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Original Article

Differences in Kinematic and Electromyographic Characteristics Between Young and Older Adults During Circular Turning☆

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SUMMARY

Background: Direction change while walking is a complex task of locomotor activity and is necessary during daily activities, but little is known about whether aging alters turn-related characteristics compared with straight walking. The objective of this study was to investigate the effects of aging on the biomechanical characteristics and walking velocity during circular turning.
Methods: The participants included 17 healthy older adults (65–80 years old) and 16 young adults. Walking velocity, the first and second peak knee flexion, ankle plantarflexion, ankle dorsiflexion, and electromyographic amplitudes of the rectus femoris, biceps femoris, tibialis anterior, and gastrocnemius medialis were measured during walking along a 5 m straight path and a 5 m circumference curved path with a radius of 0.8 m.
Results: The two groups made comparable decreases in turning velocity as compared with straight walking, but older adults decreased the second peak knee flexion instead of the second peak ankle plantarflexion, and the knee remained flexed during the loading response. Older people also needed higher amplitudes of the tibialis anterior in the outer leg, and biceps femoris in the inner leg, to facilitate turning, which were not seen in young adults. Moreover, older adults did not decrease amplitudes of the rectus femoris and biceps femoris in the outer leg, and tibialis anterior in the inner leg, as noted in young adults.
Conclusion: Aging does not exert further effects on turning velocity, but older adults use different biomechanical strategies to turn.

1. Introduction

Direction change while walking is a complex task of locomotor activity, and is necessary during daily activities[1]. Previous research has shown that self-selected velocity while walking along a circular path (circular turning) was significantly slower than walking straight ahead[2]. Additionally, side-specific modulations of the muscle synergies during circular turning were observed[1,3]. For the outer leg, stronger plantarflexor actions are required to propel the body, due to the longer path needed to travel along the turning trajectory. For the inner limb, increased muscle activities around the knee, during the stance phase of turning, are needed for body support and knee control. Furthermore, a greater threat to balance emerges because the body center of mass leans towards the inner side of the turning path.

Age-related changes in the muscular activation of walking are clearly present among active and healthy older adults[4]. Compared to young adults, older adults exhibited increased coactivation across the ankle and knee joints, which likely contributes to reduced power during the push-off phase of the gait cycle. In addition, studies have shown that healthy older adults, compared to young adults, exhibited different knee and ankle joint angles while straight walking[5]. These included decreases in knee flexion at the loading phase and reductions in knee flexion and ankle plantarflexion in the push-off phase of the gait cycle. With the prominent contributors of the knee and ankle joints to body support and

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propulsive forces during turning, the comprised muscular activities and joint angles due to aging, may affect the extent to which healthy older adults are able to modulate their locomotor patterns to achieve circular turning.

Numerous studies indicated that older adults took more time, but used a strategy with less stability and greater biomechanical cost, to change directions[1,6,7]. However, little is known about the effects of aging on kinematic characteristics or muscle patterns in the lower extremities during turning, although such aging effects on kinematic characteristics and muscle activities during straight walking have been noted.

The purpose of this study was to investigate the aging effects on turning-related strategies. Both healthy older and young adults were recruited. In addition to walking velocity, we documented kinematic and electromyographic (EMG) data of the lower extremities during circular turning and straight walking. Because slower turning velocity is also the turn-related modulation in young adults, we hypothesized that aging may not exert further effects on turning velocity, but may alter more turning-related characteristics of joint angles and muscle activities of the lower extremities compared with straight walking.

2. Methods

2.1. Participants

Seventeen older adults (8 males, 9 females; age: 65−80 years) and 16 young adults (8 males, 8 females; age: 21−25 years) volunteered for this study (Table 1). The participants had no history of medical problems affecting their balance or walking performance. The study was approved by the Institutional Review Board of Mackay Memorial Hospital and all was explained to the participants prior to the study.

