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Effects of age-related changes in step length and step width on the required coefficient of friction during straight walking

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ABSTRACT

Background: Slipping is one of the leading causes of falls among older adults. Older adults are considered to walk with a small anteroposterior (AP) component and a large mediolateral (ML) component of the required coefficient of friction (RCOF) owing to a short step length and a wide step width, respectively. However, limited information is available.
Research question: What are the effects of aging on the resultant RCOF ($RCOF_{res}$) and its ML ($RCOF_{ML}$) and AP ($RCOF_{AP}$) components during straight walking?
Methods: We used the kinetic and kinematic data of 188 participants aged 20–77 years from a publicly available database (National Institute of Advanced Industrial Science and Technology Gait Database 2015). The participants were divided into the following three groups: young group (n = 56; age range, 20–34 years), middle-aged group (n = 50; age range, 35–64 years), and old group (n = 82; age range, 65–77 years).
Results: The $RCOF_{res}$ and $RCOF_{AP}$ were lower in the old group than in the other groups, indicating a lower slip risk in this group. However, the $RCOF_{ML}$ was higher and the step width was greater in the old group than in the other groups. The higher $RCOF_{ML}$ and lower $RCOF_{AP}$ in the old group might be associated with slips in a more lateral direction.
Significance: Our findings suggest that older adults have a high risk of slipping in a more lateral direction. Shoes with high-slip resistance in the lateral direction are recommended to prevent hazardous lateral slips among older adults.

1. Introduction

Slipping is one of the leading causes of falls among older adults [1,2]. A slip occurs when the ratio of the traction force to the vertical force applied to a floor (the traction coefficient) reaches the coefficient of friction (COF) between a shoe and the floor. Therefore, for a shoe–floor combination, i.e., for a certain COF, a larger traction coefficient is more hazardous. The largest traction coefficient is noted immediately after heel contact, and it is called the required COF (RCOF) [3]. The RCOF is equivalent to the minimum COF necessary to prevent forward slipping during the braking phase, and it can be used to evaluate the slip risk [4,5]. The magnitudes of the RCOF during straight gait and turning gait are positively and highly correlated with the tangent of the body lean angle, i.e., the angle from the vertical to the line between the body center of mass (COM) and the center of pressure (COP; COM − COP angle) [6–9]. Therefore, a gait with a small COM − COP angle can reduce the magnitude of the RCOF, resulting in a low slip risk.

The RCOF values of older adults during level straight walking are equivalent to [10,11] or lower than those of younger adults [12,13]. Previous studies have shown that the low RCOF values in older adults are associated with a short step length and a slow walking speed [11,14]. This can be accounted for by a hypothesized mechanism that the short step length in older adults reduces the COM − COP angle in the anteroposterior (AP) direction, resulting in a small AP component of the RCOF. The mediolateral (ML) component of the RCOF is usually small but not negligible [15]. As the step width during walking is larger in older adults than in younger adults [16,17], it is hypothesized that the COM − COP angle in the frontal plane is larger in older adults than in younger adults, which can result in a larger ML component of the RCOF in older adults than in younger adults. However, there is no evidence supporting these hypotheses (older adults walk with a small AP

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component and large ML component of the RCOF).

The resultant RCOF ($RCOF_{res}$; i.e., the resultant value of the ML and AP components of the RCOF) is often used to evaluate the slip risk, and the slip direction at slip onset is determined by the direction of the traction force vector (opposite to the ground reaction force [GRF] vector), which can be determined by the ratio of the ML and AP components of the RCOF. Therefore, it is hypothesized that a small AP component and large ML component of the RCOF may cause slips in a more lateral direction. The fall risk is believed to be higher with lateral slip than with forward slip [18], and older adults have difficulty in controlling balance with regard to lateral perturbation [19,20]; therefore, older adults are more likely to fall when slipping in the lateral direction compared with younger adults.

The current study aimed to assess the effects of aging on the $RCOF_{res}$ and its ML and AP components during straight walking. The study tested the following three hypotheses: 1) older adults walk with a short step length, resulting in a small AP COM − COP angle and small AP component of the $RCOF_{res}$; 2) older adults walk with a wide step width, resulting in a large ML COM − COP angle and large ML component of the $RCOF_{res}$; and 3) a small AP component and large ML component of the $RCOF_{res}$ increase the slip risk in the ML direction among older adults.

