Journal of Biomechanics 74 (2018) 163–170

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Decrease in required coefficient of friction due to smaller lean angle during turning in older adults

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ARTICLE INFO

Article history:
Accepted 22 April 2018

Keywords:
Slips and falls
Required coefficient of friction
Turn
Aging
Mediolateral direction

ABSTRACT

We investigated age-related differences in the required coefficient of friction (RCOF) during 90° turning, the difference of RCOF during step and spin turn, and how affects observed differences. Sixteen healthy young and healthy older adults (eight men and eight women in each group) participated. Participants performed 90° step and spin turns to the right at a self-selected normal speed. Older adults turned with lower RCOF than the young adults during both step and spin turns. This was associated with reduced mediolateral (ML) RCOF component ($RCOF_{ML}$) for the older adults. Reduced $RCOF_{ML}$ in older adults was associated with reductions in the ML component of the lean angle of the body during turning. This age-related gait changes during turning can be compensatory mechanisms that allowed older adults to turn while reducing the risk of slipping. Spin turns exhibited lower RCOF, resulting from significantly lower $RCOF_{ML}$, than step turns in young and older adults; thus, spin turning is a safer turning strategy for preventing lateral slips. This may suggest that, in older adults, slip prevention may take precedence over balance recovery after slips sustained during turning. These results illustrate a turning gait mechanism that helps prevent slips and falls, and how age affects this mechanism.

1. Introduction

Fall-related injuries are a serious public health problem among older (aged 65 years and over) adults. Hip fractures and head traumas that result from falls can reduce both mobility and independence (Stevens et al., 2006; Ambrose et al., 2013). It is estimated that one in three older adults falls at least once per year (Hausdorff et al., 2001). The cost of fall-related injuries is increasing as the elderly population increases (Englander et al., 1996); these costs in turn increase the total medical costs to society (Stevens et al., 2006).

Slips are a leading cause of falling accidents among older adults (Luukinen et al., 2000; Rubenstein, 2006). To avoid slips, the ratio of the tangential force to the vertical force applied to the floor (i.e., the *traction coefficient*), must be lower than the friction coefficient at the shoe–floor interface during the stance phase. The traction coefficient can be calculated by dividing the horizontal ground reaction force (GRF) by the vertical GRF. The peak traction coefficient observed just after heel contact (Redfern and Andres, 1984) is called the *required coefficient of friction* (RCOF). RCOF is necessary for preventing forward slips during the braking phase, and is used to predict slipping risk (Hanson et al., 1999; Beschorner et al., 2016). Therefore, gait with lower RCOF reduces the risk of slipping when walking.

In daily life, turns, straight steps, and non-straight steps are common (Glaister et al., 2007). However, slips and falls during non-straight steps are poorly investigated, and the mechanisms that contribute to slips during gait remain unexplored, particularly among the elderly. Only a few research studies have investigated RCOF during turning by conducting turning gait trials with young adults (Yamaguchi et al., 2013, 2017; Fino et al., 2015). These studies have indicated that, compared with straight walking, turning requires greater RCOF. This suggests that turning gait may carry a higher risk of slipping than straight gait. Yamaguchi et al. (2017) suggested that this is because of the increased mediolateral (ML) component of RCOF ($RCOF_{ML}$), which is due to the increased lean angle of body [i.e., body center of mass (COM) and center of pressure (COP) angles], that produces the increased centripetal force needed for turning. Therefore, slips are more likely to occur

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https://doi.org/10.1016/j.jbiomech.2018.04.038
0021-9290/

laterally, during turning, than during straight walking (Yamaguchi et al., 2012, 2016).

Older adults walk with decreased speed and shorter step lengths than young adults (Hageman and Blanke, 1986; Menz, et al., 2003); thus, it is assumed that older adults will exhibit slower turning speeds and shorter turning radii than young adults. Because centripetal force is proportional to the square of the turning speed and the inverse of the turning radius, the centripetal force during turning will differ across age groups, thereby affecting the ML component of the COM–COP angle and the RCOF during turning in adults. Burnfield et al. (2005) indicated RCOF during a 90° turn was significantly lower for older adults than for young adults. They stated that this lower RCOF was attributed to the slower turning speed exhibited by older adults; however, they didn't quantitatively investigate the effects of age-related difference in turning speed on RCOF. This age-related RCOF difference could be due to a difference in the ML and anteroposterior (AP) components of RCOF, resulting from a difference in ML and AP COM–COP angles. However, no study has investigated this hypothesis.

Turning gait can be classified into two strategies: spin turns (ipsilateral turns) and step turns (Hase and Stein, 1999; Taylor et al., 2005). The step turn involves a change in the direction opposite of the stance limb, whereas the spin turn involves a change in the direction toward the stance limb. Akram et al. (2010) found that healthy older adults preferred spin turning. However, it is unknown which turning strategy helps prevent slipping in older adults.

This study sought to investigate (1) the age-related effects on RCOF during turning; (2) the differences in RCOF during step and spin turning, and the age-related effects on these differences.

2. Methods

2.1. Subjects

This study included 16 healthy young adults (Yamaguchi et al., 2017) and 16 healthy older adults (eight men and eight women in each group). The experimental data for young adults were acquired in our previous study (Yamaguchi et al., 2017). For young adults, the age, height, and body mass were 21.4 ± 1.2 years, 1.65 ± 0.08 m, and 60.1 ± 7.4 kg (mean ± standard deviation), respectively. For older adults, the corresponding values were 71.8 ± 4.5 years, 1.58 ± 0.07 m, and 63.2 ± 11.6 kg. Participants were informed of the protocol and gave written informed consent prior to the experiment. The protocol was approved by the Institutional Review Board of Tohoku University.