2.2. Experimental protocol

Participants walked three times along a 5 m long straight path (straight walking, Fig. 1) and a 5 m circumference curved path, with a radius of 0.8 m (circular turning), in a random sequence, at a self-selected, comfortable speed. Walking velocity was measured by a stopwatch. Kinematic and EMG data were simultaneously obtained using the BIOPAC MP150WMW System (BIOPAC System Inc., Goleta, CA, USA) and AcqKnowledge software, with a sampling rate of 1000 Hz. Based on our pilot work, there was no difference in walking velocity, kinematics, or EMG between right and left turns, so turning to the right was used to document the turning characteristics in this study. The right leg was referred to as the inner leg and the left leg as the outer leg.

Table 1
Basic data of the participants.

	Young group ($n = 16$)	Older group ($n = 17$)	p^*
Sex (male/female)	8/8	8/9	0.866
Age (y)	23.9 ± 3.3	71.8 ± 5.2	<0.001
Height (cm)	165.3 ± 7.2	160.8 ± 6.6	0.072
Weight (kg)	58.3 ± 7.5	63.4 ± 7.7	0.063
Dominant leg (right/left)	13/3	14/3	0.935
Walking velocity during straight walking	1.4 ± 0.2	1.1 ± 0.1	<0.001
Walking velocity during turning	1.2 ± 0.2	0.9 ± 0.2	<0.001

Note: Values are mean ± standard deviation.
*p values for young and older group comparisons.

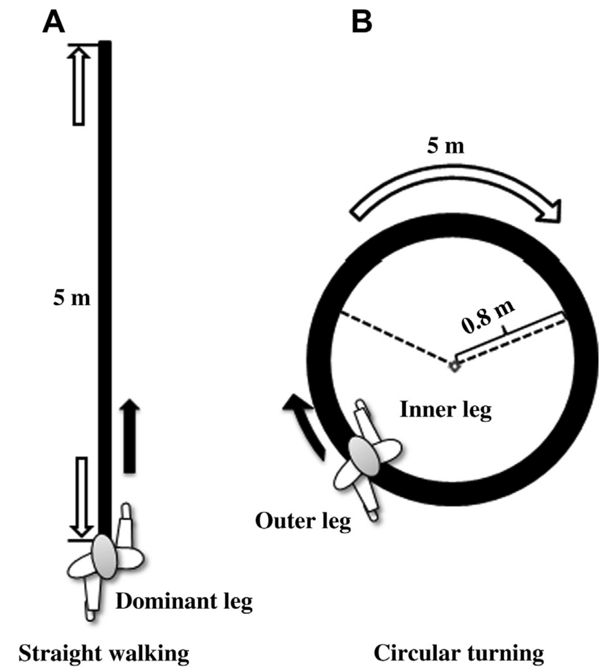

Fig. 1. Depiction of the locomotor tasks. The walkway used for (A) straight walking and (B) circular turning.

2.3. Measures

Walking velocity: Walking velocity was derived from dividing the distance (5 m) by the time needed to complete the locomotor tasks.

Kinematics: Four electrogoniometers (Biometrics Ltd, Ladysmith, VA, USA) were placed on the knee and ankle joints of each leg, to measure joint angles during walking. The electrogoniometer had two end blocks: a telescopic and a fixed end block, joined by an instrumented spring with a strain gauge[8]. For measuring the knee joint angle, the fixed end block paralleled with the line of the greater trochanter and lateral epicondyle of the femur, and the telescopic end block paralleled with the line of the lateral malleolus and lateral epicondyle[9]. For measuring the ankle joint angle, the fixed end block paralleled with the line of the fifth metatarsal head and lateral malleolus, and the telescopic end block paralleled with the line of the head of fibula and lateral malleolus[9]. Six peak values of joint angles, the first and second peak knee flexion, the first and second peak ankle plantarflexion, and the first and second peak ankle dorsiflexion, during each gait cycle, were calculated offline. FlexiForce footswitches (Tekscan, Boston, MA, USA) placed beneath each heel were used to identify heel strikes for time normalization of the kinematic data. The gait cycle was defined as the time interval between two successive heel strikes of one leg.

