‘functional asymmetry’ hypothesis would be revised accordingly.

As found in earlier work (e.g., Seeley et al.[15]) the young adults in this experiment did not demonstrate functional differences between the two limbs; but it is noteworthy that earlier investigators had not examined limb dominance effects on the kinematic characteristics of step cycle parameters.

In addition to limb dominance brain laterality may also have influenced gait asymmetry. [11] Due to the limited number of left-limb dominant subjects, the current study could not effectively explore the possibility of whether further classification into the right or left limb dominance would reveal any evidence of brain laterality but this hypothesis could be usefully addressed in future work.

In support of a previous treadmill gait validation study[27] both age groups reduced step length and in older subjects ambulation was slower than overground. The young adults, however, significantly reduced step time (higher step frequency) to compensate reduced step length to maintain the same walking velocity on both surfaces. In contrast, older adults prolonged step time (lower step frequency) in addition to reducing step length, resulting in significantly slower step velocity in treadmill walking. Double support time and swing time showed the age by surface interaction similar to step time; in older participants double support and swing increased on the treadmill while for young subjects the effect was opposite, with shorter double support and swing. The proportion analysis revealed a significant increase in double support when older adults walked on the treadmill while there were no age group differences on time-normalised double support in overground walking. This finding is important in suggesting that physically active older adults, who did not walk overground significantly slower than their young counterparts, may have increased double support in response to the more destabilizing treadmill task. Reduction in step length and associated step velocity also support this hypothesis because these responses have previously been reported as safety-related adaptations.[4, 7, 28, 29] Whittle[4] identified typical age-related changes in spatio-temporal parameters as including reduced step length and associated walking velocity, increased step width and greater double support duration. These responses were also seen here when comparing older adults’ overground walking to their treadmill gait. It is, therefore, reasonable to conclude that treadmill walking challenged the healthy older adults recruited for this study. If the link between spatio-temporal asymmetry and age-related gait deterioration is further confirmed, portable gait assessment tools such as the Gaitrite system could be used in clinical settings to identify individuals with higher falls risk.

In summary, the results supported the asymmetry hypothesis in older adults' gait, with significantly lower velocity and spatially shorter steps for the non-dominant limb on both surfaces, supporting the 'functional asymmetry' hypothesis proposed by Sadeghi[11] in which step asymmetry is functional in assigning the dominant limb a primary role in progression while the non-dominant limb stabilizes or "secures" gait. In the data presented here, however, there was no evidence to support the proposition that the non-dominant limb serves a "gait securing" function. Older individuals increased step time in treadmill walking while young controls decreased step time but both groups decreased step length relative to overground locomotion. In older adults, relative to overground gait, increased double support and reduced swing time (percentages) in both limbs were found in treadmill walking.

References

1. Berg, W.R., Alessio, H.M., Mills, E.M., & Tong, C. (1997). Circumstances and consequences of falls in independent community dwelling older adults. *Age and Ageing*, 26, 261-268. **[journal article]**

2. Perry, M.C., Carville, S.F., Smith, I.C.H., Rugherford, O.M., & Newham, DiJ. (2007). Strength, power output and symmetry of leg muscles: effect of age and history of falling. *European Journal of Applied Physiology, 100,* 553-561. **[journal article]**

3. Kirkwood, R.N., Moreira, B.S., Vallone, M.L.D.C., Mingoti, S.A., Dias, R.C., & Sampaio, R.F. (2010). Step length appears to be a strong discriminant gait parameter for elderly females highly concerned about falls: across-sectional observational study. *Physiotherapy, 97,* 126-131. **[journal article]**

4. Whittle M. (2007). Gait analysis: an introduction. 4th edition. *Butterworth-Heinemann Elsevier*.**[entire book]**

5. Brujin, S.M., vanDieën, J.H., Meijer, O.G., & Beek, P.J. (2009). Is slow walking more stable? *Journal of Biomechanics, 42,* 1506-1512. **[journal article]**