2.2. Experimental procedure

The experimental setup was as previously described (Yamaguchi et al., 2017). Gait trials were conducted in a 5 m-long walkway, in which two force plates for collecting GRFs (MG-2060; Anima, Tokyo, Japan) were installed approximately 2 m from the start position. A motion-capture system with eight cameras (MA8000; Anima) was used to measure full body kinematics from 16 infrared-reflective markers placed bilaterally on all four extremities and the torso. The sampling frequency for GRFs and 3D motion data was 500 Hz. Participants were asked to wear commercially-available walking shoes (EASYSTAR2; Mizuno, Osaka, Japan).

Participants performed two blocks of trials: a 90° step turn and a 90° spin turn to the right at a self-selected normal speed. They were instructed to walk in a straight line and turn 90° to the right with the left foot [step turn, Fig. 1(a)] or right foot [spin turn, Fig. 1(b)] on the second force plate. To indicate the turning direction, lines were marked on the floor. We used 90° turn trials in this study because most turning angles in daily life activities are between 76° and 120° (Sedgman et al., 1994). The participants were given a practice period to become accustomed to step turning and spin turning. The starting position (approximately 2 m from the first force plate) was adjusted so that foot strikes occurred on the force plate. We randomized the order of each block of trials. Each trial was replicated five times; thus, data for 10 trials were collected, per subject.

2.3. Data analysis

GRF data (F_x, F_y, and F_z) for the second force plate were collected and used to calculate COP with motion analysis software (MA8000; Anima). The position and velocity of the whole-body COM were estimated using a seven-segment model from kinematic data within the motion analysis software. A fourth-order, zero-lag, Butterworth low-pass filtering, with a 10-Hz cutoff frequency, was performed on GRF and kinematic data. Matlab (Mathworks, Natick, MA, USA) was used to conduct the subsequent analyses.

The turning speed, turning radius, and the centripetal force were calculated to investigate the age-related differences in turning gait. The turning speed was defined as the average velocity of the COM during the stance phase of the pivoting foot. The turning radius was calculated as the curvature radius of the COM trajectory. The curvature radius of the COM trajectory during turning was calculated using a least-square circle fit to the COM trajectory in the x–y plane. Minimization of the following equation was performed with Matlab. Using the COM trajectory data (x_i, y_i), we determined the center of the circle (x_c, y_c) and turning radius r_{COM}.

$$f = \sum_{i=1}^{N} \left\{ (x_i - x_c)^2 + (y_i - y_c)^2 - r_{COM}^2 \right\}^2 \tag{1}$$

The centripetal force F_c applied to COM was computed using the turning speed and turning radius (Yamaguchi et al., 2017).

The traction coefficient was defined as the ratio between the horizontal and the vertical GRF (F_h/F_z). The horizontal GRF was calculated as follows:

$$F_h = \sqrt{F_x^2 + F_y^2}. \tag{2}$$

The maximum peak value of the traction coefficient, between 5% and 50% of the stance phase, was used as RCOF (Yamaguchi et al., 2017).

The ML (x' axis) and AP (y' axis) directions during turning were defined using the orientation of the pelvis to construct a body-fixed reference frame (Fino et al., 2015; Yamaguchi et al., 2017). As shown in Fig. 2(a), the x' axis originates parallel to the line through the mean position of the left iliac crest and left trochanter markers and the mean position of the right iliac crest and right trochanter markers. The y' axis was defined as the line perpendicular to the x' axis on the x–y plane. The ML and AP components of horizontal GRFs $F_{x'}$ and $F_{y'}$, respectively, during turning were calculated using the pelvis rotation angle α (Fig. 2(a)) as follows:

$$\begin{bmatrix} F_{x'} \\ F_{y'} \end{bmatrix} = \begin{bmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} F_x \\ F_y. \end{bmatrix} \tag{3}$$

The $F_{x'}/F_z$ and $F_{y'}/F_z$ are the traction coefficients in the ML and AP directions, respectively. The RCOF values in the ML and AP directions ($RCOF_{ML}$, $RCOF_{AP}$, respectively) are the values of the traction coefficient in the ML and AP directions at the instant of RCOF (Fig. 3).

The COM–COP angle θ was calculated using COM (x_{COM}, y_{COM}, z_{COM}), COP (x_{COP}, y_{COP}, 0) of the supporting foot (on the 2nd force

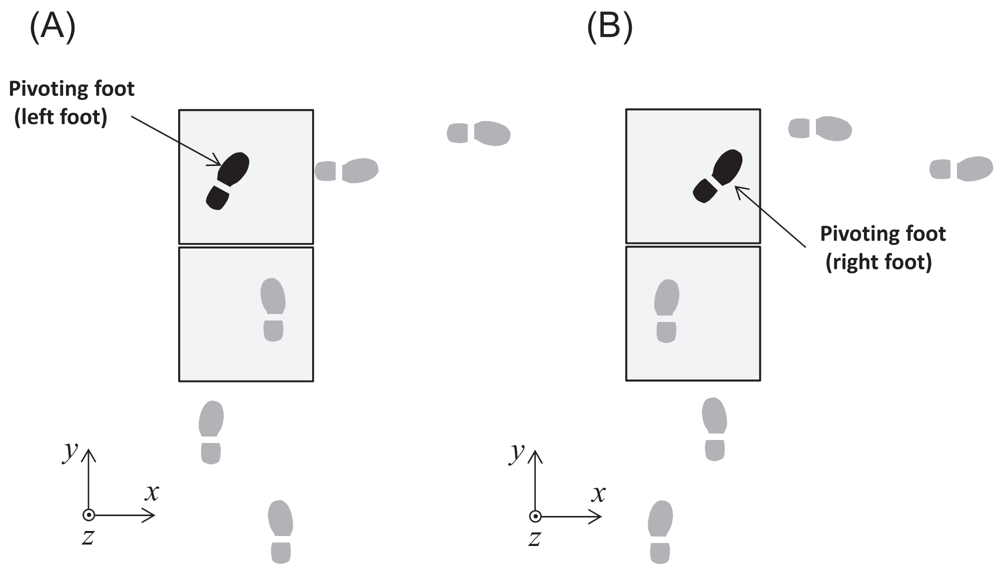

Fig. 1. Schematic footprints of (A) 90° step turn to the right and (B) 90° spin turn to the right.