EMG: The skin was shaved and cleaned with alcohol swabs, before applying 11 mm Ag−AgCl surface electrodes (BIOPAC System Inc., Goleta, CA, USA) for recording EMG. Surface EMG from the following muscles were recorded in each leg: rectus femoris (RF), biceps femoris (BF), tibialis anterior (TA), and gastrocnemius medialis (GM). Electrode placements for these muscles were in accordance with recommendations from the Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles committee[10]. All EMG data were band-pass filtered (40−400 Hz) and full-wave rectified. Then, a second-order Butterworth low-pass filter, with a cutoff frequency of 9 Hz, was used to produce a linear envelope representation[11]. Footswitch data were also used for time normalization. The amplitude of muscle bursts during each gait cycle was computed by integrating the activity of each individual EMG burst during the time interval (onset-end) defined during walking along each locomotor path, as described below. Onset and offset of the EMG burst were established at points in which the muscle activity exceeds and falls below the mean activity, respectively, plus three standard deviations were recorded during a period when these muscles are least active[12]. The amplitudes of RF, BF, and GM (A_{RF}, A_{BF}, and A_{GM}) from onset to offset of bursts were calculated. The amplitude of TA (A_{TA}) was calculated from the onset of burst to the end of the swing phase. The amplitude of EMG activity of each muscle was normalized to the mean activity of the same muscle in the dominant leg during straight walking, for further statistical analysis. This method of amplitude normalization was chosen, to explore whether there are more alterations in muscle activities during circular turning compared with straight walking, since aging effects on muscle activities during straight walking have been noted.

2.4. Statistical analysis

All data were analyzed using SPSS version 16.0 statistical software (SPSS Inc, Chicago, IL, USA). Descriptive statistics are expressed as means ± standard deviations for all variables. To examine whether aging exerts further effects on turning compared with straight walking, a repeated-measures analysis of variance, with task (straight walking vs. turning activity) as the within-participant factor and participant group (young adults vs. older adults) as the between-group measure, were first performed for walking velocity and kinematic data. Data from the outer and inner legs during turning were compared, respectively, with the dominant leg during straight walking. If an interaction was indicated by the repeated-measures analysis of variance, *post hoc* comparisons (with Bonferroni correction) were used for within-participant comparisons. Due to the fact that the *post hoc* comparisons were for the outer leg and inner leg, respectively, the statistical significance was corrected to $p < 0.025$. Because the EMG amplitude of each muscle was normalized to the mean activity of the same muscle in the dominant leg during straight walking, EMG amplitudes were then analyzed by paired *t* tests for within-participant comparisons. Statistical significance was set at $p < 0.05$.

3. Results

3.1. Walking velocity

Walking velocities during straight walking and turning were 1.4 ± 0.2 m/sec and 1.2 ± 0.2 m/sec, respectively, for young adults, and 1.1 ± 0.1 m/sec and 0.9 ± 0.2 m/sec, respectively, for older adults. No significant interaction effect was noted. There were significant main effects of group ($F_{1,31} = 26.7$, $p < 0.001$) and task ($F_{1,31} = 76.7$, $p = <0.001$) for walking velocity, but the two groups made comparable decreases in walking velocity while comparing turning activity with straight walking.

3.2. Kinematics

Ensemble-averaged joint angles for young and older groups over one complete time-normalized gait cycle (100%) are presented in Table 2.