6. Espy, D.D., Yang, F., Bhatt, T., & Pai, Y-C. (2010). Independent influence of gait speed and step length on stability and fall risk. *Gait and Posture, 32,* 378-382. **[journal article]**

7. Menz, H.B., Lord, S.R., & Fitzpatrick, R.C. (2007). A structural equation model relating

impaired sensorimotor function, fear of falling and gait patterns in older people. *Gait and Posture, 25,* 243-249. **[journal article]**

8. Prince, F., Corriveau, H., Hebert, R., & Winter, D.A. (1997). Gait in the elderly: Review article. *Gait and Posture, 5,* 158-135. **[journal article]**

9. Rochart, S., Bula, C.J., Martin, E., Seematter-Bagnoud, L., Karmaniola, A., Aminian, K., Piot-Ziegler, C., & Santos-Eggimann, B. (2010). What is the relationship between fear of falling and gait in well-functioning older persons aged 65 to 70 years? *Archives of Physical Medicine and Rehabilitation, 91,* 879-884. **[journal article]**

10. Sadeghi, H., Allard, P., & Duhaime, M., (1997). Functional gait asymmetry in able-bodied subjects. *Human Movement Science. 16,* 243-258. **[journal article]**

11. Sadeghi, H., Allard, P., Prince, F., & Labelle, H. (2000). Symmetry and limb dominance in able-bodied gait: a review. *Gait and Posture, 12,* 34-45. **[journal article]**

12. Sadeghi, H. (2003). Local or global asymmetry in gait of people without impairments. *Gait and Posture, 17,* 197-204. **[journal article]**

13. Du Chatinier, K., & Rozendal, R. (1970). Temporal symmetry gait of selected normal subjects. *Anatomy, 73,* 353-361. **[journal article]**

14. Rosenrot, P. (1980). Asymmetry of gait and the relationship to lower limb dominance.

Proceeding of the special conference of the Canadian Society of Biomechanics, 26-27. **[conference paper]**

15. Seeley, M.K., Umberger, B.R., & Shapiro, R. (2008). A test of the functional asymmetry hypothesis in walking. *Gait and Posture*, *28,* 24-28. **[journal article]**

16. Hill, K., Schwarz, J., Flicker, L., & Carroll, S. (1999). Falls among healthy, community-dwelling, older women: a prospective study of frequency, circumstances, consequences and prediction accuracy. *Australian and New Zealand Journal of Public Health, 23,* 41-48. **[journal article]**

17. Di Fabio, R.P., Kurszewski, W.M., Jorgenson, E.E., & Kunz, R.C. (2004). Footlift asymmetry during obstacle avoidance in high-risk elderly. *Journal of American Geriatrics Society, 52,* 2088-2093. **[journal article]**

18. Matsas, A., Taylor, N., & McBurney, H. (2000). Knee joint kinematics from familiarised treadmill walking can be generalised to overground walking in young unimpaired subjects. *Gait and posture, 11,* 469-53. **[journal article]**

19. Wass, E., Taylor, N., & Matsas, A. (2005). Familiarisation to treadmill walking in unimpaired older people. *Gait and Posture, 21,* 72-79. **[journal article]**

20. Dingwell, F.N., & Marin, L.C. (2006). Kinematic variability and local dynamic stability of upper body motions when walking at different speeds. *Journal of Biomechanics*, *39,* 444-452. **[journal article]**

21. England, S.A., & Granata, K.P. (2007). The influence of gait speed on local dynamic stability of walking. *Gait and Posture*, 25, 172-178. **[journal article]**

22. Jordan, K., Challis, J.H., & Newell, K.M. (2007). Walking speed influences on gait cycle variability. *Gait and Posture*, 26, 128-134. **[journal article]**

23. Cappozzo, A., Della C.U., Leardini, A., & Chiari, L. (2005), Human movement analysis using stereophotogrammetry: Part 1: theoretical background. *Gait and Posture*, 21, 186-196. **[journal article]**