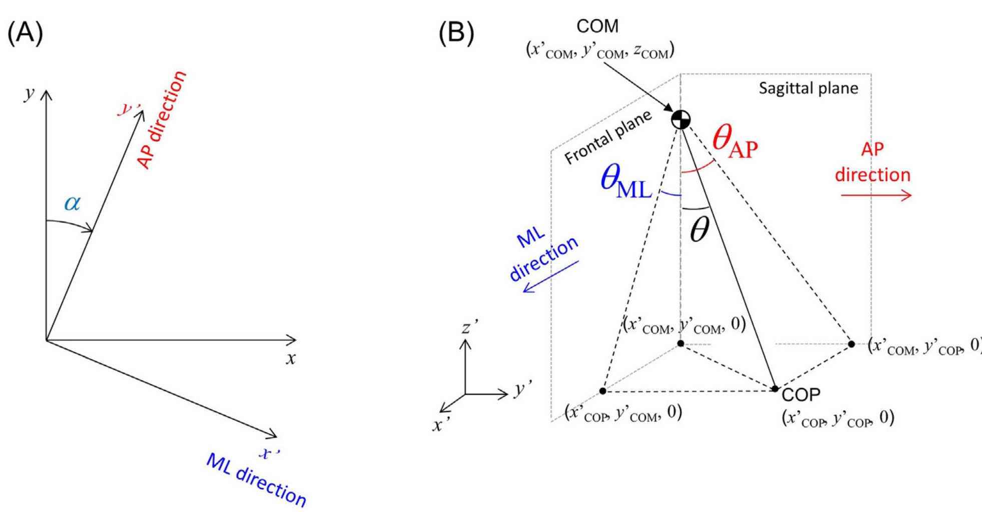

Fig. 2. Schematic diagram of (A) the transverse pelvis rotation angle α and (B) COM–COP angle in AP (θ_{AP}) and ML (θ_{ML}) directions during turning.

plate) and the vertical projection of COM on the floor (x_{COM}, y_{COM}, 0) as follows:

$$\theta = \text{atan}\left(\frac{\sqrt{(x_{COP} - x_{COM})^2 + (y_{COP} - y_{COM})^2}}{z_{COM}}\right). \tag{4}$$

The ML and AP components of the COM–COP angle θ_{ML} and θ_{AP}, defined as shown in Fig. 2(b) were calculated as follows:

$$\theta_{ML} = \text{atan}\left(\frac{x'_{COP} - x'_{COM}}{z_{COM}}\right), \tag{5}$$

$$\theta_{AP} = \text{atan}\left(\frac{y'_{COP} - y'_{COM}}{z_{COM}}\right), \tag{6}$$

where x'_{COM}, y'_{COM}, and z_{COM} were x', y', and z coordinates of COM, and x'_{COP} and y'_{COP} were the x' and y' coordinates of COP of the supporting foot. The values of tan $\theta_{\_RCOF}$ were defined as the values of tan θ at the instant of RCOF. The values of tan θ_{ML_RCOF} and tan θ_{AP_RCOF} were the values of tan θ in the ML and AP directions at the instant of RCOF (Fig. 3).

2.4. Statistical analysis

Statistical analyses were performed using SPSS Statistics for Windows, Version 19.0 (IBM, Armonk, NY, USA). We performed a two-way mixed-effects repeated-measures ANOVA to investigate whether RCOF, $RCOF_{ML}$, $RCOF_{AP}$, tan $\theta_{\_RCOF}$, tan θ_{ML_RCOF}, and tan θ_{AP_RCOF} were affected by age, as the between-subjects factor, and turning strategy (step and spin turns), as the within-subject factor. A Spearman rank correlation test investigated the correlation between RCOF variables (RCOF, $RCOF_{ML}$, or $RCOF_{AP}$ values) and gait parameters (r_{COM}, v_{COM}, and F_c) in addition to COM–COP angle tangents (tan $\theta_{\_RCOF}$, tan θ_{ML_RCOF}, or tan θ_{AP_RCOF} values) for both age groups. A post hoc paired *t*-test with a Bonferroni correction was used to determine specific significant differences between the types of turns and the two age groups. *P* values of <0.05 indicated statistical significance.