There was a significant interaction effect for the first peak knee flexion of the outer leg ($F_{1,31} = 25.3$, $p < 0.001$), whereby young adults decreased the first peak knee flexion of the outer leg during circular turning (16.5 ± 4.2°) compared with straight walking (21.9 ± 4.0°, $p = 0.001$), but older adults demonstrated increases (straight walking: 18.6 ± 4.3°, turning: 21.3 ± 3.2°, $p = 0.007$). There was also a significant interaction effect for the first peak knee flexion of the inner leg ($F_{1,31} = 12.6$, $p = 0.001$). Young adults demonstrated a lower first peak knee flexion of the inner leg during turning (18.1 ± 4.8°, $p < 0.001$) than that during straight walking, but older adults did not change accordingly (turning: 17.8 ± 3.9°).

There was a significant interaction effect for the second peak knee flexion of the outer leg ($F_{1,31} = 10.7$, $p = 0.003$). Young adults did not alter the second peak knee flexion of the outer leg during turning (66.0 ± 6.0°) compared with straight walking (65.3 ± 5.2°), but older adults showed decreases (straight walking: 66.9 ± 4.9°, turning: 63.9 ± 5.7°, $p = 0.005$). There was also a significant interaction effect for the second peak knee flexion of the inner leg ($F_{1,31} = 7.2$, $p = 0.012$). The second peak knee flexion of the inner leg during turning (67.0 ± 6.1°) was not different from that during straight walking in young adults, but older adults showed decreases (turning: 63.4 ± 6.2°, $p = 0.024$).

There was a significant interaction effect for the second peak ankle plantarflexion of the inner leg ($F_{1,31} = 12.9$, $p = 0.001$). While young adults decreased the second ankle plantarflexion of the inner leg during turning (−5.3 ± 4.7°) compared with straight walking (−14.3 ± 5.1°, $p < 0.001$), older adults did not change significantly (straight walking: −8.1 ± 6.2°, turning: −5.5 ± 3.1°).

There were no significant interaction effects for the second peak ankle plantarflexion of the outer leg, the first peak ankle plantarflexion of both legs, the first peak ankle dorsiflexion of both legs, or the second peak ankle dorsiflexion of both legs.

Table 2
Kinematic and electromyographic characteristic of participants.

	Young group ($n = 16$)			Older group ($n = 17$)		
	Dominant leg	Outer leg	Inner leg	Dominant leg	Outer leg	Inner leg
Joint angles (degree)						
1st peak knee flexion	21.9 ± 4.0	16.5 ± 4.2	18.1 ± 4.8	18.6 ± 4.3	21.3 ± 3.2	17.8 ± 3.9
2nd peak knee flexion	65.3 ± 5.2	66.0 ± 6.0	67.0 ± 6.1	66.9 ± 4.9	63.9 ± 5.7	63.4 ± 6.2
1st peak ankle plantarflexion	−8.7 ± 1.5	−6.8 ± 1.1	−8.4 ± 2.2	−7.9 ± 1.2	−6.6 ± 1.0	−6.6 ± 0.8
1st peak ankle dorsiflexion	7.7 ± 3.0	2.6 ± 2.8	8.9 ± 2.2	11.4 ± 2.5	6.6 ± 3.5	11.0 ± 3.2
2nd peak ankle plantarflexion	−14.3 ± 5.1	−11.8 ± 5.3	−5.3 ± 4.7	−8.1 ± 6.2	−8.9 ± 5.4	−5.5 ± 3.1
2nd peak ankle dorsiflexion	1.7 ± 2.6	0.1 ± 2.2	2.8 ± 2.7	3.7 ± 2.3	0.6 ± 2.8	3.2 ± 3.1
Electromyographic amplitudes						
Bicep femoris	1.0 ± 0.0	0.6 ± 0.2	1.1 ± 0.3	1.0 ± 0.0	0.9 ± 0.2	1.2 ± 0.3
Rectus femoris	1.0 ± 0.0	0.8 ± 0.1	0.9 ± 0.2	1.0 ± 0.0	1.0 ± 0.3	0.9 ± 0.3
Gastrocnemius medialis	1.0 ± 0.0	1.1 ± 0.2	0.8 ± 0.1	1.0 ± 0.0	1.2 ± 0.2	0.8 ± 0.3
Tibialis anterior	1.0 ± 0.0	1.0 ± 0.1	0.9 ± 0.2	1.0 ± 0.0	1.1 ± 0.2	1.0 ± 0.1

Note: Values are mean ± standard deviation. Electromyographic amplitudes are normalized on the averaged activity computed for each leg and subject during straight walking.