2. Methods

2.1. National institute of advanced industrial science and technology gait database

We used the publicly available National Institute of Advanced Industrial Science and Technology (AIST) Gait Database 2015 [21], which includes kinetic and kinematic data of level straight gait for 214 Japanese individuals aged 7–77 years. The individuals lived independently in local communities and they were able to walk independently without assistive devices. The experimental protocol was approved by the local institutional review board, and all the participants gave their written informed consent before participating.

The experimental setup and protocol were as described elsewhere [22]. Briefly, gait trials were conducted on a straight 10-m walkway, in which six force plates (BP400600-2000PT; AMTI, Watertown, MA, USA) were installed to record GRF components; F_x, F_y, and F_z for ML, AP, and vertical reaction force components, respectively. A 3D motion capture system (Vicon MX; Vicon Motion Systems, Oxford, UK) was used to measure full-body kinematics with 55 infrared reflective markers attached in accordance with the guidelines of Visual 3D software (C-Motion Inc., Rockville, MD, USA). The sampling frequencies for GRFs and 3D motion data were 1 kHz and 200 Hz, respectively.

The participants were asked to walk barefoot at a comfortable self-selected speed. They were allowed sufficient practice walks to ensure a natural gait. After practice, five successful trials were recorded. GRFs for three steps on the force plates were recorded. The kinetic and kinematic data were low-pass-filtered using a fourth-order Butterworth filter with zero lag and cut-off frequencies of 10 and 6 Hz, respectively. Low-pass filtering and calculation of the COP for each foot and the whole body COM were performed using Visual 3D software.

2.2. Data analysis

From the database, the kinetic and kinematic data of 188 participants aged 20–77 years were used in the current study. We excluded the data of 26 participants who were younger than 20 years. The participants were divided into the following three age groups: young group (age range, 20–34 years), middle-aged group (age range, 35–64 years), and old group (age range, 65–77 years).

For the analysis, we used GRF, COM, and COP data of the first two steps (left and right feet) in each trial (10 steps in total among five trials per participant). We calculated gait variables (i.e., step length, step width, walking speed, and cadence), the RCOF, the COM − COP angle tangent, and the ML and AP components using Matlab ver. 8.2 (Mathworks, Natick, MA, USA).

Step length (L) was calculated as the longitudinal distance (AP [y] direction) between the heel markers of the 1st and 2nd stepping feet at the heel-strike event of each foot. Step width (W) was calculated as the lateral distance between the centers of the two feet, which were approximated as the midpoints between the toe and heel markers, at the heel-strike event of each foot [23]. Walking speed (v) was calculated as the step length divided by the time between heel contacts of the 1st and 2nd stepping feet. The step length and step width were normalized by the body height (h) of the participant and the walking speed was normalized by $\sqrt{gh}$ [24], where g is gravitational acceleration (9.8 m/s^2). Cadence was calculated as the walking speed divided by the step length. The toe out angle, which is defined as the angle of the line between toe and heel markers with respect to the y axis (AP direction), at heel-strike event of each foot was calculated.

The traction coefficients in the ML and AP directions were calculated as F_x/F_z and F_y/F_z, respectively. The resultant traction coefficient was defined as the ratio of the horizontal GRF and vertical GRF (F_h/F_z). The $RCOF_{res}$ was considered as the peak value of the traction coefficient during the braking phase defined according to Chang's method [25]. The ML and AP components of the $RCOF_{res}$ ($RCOF_{ML}$ and $RCOF_{AP}$, respectively) are the values of F_x/F_z and F_y/F_z at the point of the $RCOF_{res}$, respectively.

The COM − COP angle (θ) was calculated using the COM (x_{COM}, y_{COM}, z_{COM}), COP (x_{COP}, y_{COP}, 0), and vertical projection of the COM on the floor (x_{COM}, y_{COM}, 0) for each supporting foot as follows:

$$\theta = \mathrm{atan}\left(\frac{\sqrt{(x_{COP} - x_{COM})^2 - (y_{COP} - y_{COM})^2}}{z_{COM}}\right) \tag{1}$$

The ML and AP components of the COM − COP angle (θ_{ML} and θ_{AP}, respectively; Fig. 1A) were calculated as follows:

$$\theta_{ML} = \mathrm{atan}\left(\frac{x_{COP} - x_{COM}}{z_{COM}}\right) \tag{2}$$

$$\theta_{AP} = \mathrm{atan}\left(\frac{y_{COP} - y_{COM}}{z_{COM}}\right) \tag{3}$$

The $\tan\theta_{\_RCOFres}$ value was defined as the $\tan\theta$ value at the point of the $RCOF_{res}$. Additionally, the $\tan\theta_{ML\_RCOFres}$ and $\tan\theta_{AP\_RCOFres}$ values were the $\tan\theta_{ML}$ and $\tan\theta_{AP}$ values at the point of the $RCOF_{res}$, respectively.