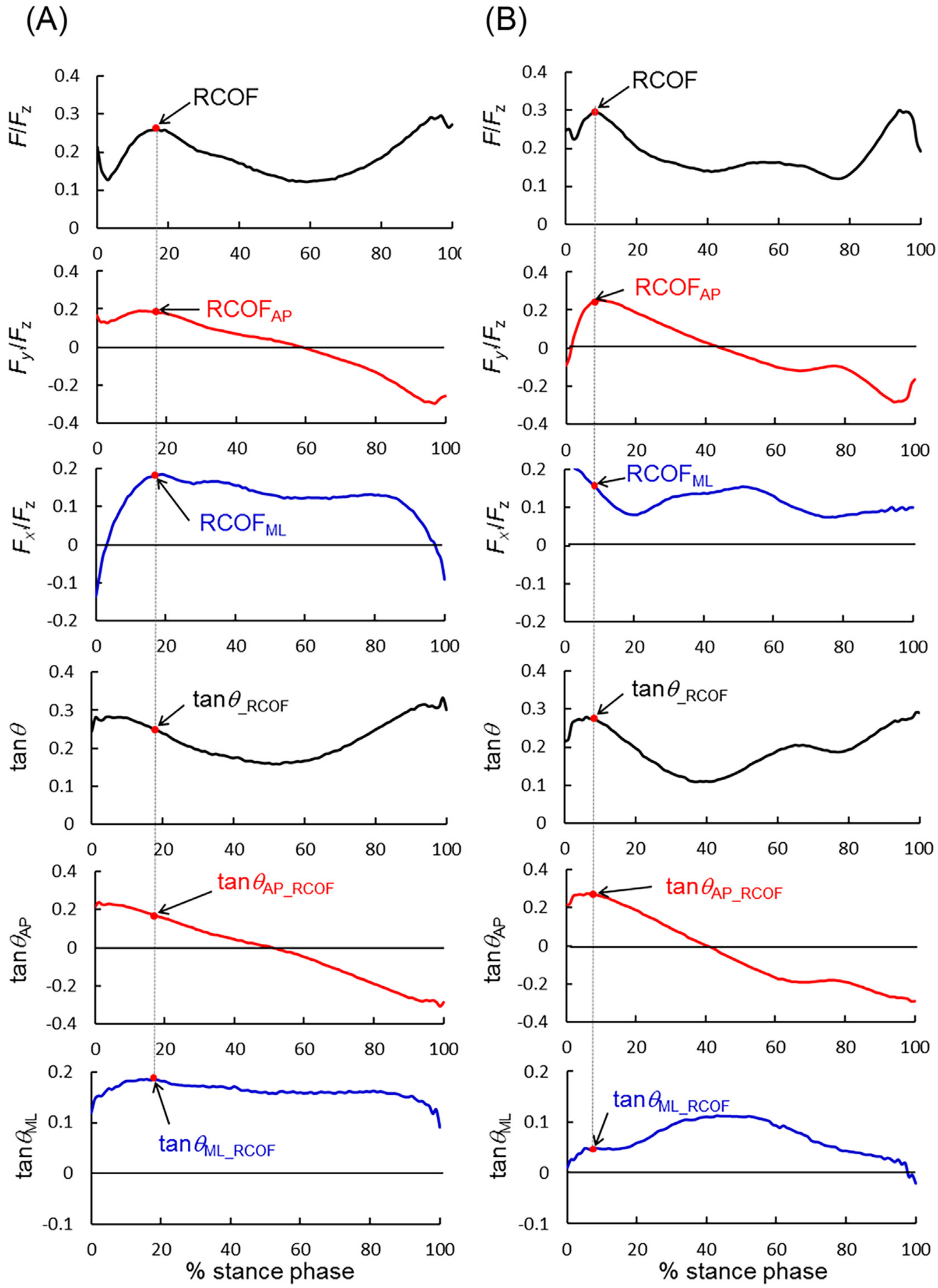

Fig. 3. Representative temporal change in traction coefficient and tan θ, and those anteroposterior (AP) and mediolateral (ML) components. $RCOF_{AP}$ and $RCOF_{ML}$ are AP and ML components of RCOF values. tan $\theta_{\_RCOF}$, tan θ_{AP_RCOF}, and tan θ_{ML_RCOF} are tan θ value at RCOF instance and its AP and ML components, respectively. (A) Step turning and (B) spin turning.

3. Results

3.1. Turning speed, turning radius, and centripetal force

Table 1 summarizes the turning radii, turning speeds, and centripetal forces for young and older adults during step and spin turns. Older adults tended to turn with shorter turning radii and slower turning speeds, resulting in smaller centripetal forces for both turn types. Step turn tended to produce larger centripetal forces because of the shorter turning radii.

3.2. RCOF, $RCOF_{AP}$, and $RCOF_{ML}$ values

Fig. 4 shows the mean values of RCOF, $RCOF_{AP}$, and $RCOF_{ML}$ for young and older adults during each turning trial. Two-way repeated-measures ANOVA indicated that RCOF was significantly

Table 1
Mean (SD) values of turning radius (r_{COM}), turning speed (v_{COM}), and centripetal force (F_c).

	Turn strategy	Young adults	Older adults
r_{COM} (m)	Step turn	0.54 (0.12)	0.35 (0.08)
	Spin turn	0.76 (0.21)	0.62 (0.18)
v_{COM} (m/s)	Step turn	1.00 (0.11)	0.74 (0.10)
	Spin turn	1.10 (0.10)	0.80 (0.13)
F_c (N)	Step turn	117.08 (26.90)	99.61 (23.33)
	Spin turn	98.23 (24.66)	66.74 (18.89)

affected by age group [$F(1, 158) = 34.472$, $p < 0.001$], type of turn [$F(1, 158) = 38.659$, $p < 0.001$], and age group–turn type interaction was not significant [F $(1, 158) = 0.001$, $p = 0.976$]. Thus, RCOF for older adults was lower than that for young adults during step and spin turns (Fig. 4(a)); RCOF for spin turning was lower than RCOF during step turn in both age groups (Fig. 4(a)). $RCOF_{AP}$ was significantly affected by age group [$F(1, 158) = 10.127$, $p < 0.001$], turn type [$F(1, 158) = 121.403$, $p < 0.001$] and age group–turn type interaction was not significant [$F(1, 158) = 0.002$, $p = 0.962$]. Thus, $RCOF_{AP}$ for older adults was higher than that for young adults during step turning and spin turning (Fig. 4(b)); $RCOF_{AP}$ for the spin turn was larger than RCOF for step turn for both age groups (Fig. 4(b)). In the ML direction (Fig. 4(c)), $RCOF_{ML}$ was significantly affected by age group [$F(1, 158) = 85.565$, $p < 0.001$], turn type [$F(1, 158) = 532.604$, $p < 0.001$] and age group–turn type interaction [$F(1, 158) = 26.307$, $p < 0.001$]. A post hoc analysis revealed that $RCOF_{ML}$ was significantly smaller in older adults than in young adults during step turning ($p < 0.001$) and spin turning ($p < 0.001$); $RCOF_{ML}$ values during step turning were higher than during spin turning in both age groups ($p < 0.001$).