24. Mathie, M.J., Coster, A.C.F., HLovell, N., & GCeller, B. (2004). Accelerometry: providing an intergrated practical method for long-term, ambulatory monitoring of human movement. *Physiological Measurement, 25*, R1-R20. **[journal article]**

25. O'Connor, C.M., Thorpe, S.K., O'Malley, M.J., & Vaughan, C.L. (2007). Automatic detection of gait events using kinematic data. *Gait and Posture, 25*, 469-474. **[journal article]**

26. Kerrigan, D., Lee, L., Collins, J., Riley, R., & Lipsitz, L. (2001). Reduced hip extension during walking: Healthy elderly and fallers versus young adults. *Archives of Physical Medicine and Rehabilitation*, 82, 26-30. **[journal article]**

27. Riley, P.O., Paolini, G., Croce, U.D., Paylo, K.W., & Kerrigan, D.C. (2007). A kinematic and kinetic comparison of overground and treadmill walking in healthy subjects. *Gait and Posture, 26,* 17-24. **[journal article]**

28. Herman, T., Giladi, N., Gurevich, T., & Hausdorff, J.M. (2005). Gait instability and fractal dynamics of older adults with a “cautious” gait: why do certain older adults walk fearfully? *Geriatric Nursing*, 23, 250-257. **[journal article]**

29. Kang, H.G., Dingwell, J.B. (2008). Separating the effects of age and walking speed on gait variability, *Gait and Posture*, 27, 572-577. **[journal article]**

Figure Captions

Figure 1. The stance and swing phases of a complete walking cycle defined by successive heel contacts of the same limb. Steps are identified for the dominant (D) and non-dominant (N) limbs with each step subdivided into double support time (DST) and swing time (SwgT). Step length is the anterior-posterior displacement of one step; step time is the time to complete one step, the sum of DST and SwgT

Figure 2. Dominant and non-dominant step parameters for treadmill and overground walking at self-selected speed for older adults and young controls. An asterisk (*) indicates a significant between-limb difference associated with an age x limb interaction; error bars indicate one standard deviation. Figure 2A: step velocity, step length, and step width; Figure 2B: step time, double support time and swing time.

Figure 3. Double support time and swing time (%) relative to step time (100%) for dominant and non-dominant steps; conventions as in Figure 2. Asterisk (*) indicates significant age x surface interaction.

Figure 1

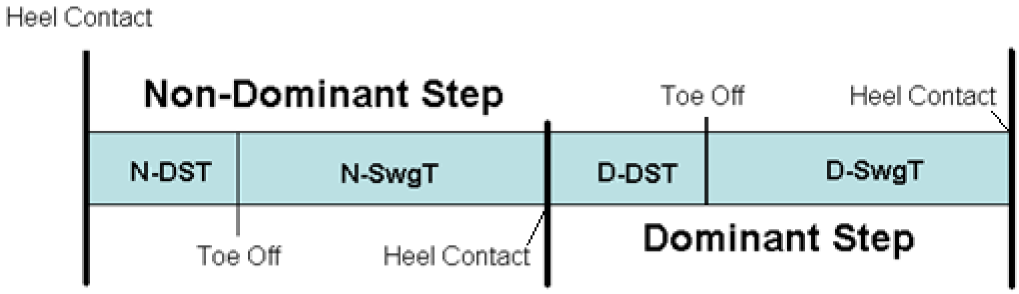

Heel Contact
Non-Dominant Step
Toe Off
Heel Contact
N-DST
N-SwgT
D-DST
D-SwgT
Toe Off
Heel Contact
Dominant Step