We defined the estimated slip angle α (degrees) using F_x and F_y as follows (Fig. 1B):

$$\alpha = \mathrm{atan}\left(\frac{F_x}{F_y}\right)\cdot\frac{180}{\pi} \tag{4}$$

The $\alpha_{RCOFres}$ value was defined as the α value at the point of $RCOF_{res}$. Eq. (5) can also be expressed as a function of the traction coefficient in the ML (F_x/F_z) and AP (F_y/F_z) directions as follows:

$$\alpha = \mathrm{atan}\left(\frac{F_x/F_z}{F_y/F_z}\right)\cdot\frac{180}{\pi} \tag{5}$$

Thus, $\alpha_{RCOFres}$ is a function of the ratio of $RCOF_{ML}$ and $RCOF_{AP}$.

2.3. Statistical analysis

We performed one-way analysis of variance (ANOVA) to investigate whether the gait variables (normalized step length, normalized step width, normalized walking speed, and cadence) and the magnitudes of the $RCOF_{res}$, $RCOF_{ML}$, $RCOF_{AP}$, $\tan\theta_{\_RCOFres}$, $\tan\theta_{ML\_RCOFres}$, $\tan\theta_{AP\_RCOFres}$, and $\alpha_{RCOFres}$ were affected by age. A post-hoc t-test with Bonferroni correction was used to determine specific significant differences among the three age groups. We also reported effect size in

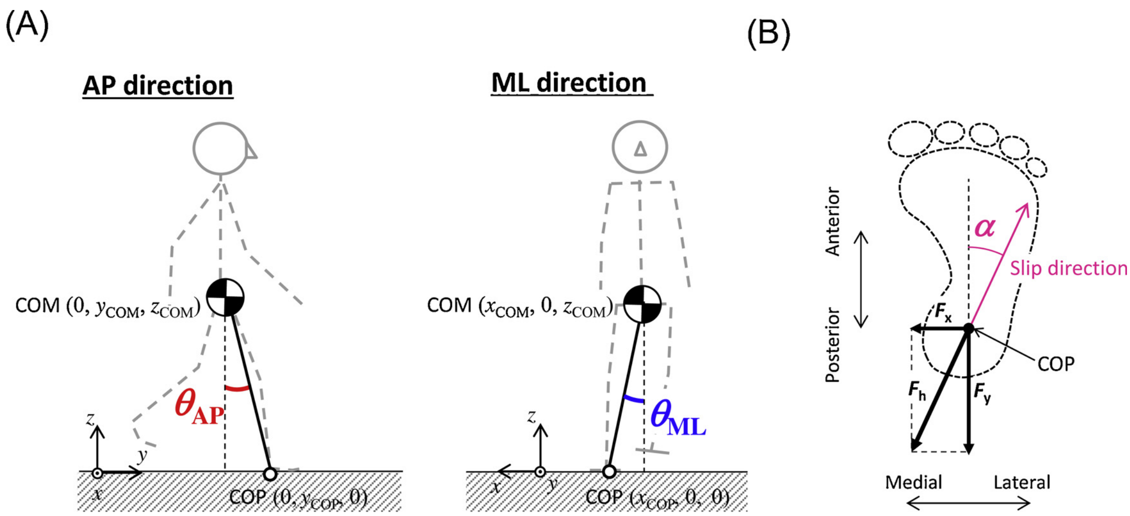

Fig. 1. Schematic of (A) the COM − COP angle in the AP (θ_{AP}) and ML (θ_{ML}) directions and (B) the estimated slip angle (α).
COM, center of mass; COP, center of pressure; AP, anteroposterior; ML, mediolateral