3.3. tan $\theta_{\_RCOF}$, tan θ_{AP_RCOF}, and tan θ_{ML_RCOF} values

Fig. 5 shows the mean values of tan $\theta_{\_RCOF}$, tan θ_{AP_RCOF}, and tan θ_{ML_RCOF} values for young and older adults during each turning trial. Two-way repeated-measures ANOVA indicated that tan $\theta_{\_RCOF}$ was significantly affected by turning turn type [$F(1, 158) = 36.327$, $p < 0.001$] but was not significantly affected by age group [$F(1, 158) = 0.541$, $p = 0.463$]. The age group–turn type interaction was not significant [$F(1, 158) = 0.118$, $p = 0.732$]. Thus, tan $\theta_{\_RCOF}$ values for step turning were significantly higher than tan $\theta_{\_RCOF}$ values for spin turn (Fig. 5(a)). The tan θ_{AP_RCOF} was significantly affected by age group [$F(1, 158) = 22.872$, $p < 0.001$], turn type [$F(1, 158) = 397.533$, $p < 0.001$] and age group–turn type interaction

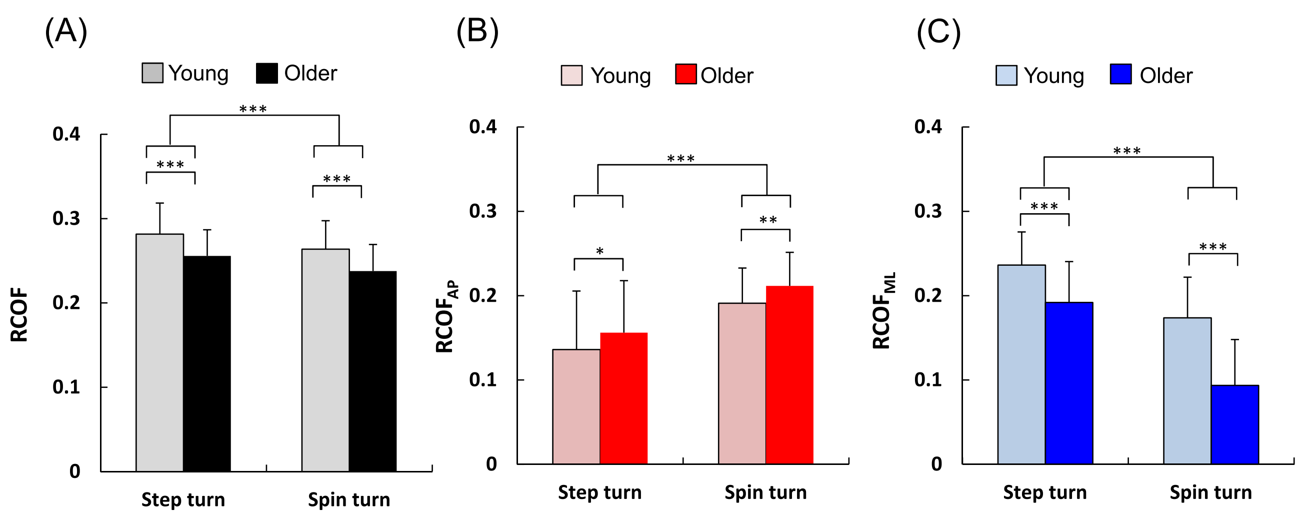

Fig. 4. Comparison of mean and SD values of (A) RCOF, (B) $RCOF_{AP}$, and (C) $RCOF_{ML}$ for young and older adults during each type of gait. * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$.

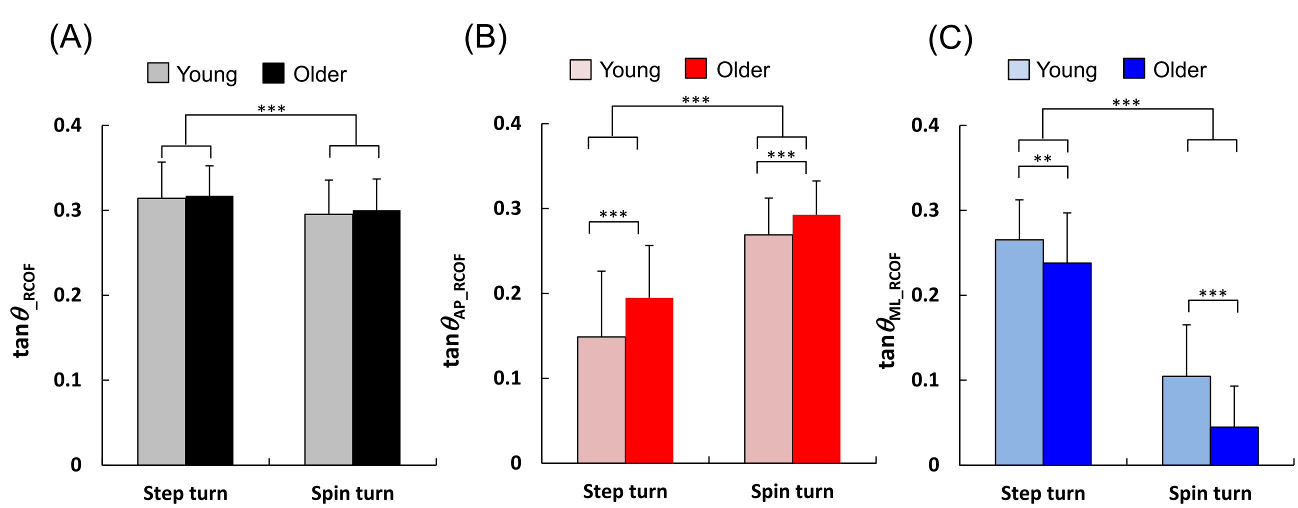

Fig. 5. Comparison of mean and SD values of (A) tan $\theta_{\_RCOF}$, (B) tan θ_{AP_RCOF}, and (C) tan θ_{ML_RCOF} for young and older adults during each type of gait. * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$.