3.3. EMG

Ensemble-averaged EMG waveforms for each group over one complete time-normalized gait cycle (100%) are presented in Table 2. During turning, the A_{BF} and A_{RF} of the outer leg decreased in young adults (A_{BF}: 0.6 ± 0.2, A_{RF}: 0.8 ± 0.1, $p < 0.001$ for both), but did not change in older adults (A_{BF}: 0.9 ± 0.2, A_{RF}: 1.0 ± 0.3), compared with straight walking. Young adults showed no change in the A_{BF} of the inner leg (1.1 ± 0.3), but older adults significantly increased the A_{BF} of the inner leg (1.2 ± 0.3, $p = 0.012$). The A_{TA} in the outer leg remained unchanged in young people (1.0 ± 0.1), but increased in older people (1.1 ± 0.2, $p = 0.042$). Moreover, the A_{TA} in the inner leg decreased in young adults (0.9 ± 0.2, $p = 0.004$), but remained unchanged in older adults (1.0 ± 0.1). Both groups showed an increase in the A_{GM} of the outer leg (young: 1.1 ± 0.2, $p = 0.039$; older: 1.2 ± 0.2, $p = 0.007$), and a decrease in the A_{GM} of the inner leg (young: 0.8 ± 0.1, $p < 0.001$; older: 0.8 ± 0.3, $p = 0.009$), but did not show changes in the A_{RF} of the inner leg (young: 0.9 ± 0.2, older: 0.9 ± 0.3) during turning as compared with straight walking.

4. Discussion

This study examined the aging effects on turning-related strategies. We noted that aging did not exert further effects on the turning velocity. However, older adults adopted an increase in the first peak knee flexion in the outer leg, a decrease in the second peak knee flexion in both legs, increased the A_{TA} in the outer leg, and increased the A_{BF} in the inner leg during circular turning, all of which were not seen in young adults. Additionally, older adults showed no decreases in the first peak knee flexion and the second peak plantarflexion of the inner leg, nor did they show a decreased A_{TA} in the inner leg, and A_{RF} and A_{BF} in the outer leg during circular turning, as was observed in young adults.

Both age groups made comparable decreases in walking velocity when turning compared with straight walking. Paquette et al[13] indicated that older adults walked with a slower velocity in both straight and turn trials, suggesting that the slower velocity is a strategy to achieve a more conservative or less destabilizing gait for older adults. Although there was no further effect of aging on turning velocity, age-related differences during turning were characterized by kinematic and EMG manifestations.

The main role of the first peak knee flexion during the loading-response phase is to assist weight bearing[14]. The needs of weight acceptance decrease when walking velocity becomes slow. Our data show that both groups walked more slowly during circular turning compared with straight walking, but older adults did not decrease the degree of knee flexion in both legs, as noted in young adults. In addition, older persons exhibited higher activation of knee flexors (A_{BF}) in the inner legs. Therefore, older individuals may favor a flexed-knee gait to assist weight acceptance during circular turning[5]. To facilitate turning, the flexed-knee gait may also compensate for the decreased spinal flexibility usually seen in older adults[15].

Muscle coactivation around the knee has been observed as a task-independent strategy to enhance stability[4]. The need for coactivation is decreased during turning, because of slower walking velocity and a shorter stance duration of the outer leg[12]. Young adults decreased coactivation in the A_{RF} and A_{BF} of the outer leg during turning accordingly, but older adults maintained the same amount of coactivation in the RF and BF of the outer leg during turning, perhaps for more stability. However, higher levels of muscle coactivation around the knee have been described as a potential contributor to the higher metabolic cost of walking in older adults. In addition, advanced age is related to a decline in maximum metabolic capacities. The likelihood of fatigue for older adults to perform a turning activity warrants notice, since fatigue is one possible factor for fall, especially for older people[16,17].