terms of η_p^2 for one-way ANOVA and Cohen's *d* for *t*-tests in the supplemental data. Pearson correlation tests were performed to investigate correlations between the magnitudes of RCOF variables ($RCOF_{res}$, $RCOF_{ML}$, and $RCOF_{AP}$) and COM − COP angle tangents ($\tan\theta_{\_RCOFres}$, $\tan\theta_{ML\_RCOFres}$, and $\tan\theta_{AP\_RCOFres}$). Additionally, correlations of $RCOF_{AP}$ and $RCOF_{ML}$ with normalized step length and normalized step width, respectively, were investigated. A correlation of the ratio of step width to step length with $\alpha_{RCOFres}$ was also investigated. All statistical analyses were performed using SPSS Statistics for Windows, Version 19.0 (IBM Corp., Armonk, NY, USA). A *p*-value < 0.05 was considered to indicate statistical significance.

3. Results

Participants' height and weight data are listed in Table 1. The weight was not significantly different among the age groups ($F[2,185] = 0.968$, $p > 0.05$). However, height was significantly different among the age groups (one-way ANOVA, $F[2,185] = 10.341$, $p < 0.001$). Additionally, the height was lower in the old group than in the young (post-hoc *t*-test with Bonferroni correction, $p < 0.001$) and middle-aged ($p < 0.001$) groups.

As shown in Fig. 2, the normalized step length and normalized walking speed were not significantly different among the age groups ($F[2,185] = 1.107$, $p = 0.333$ and $F[2,185] = 2.797$, $p = 0.064$, respectively). However, the normalized step width and cadence were significantly different among the age groups ($F[2,185] = 10.693$, $p < 0.001$, and $F[2,185] = 5.166$, $p < 0.01$, respectively). The step width was significantly greater in the old group than in the young group ($p < 0.001$), and cadence was significantly larger in the young group than in the middle-aged group ($p < 0.01$). There was no significant differences in the toe out angle among age groups ($F(2, 185) = 1.980$, $p > 0.05$)

The $RCOF_{res}$ was significantly different among the age groups ($F[2,185] = 9.027$, $p < 0.001$). It was significantly lower in the old group than in the young ($p < 0.001$) and middle-aged ($p < 0.01$) groups (Fig. 3A). Additionally, the $RCOF_{AP}$ was significantly different among the age groups ($F[2,185] = 10.880$, $p < 0.001$); it was significantly lower in the old group than in the young ($p < 0.001$) and middle-aged ($p < 0.01$) groups (Fig. 3B). The $RCOF_{ML}$ was also significantly different among the age groups ($F[2,185] = 5.920$, $p < 0.01$); it was significantly higher in the old group than in the young ($p < 0.01$) and middle-aged ($p < 0.05$) groups (Fig. 3C).

The $\tan\theta_{\_RCOFres}$ was significantly different among the age groups ($F[2,185] = 3.663$, $p < 0.05$); it was significantly lower in the old group than in the young group ($p < 0.05$) (Fig. 3D). Additionally, the $\tan\theta_{AP\_RCOFres}$ was significantly different among the age groups ($F[2,185] = 5.642$, $p < 0.01$); it was significantly lower in the old group than in the young group ($p < 0.01$; Fig. 3E). The $\tan\theta_{ML\_RCOFres}$ was also significantly different among the age groups ($F[2,185] = 10.448$, $p < 0.001$); it was significantly higher in the old group than in the young group ($p < 0.001$; Fig. 3F). The $\alpha_{RCOFres}$ was significantly different among the age groups ($F[2,185] = 11.273$, $p < 0.001$); it was significantly higher in the old group than in the young ($p < 0.001$) and middle-aged ($p < 0.05$) groups (Fig. 3G).

As shown in Fig. 4, there were positive correlations between $\tan\theta_{\_RCOFres}$ and $RCOF_{res}$ ($r = 0.807$, $p < 0.001$), between $\tan\theta_{AP\_RCOFres}$ and $RCOF_{AP}$ ($r = 0.823$, $p < 0.001$), and between $\tan\theta_{ML\_RCOFres}$ and $RCOF_{ML}$ ($r = 0.592$, $p < 0.001$).

There were positive correlations between $RCOF_{AP}$ and normalized step length ($r = 0.644$, $p < 0.001$; Fig. 5A) and between $RCOF_{ML}$ and normalized step width ($r = 0.527$, $p < 0.001$; Fig. 5B). As shown in Fig. 5C, there was positive correlation between the $\alpha_{RCOFres}$ and the ratio of step width to step length ($r = 0.541$, $p < 0.001$).