[$F(1, 158) = 4.250$, $p < 0.05$]. A post hoc analysis revealed that tan θ_{AP_RCOF} for older adults was significantly higher during step turning and spin turning ($p < 0.001$) (Fig. 5(b)); additionally, tan θ_{AP_RCOF} for spin turning was significantly larger than that for step turning for both age groups ($p < 0.001$) (Fig. 5(b)). The tan θ_{ML_RCOF} was significantly affected by age group [$F(1, 158) = 33.712$, $p < 0.001$], turn type [$F(1, 158) = 1845.591$, $p < 0.001$] and age group–turn type interaction [$F(1, 158) = 15.481$, $p < 0.001$]. A post hoc analysis revealed that tan θ_{ML_RCOF} was significantly smaller in older adults than in young adults during step turning ($p < 0.01$) and spin turning ($p < 0.001$) (Fig. 5(c)); tan θ_{ML_RCOF} values during step turning were higher than during spin turning for both age groups ($p < 0.001$) (Fig. 5(c)).

3.4. Correlation between RCOF values and tangent of COM–COP angles

Fig. 6 show the relation between tan $\theta_{\_RCOF}$ and RCOF (Fig. 6(a)), between tan θ_{AP_RCOF} and $RCOF_{AP}$ (Fig. 6(b)), and between tan θ_{ML_RCOF} and $RCOF_{ML}$ (Fig. 6(c)). The plots in each graph include both turning trials for young and older adults, thus there were 320 points for each graph (32 participants $\times$ 2 turning strategies $\times$ 5 replications). As shown in Fig. 6, there is a strong positive correlation between tan $\theta_{\_RCOF}$ and RCOF ($r = 0.684$, $p < 0.001$), tan θ_{AP_RCOF} and $RCOF_{AP}$ ($r = 0.841$, $p < 0.001$), or tan θ_{ML_RCOF} and $RCOF_{ML}$ ($r = 0.887$, $p < 0.001$).

3.5. Correlation between RCOF variables and turning radius, turning speed, and centripetal force

Fig. 7 shows the relationship between RCOF (Fig. 7(a)), $RCOF_{AP}$ (Fig. 7(b)), $RCOF_{ML}$ (Fig. 7(c)), and gait parameters such as turning radius, turning speed, and centripetal force. As shown in Fig. 7, there is a positive correlation between centripetal force and $RCOF_{ML}$ ($r = 0.669$, $p < 0.001$). RCOF correlated positively with centripetal force ($r = 0.610$, $p < 0.001$). Turning speed also exhibited a positive correlation with RCOF ($r = 0.497$, $p < 0.001$) and $RCOF_{ML}$ ($r = 0.351$, $p < 0.001$).

4. Discussion

This was the first study to investigate RCOF, and its ML and AP components, during step and spin turning in young and older adults. Fino et al. (2015) investigated the relationship between approach speed/turning speed on RCOF values and ML COM-COP angles while turning corners using a step or spin turn method. There are a few methodological differences in their study, compared to ours. First, their study participants were young (18–45 yr); the turning speed during the normal walking speed condition (1.27 ± 0.26 m/s) was higher than that exhibited by our young adult participants (1.00 ± 0.74 m/s for step turn; 1.10 ± 0.80 m/s for spin turn). Additionally, the RCOF values (0.30 ± 0.07) for normal turning speed trials in their study were relatively larger than those produced by our young adult participants (RCOF value: 0.28 ± 0.04 step turn and 0.26 ± 0.03 for spin turn), attributable to the faster turning speed. RCOF values and ML COM-COP angles for step turn were larger than those for spin turn in their study, which was also confirmed in our study.

Our results indicated that the RCOF values in the older adults were significantly lower than those in the young adults during both step and spin turns (Fig. 4(a)). This was mostly due to the decreased $RCOF_{ML}$ in the older adults during both turning trials (Fig. 4(c)), whereas older adults exhibited slightly increased $RCOF_{AP}$ during turning (Fig. 4(b)). We also found that, irrespective of age group and the type of turn, RCOF, $RCOF_{AP}$, and $RCOF_{ML}$ values were strongly associated with the tan θ_{RCOF} ($r = 0.684$), tan θ_{AP_RCOF} ($r = 0.841$), and tan θ_{ML_RCOF} values ($r = 0.887$), respectively (Fig. 6). Considering the dynamics, increased θ_{RCOF}, θ_{AP_RCOF}, and θ_{ML_RCOF} at the instant of RCOF similarly increases RCOF, $RCOF_{AP}$, and $RCOF_{ML}$, respectively during turning. Therefore, lower RCOF in the older adults is primarily due to the lower $RCOF_{ML}$, which is probably due to smaller θ_{ML_RCOF} in this population. This smaller θ_{ML_RCOF} is likely due to the slower speed in the older adults that causes diminished centripetal force (Table 1). This age-related change in turning gait reduced the ML component of RCOF during turning, reducing the slip risk for older adults during step and spin turning. This compensatory action thus reduces the slip risk.