Figure 2

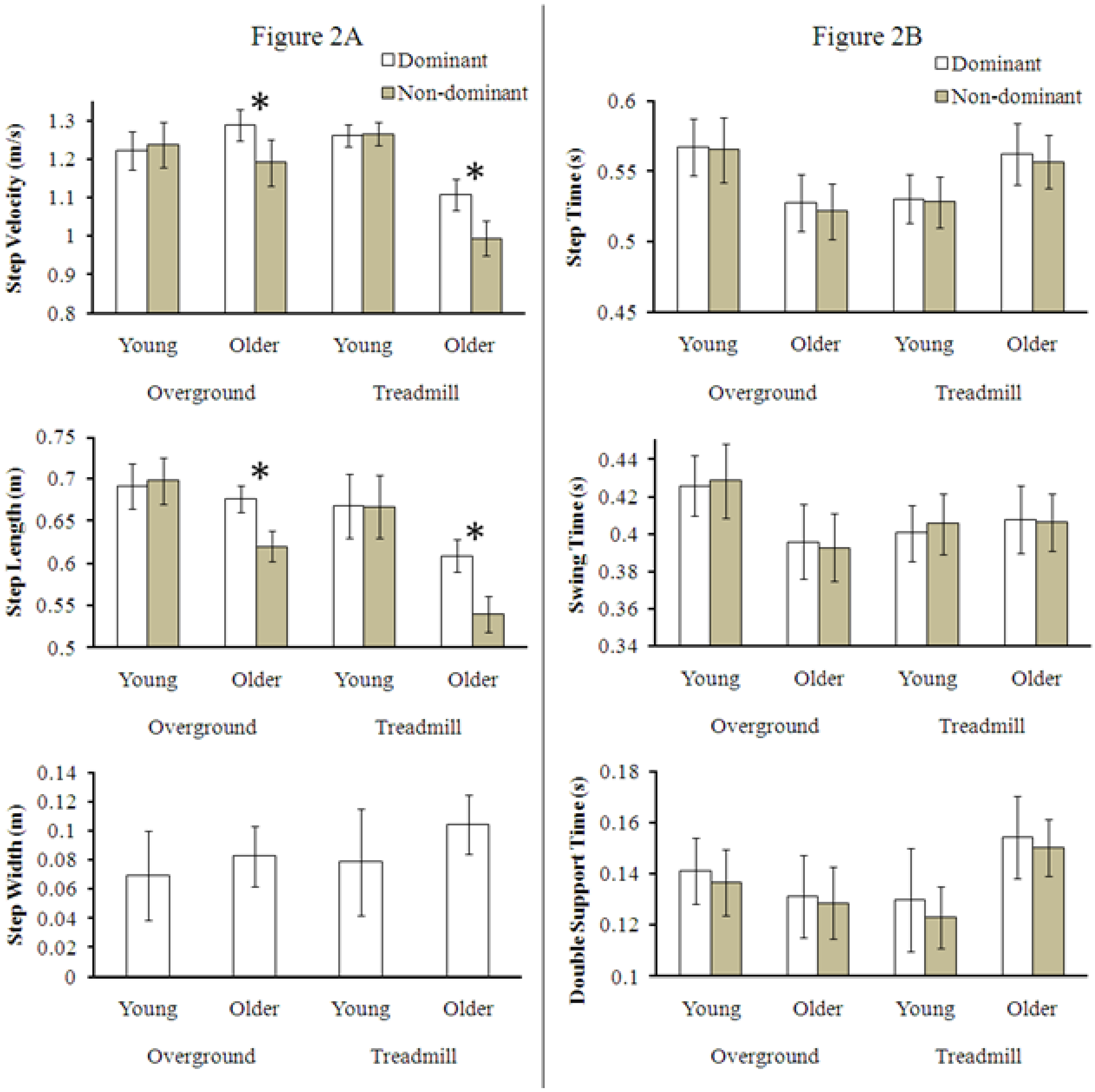
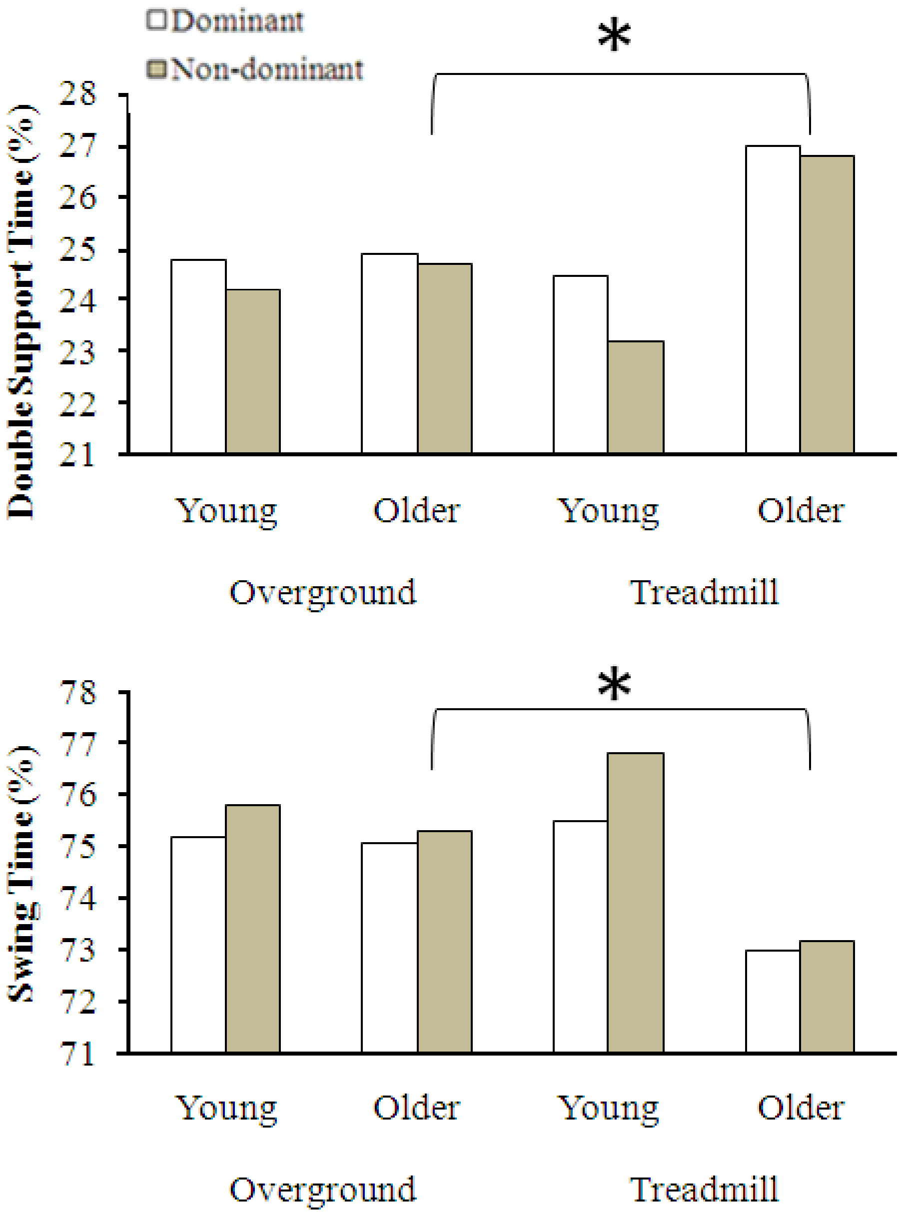


Figure 2A
☐Dominant
▨Non-dominant
Step Velocity (m/s)
1.3
1.2
1.1
1
0.9
0.8
Step Length (m)
0.75
0.7
0.65
0.6
0.55
0.5
Step Width (m)
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
*
Young
Older
Overground
Treadmill
Figure 2B
☐Dominant
▨Non-dominant
Step Time (s)
0.6
0.55
0.5
0.45
Swing Time (s)
0.44
0.42
0.4
0.38
0.36
0.34
Double Support Time (s)
0.18
0.16
0.14
0.12
0.1

Figure 3


□ Dominant
▨ Non-dominant
*
Double Support Time (%)
28
27
26
25
24
23
22
21
Young
Older
Young
Older
Overground
Treadmill
*
Swing Time (%)
78
77
76
75
74
73
72
71
Young
Older
Young
Older
Overground
Treadmill