Table 1
Number of participants, mean (SD) value of participants' body height and weight in each age group.

	Young	Middle-aged	Old
Number of participants	56 23 male and 33 female	50 24 male and 26 female	82 51 male and 31 female
Body height, cm	164.5[a] (7.7)	165.4[b] (8.8)	159.8[a,b] (8.1)
Body weight, kg	57.0 (12.7)	59.8 (10.9)	59.0 (9.1)

[a] $p < 0.001$ between young group and old group.
[b] $p < 0.001$ between middle-aged group and old group.

4. Discussion

Our study revealed that, in straight waking, the $RCOF_{res}$ was significantly lower in the old group than in the young and middle-aged groups, indicating that old individuals had a low slip risk when walking, which is consistent with previous findings [12,13]. The lower $RCOF_{res}$ in the old group than in other groups can be accounted for by the lower $RCOF_{AP}$ in this group. On the other hand, the $RCOF_{ML}$ was higher in the old group than in the other groups. These high $RCOF_{ML}$

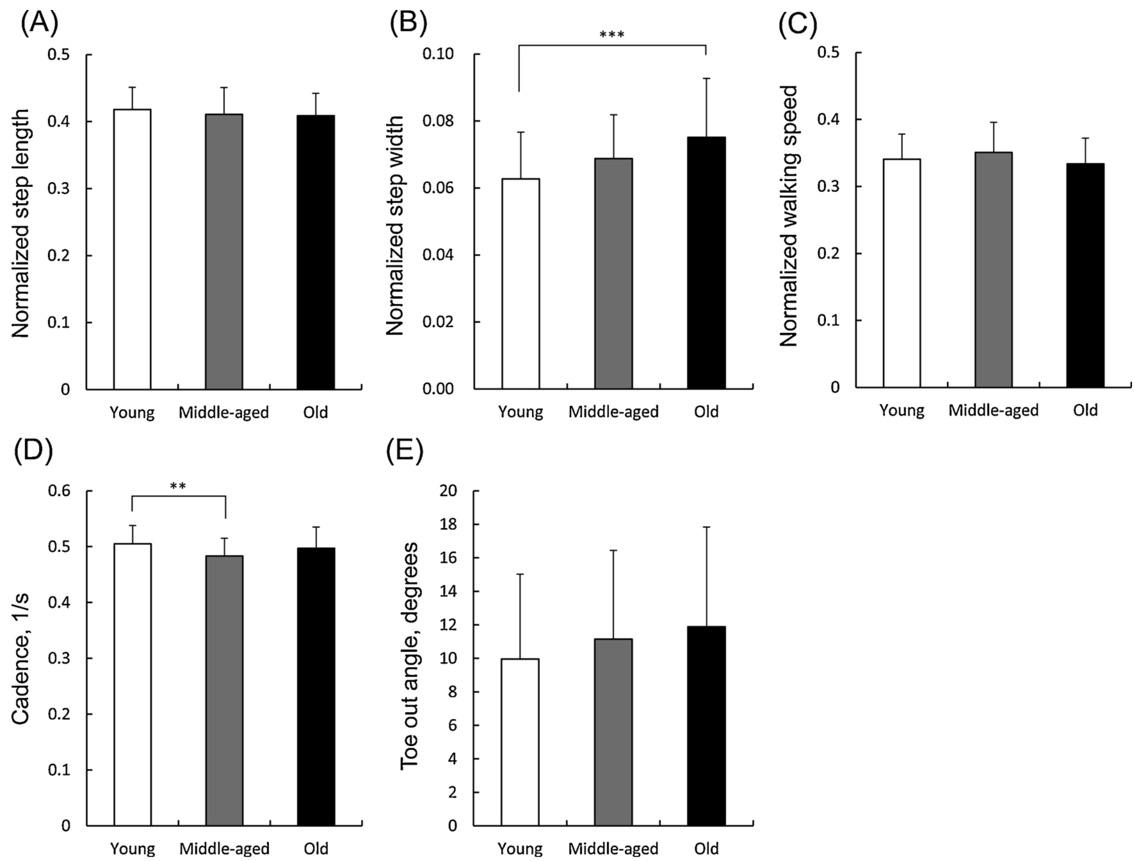

Fig. 2. Gait parameters and toe out angle for each age group. The step length and step width are normalized by body height. The walking speed is normalized by $\sqrt{gh}$. $^{**}p < 0.01$, $^{***}p < 0.001$.