The smaller lean angle of the body during turning helps older adults avoid falling due to slips, as it results in lower RCOF. Further, even when a slip occurs in the ML direction during turning, the smaller lean angle helps the swing foot arrest the COM within the base-of-support (BOS) to prevent falling. Carbonneau and Smeesters (2014) found that the maximum lateral lean angle, from which one could recover balance using a single step, decreased with age. The smaller COM–COP angle in the ML direction during turning may help older adults step to recover their balance when slipping occurs in the ML direction.

During turning, medial lateral ground reaction forces are needed to produce the centripetal force to turn. In order to compensate for the centripetal force, individuals must lean in toward the center of the turning circle (Courtine and Shieppati, 2003). This

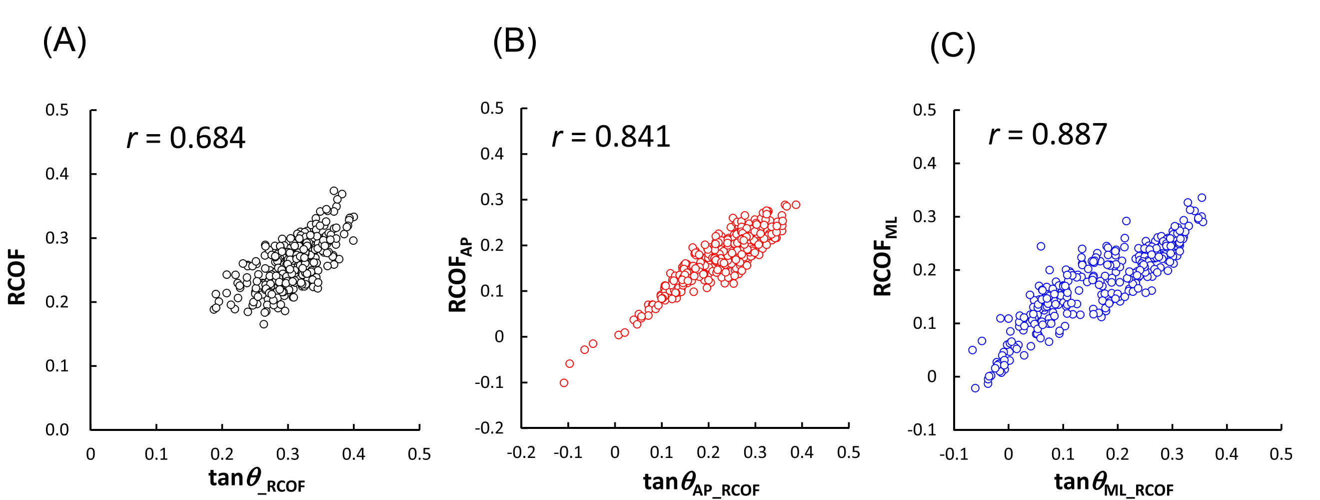

Fig. 6. Relation between (A) tan $\theta_{\_RCOF}$ and RCOF, (B) tan θ_{AP_RCOF} and $RCOF_{AP}$, and (C) tan θ_{ML_RCOF} and $RCOF_{ML}$. The number of points for each graph is 320.