While walking along the circular path, the body center of mass shifts directly over the inner foot, and greater propulsion forces are provided by the outer leg to generate centripetal forces for the direction change[2,18]. To adapt locomotor patterns to circular turning, older people increased the A_{GM} of the outer leg and decreased the A_{GM} of the inner leg. These opposite adaptations in plantarflexor activity in older adults were the same as changes demonstrated in young adults in the present study and those of others[3,12]. An increase in plantarflexor activity of the outer leg may facilitate the segments to rotate in the direction of travel. Less propulsion force is needed for the inner leg during circular turning, and the A_{GM} is then adjusted accordingly.

We also noted that the accompanied decrease in the second peak ankle plantarflexion occurred in the inner leg of the young group during circular turning. This pattern of ankle range seen in the inner leg of young people is a novel finding. The reduced ankle plantarflexion may be associated with less propulsion force needed for the smaller step of the inner leg during circular turning[12]. Another possibility, is that this modulation in the inner leg is to maintain greater foot—floor contact for an increased base of support at the terminal stance phase[19], given that a greater threat to balance emerges during turning. In contrast, older adults did not change the second peak ankle plantarflexion to increase stability in the pre-swing phase, but decreased the second peak knee flexion in the subsequent initial swing phase. The second peak knee flexion of the swing leg occurs in the single-stance phase of the contralateral leg, so reduced knee flexion could decrease the need for balance maintenance during turning in older people. Therefore, it seems that older persons adopt a knee rather than an ankle strategy to maintain balance during circular turning. However, flexion of the knee is of primary importance while crossing obstacles, which have also been identified as common causes of falls in older persons[20]. Further studies are encouraged to investigate whether the decreased knee flexion adopted for regular turning activity in older people increases the risk of fall, especially when encountering turning-related obstacles.

The onset of TA activity follows the moment of push off to reverse ankle plantarflexion into dorsiflexion for subsequent floor clearance[14]. In young adults, the second peak ankle plantarflexion was decreased for balance maintenance, and thus the following A_{TA} was decreased in the inner leg. In older adults, the A_{TA} of the inner leg did not change, because they adopted a knee strategy instead of an ankle strategy for turning, as described above. Older adults also recruited an increased A_{TA}, to fulfill the higher swing velocity of the outer leg. Taken together, older adults recruited relatively more A_{TA} in both legs during comfortable turning. However, an age-related deficit in the TA for rapid, repetitive contractions has been identified[21]. It is not immediately clear whether the higher demand of the A_{TA} during comfortable turning in older adults will increase the risk of fall during fast turning.

Since turning has recently been included in developing the reliable index for falls in older people[22], these age-related characteristics of turning could provide information concerning the cause of falling or falls prevention programs for older adults in the future.

5. Limitations

Several limitations need to be noted in this study. First, we only investigated turning characteristics during a comfortable speed. It is not known whether speed differences would affect our studied characteristics. Second, the small sample size may limit generalizations of our results. Furthermore, the frontal and transverse plane kinematics, in addition to sagittal plane kinematics, should also be considered to fully present the turning task.

6. Conclusion

In this study, we found that aging did not exert further effects on the turning velocity. However, older adults adopted a decreased range of the knee instead of the ankle during the swing phase, and the knee remained flexed during the loading response phase. In addition, older people needed more muscle activities of the lower extremities to facilitate turning. Our results provide an understanding of age-related biomechanical strategies in turning modulation. We hope that these findings will pave the way for further exploration of the risk of falls, especially during fast turning or when encountering turning-related obstacles.

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