and low $RCOF_{AP}$ values in the old group might be due to a high $\tan\theta_{ML\_RCOFres}$ and low $\tan\theta_{AP\_RCOFres}$, respectively. The $\alpha_{RCOFres}$ was higher in the old group than in the young and middle-aged groups, as it is equivalent to the ratio between $RCOF_{ML}$ and $RCOF_{AP}$ ($RCOF_{ML}$/$RCOF_{AP}$; Eq. (6)), indicating that older adults could slip more laterally compared with younger adults. As lateral slips are more hazardous in terms of an increase in the fall risk [18] and older adults have difficulty in controlling lateral balance with respect to lateral perturbation [19,20], our results may suggest that shoes with high-slip resistance in the lateral direction in addition to that in the AP direction are necessary to prevent hazardous lateral slips among older adults. Furthermore, the $RCOF_{ML}$ and $RCOF_{AP}$ were positively correlated with step width and step length, respectively. The normalized step length tended to be shorter in the old group than in the young group, and the normalized step width was significantly greater in the old group than in the young group. Thus, the high $RCOF_{ML}$ and low $RCOF_{AP}$ in the old group might be attributable to the wide step width and short step length, respectively, in this group. These results support our hypotheses. Our results also indicated that the $\alpha_{RCOFres}$ can be predicted by the ratio of step width to step length.

The wider step width in older adults might be an adaptive response to reduced muscular strength [26], as an increased step width can provide a larger base of support during the double-support period to improve lateral balance [27]. However, as a stride mainly involves single support, balance maintenance during the single-support period is more important than that during the double-support period. As reported in the literature [26], a wider step width causes faster COM movement toward the swing foot during the single-stance period, which further increases the COM − COP distance in the ML direction and reduces ML postural stability [27]. The $\tan\theta_{ML\_RCOFres}$ was significantly higher in the old group than in the young group, which might be due to an increase in the COM − COP distance in the ML direction associated with a wide step width and fast COM movement in the ML direction. Therefore, the high $\tan\theta_{ML\_RCOFres}$ in the old group was associated with a high $RCOF_{ML}$.

Yamaguchi et al. [28] indicated that older adults turned with a lower RCOF owing to a decreased $RCOF_{ML}$ attributable to a lower turning speed compared with the findings in young adults. Therefore, older adults avoid slipping in the ML direction during turning. On the other hand, this study revealed that during straight gait, older adults walked with a high $RCOF_{ML}$, which increased the risk of slipping in the lateral direction.

The present study has an important limitation. First, the slip angle $\alpha_{RCOFres}$ was estimated according to the direction of the horizontal GRF, and this was the direction when a slip occurred at the point of $RCOF_{res}$. However, the slip direction during slipping was not measured. According to a previous study [29], it was found that the side-slip angle at the slip initiation is primarily in the medial direction then the side-slip angle at the peak sliding speed changes to the lateral direction in young subjects. The change in the side-slip direction can be due to the change in the direction of horizontal acting force from shoe to floor (opposite to the horizontal GRF). According to our previous study [7], although the horizontal force acts in the medial direction just after the heel contact on a dry level floor, the direction changes to the lateral direction after approximately 10% stance phase, which demonstrates that the ground reaction force vector is generally consistent with the slipping direction previously reported [29,30]. Thus, the estimated slip direction at RCOF instant shown in this study can predict actual slip direction. However, in the future, we need to confirm how a wide step width and short step length in older adults affect the slip direction through experiments performed on a slippery floor.