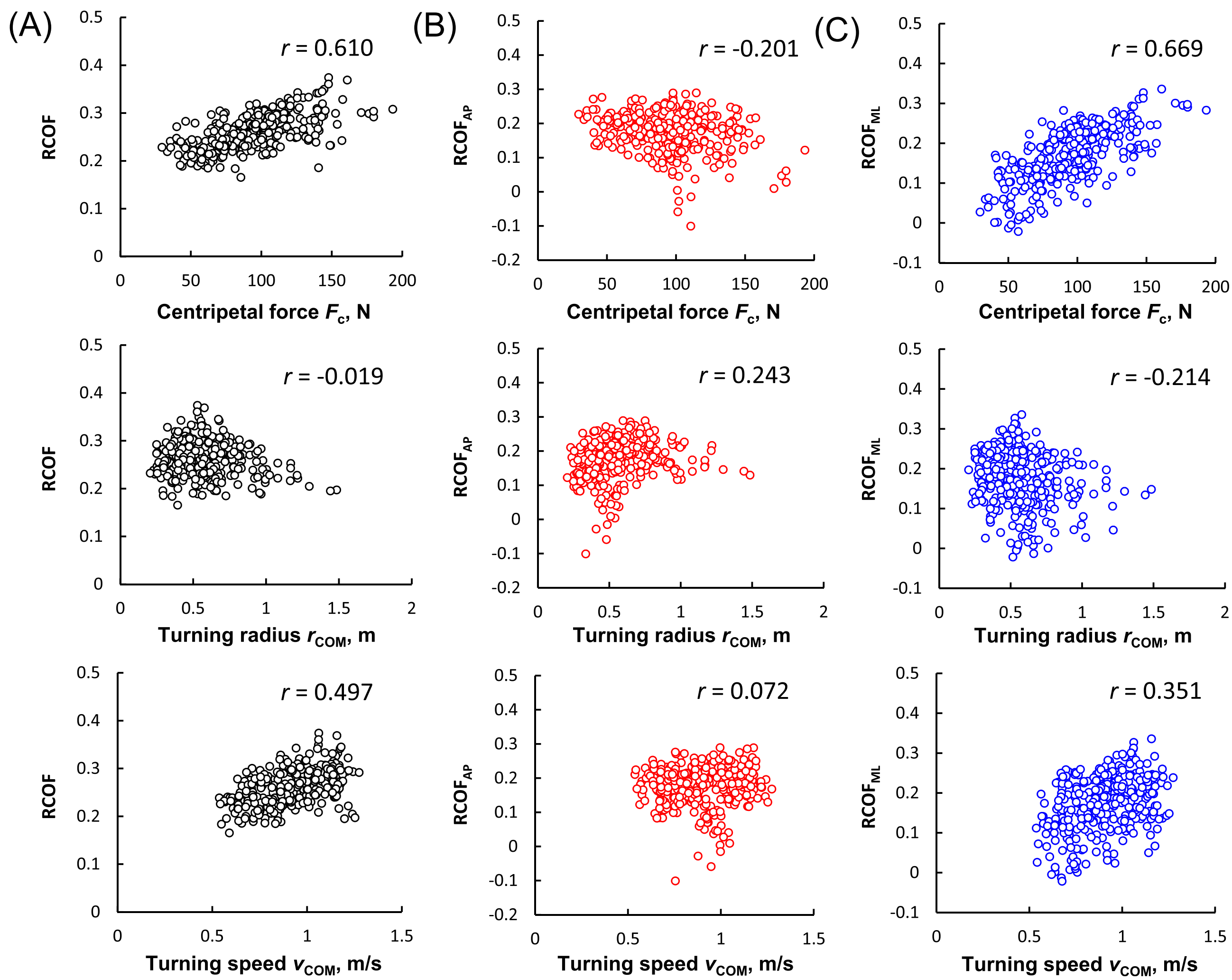

Fig. 7. Relationship between (A) RCOF, (B) $RCOF_{AP}$, and (C) $RCOF_{ML}$ and gait parameters (centripetal force, turning radius, and turning speed). The number of points for each graph is 320.

leaning action also produces a medial or lateral shift in the COM during step or spin turn, respectively, in order to counterbalance the moment around COM, against medial lateral ground reaction forces. Fino et al. (2015) found from turning trials that reduced turning speeds reduced the RCOF values and body lean angle in the ML direction during turning. The reduction in the ML body lean angle was attributed to the diminished centripetal force, being proportional to the square turning speed and the inverse of the turning radius. In our study, older adults tended to turn more slowly (Table 1), and exhibited a smaller ML body lean angle and $RCOF_{ML}$. In addition, as shown in Fig. 7, centripetal force was positively correlated with $RCOF_{ML}$ ($r = 0.669$, $p < 0.001$). Because $RCOF_{ML}$ and tan θ_{ML} are positively correlated ($r = 0.887$, $p < 0.001$), age-related reductions in turning speed reduced the centripetal force and decreased the lean angle in the ML direction for older adults. Therefore, older adults exhibited a reduced $RCOF_{ML}$ and RCOF values. On the other hand, as shown in Fig. 7, there was a weak negative correlation between centripetal force and $RCOF_{AP}$ ($r = -0.201$, $p < 0.001$). This may indicate that, during turning, there are different mean of controlling body lean angle in the AP and ML directions. The body lean angle in the AP direction (in the sagittal plane) during turning is the product of the inverted COM–COP pendulum system that the human body uses to ambulate; however, the body lean angle in the ML direction (in the frontal plane) is mainly a product of centripetal force compensation during turning.

In contrast to the ML direction, the older adults turned with larger $RCOF_{AP}$ than the young adults (Fig. 4(b)), which was probably due to the larger tan θ_{AP_RCOF} in the older adults (Fig. 5(b)). We found that, in older adults, the pelvis rotation angle α during the early stance phase was smaller than that exhibited by young adults. Further, α differed according to the type of turn, e.g. α at heel contact for step turn: 35.5 ± 13.1° for young adults; 31.5 ± 17.0° for older adults, at heel contact timing for spin turn: 16.1 ± 11.0° for young adults; 11.6 ± 9.1° for older adults. This result may indicate that older adults brake first, then rotate their bodies, while young adults simultaneously brake and rotate. Furthermore, older adults turned with shorter turning radii, as shown in Table 1. Therefore, older adults may direct their step length more toward the AP direction, which increases AP lean angle and braking forces (AP GRF) during weight acceptance, resulting in increased $RCOF_{AP}$ values. In turn, this can lessen the ML lean angle for older adults during weight acceptance, in addition to producing speed-related changes in centripetal force. These trade-off effects on AP and ML lean angles would result in no between age-group differences in the overall COM-COP angle.

For older and young adults, RCOF was lower during spin turns than step turns, which was predominantly due to the lower $RCOF_{ML}$ during spin turns than step turns (Fig. 4(c)). Therefore, the spin turn is a safer turning strategy for preventing slipping. When slipping occurs in the ML direction during spin turns, the swing foot must cross-over to arrest COM within BOS. Older adults often avoid doing this when stepping in response to lateral perturbation (Maki et al., 2000; Maki and McIlroy, 1999). During step turning, the swing foot can easily arrest COM within BOS and prevent falling, even when slipping occurs in the ML direction. Therefore, the step turn could have an advantage over the spin turn for maintaining postural balance after slipping. However, healthy older adults prefer spin turning (Akram et al., 2010), even though it is more unstable (Patla et al., 1991) and a biomechanically inefficient (Taylor et al., 2005) turning strategy, compared with step turning. These results suggest that, in older adults, slip prevention takes precedence over balance recovery after slipping during turning.

In conclusion, we found that older adults turned with the lower ML component of RCOF during step and spin turns, resulting in smaller RCOF, (lower slip risk during turning). This smaller RCOF is related to the smaller lean angle of the body in the ML direction (ML COM–COP angle), which is probably due to a fact that older adults turned with slower speeds and require lower centripetal forces to turn. Because of these age-related compensatory mechanisms that change gait while turning, older adults turned with lower slip risk than young adults. In addition, our findings suggest that spin turning is a safer turning strategy for preventing lateral slips. Further research is needed to investigate whether our results apply to elderly people with impaired health and mobility.

Acknowledgments

This work was partially supported by JSPS KAKENHI Grant Numbers 25420080, 16K06038.

Conflict of interest statement

No author of this study has a conflict of interest, including specific financial interests, relationships, and/or affiliations relevant to the subject matter or materials included in this manuscript.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jbiomech.2018.04.038.

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