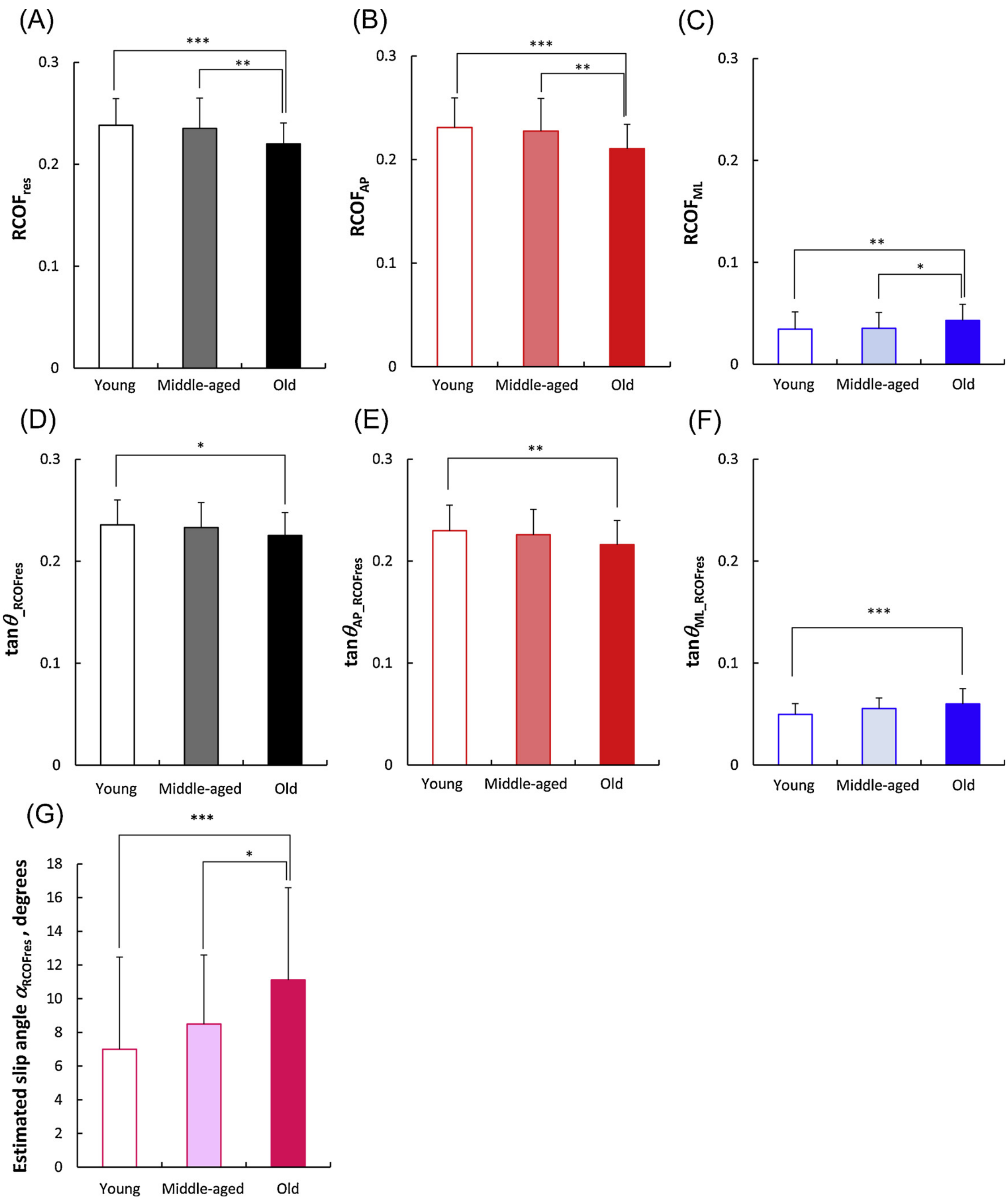

Fig. 3. Comparisons of the values of the (A) $RCOF_{res}$, (B) $RCOF_{AP}$, (C) $RCOF_{ML}$, (D) $\tan\theta_{\_RCOFres}$, (E) $\tan\theta_{AP\_RCOFres}$, (F) $\tan\theta_{ML\_RCOFres}$, and (G) $\alpha_{RCOFres}$ among the three age groups. $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.
$RCOF_{res}$, resultant required coefficient of friction; $RCOF_{AP}$, anteroposterior required coefficient of friction; $RCOF_{ML}$, mediolateral required coefficient of friction; $\tan\theta_{\_RCOFres}$, $\tan\theta$ value at the point of the $RCOF_{res}$; $\tan\theta_{AP\_RCOFres}$, $\tan\theta_{AP}$ value at the point of the $RCOF_{res}$; $\tan\theta_{ML\_RCOFres}$, $\tan\theta_{ML}$ value at the point of the $RCOF_{res}$; $\alpha_{RCOFres}$, α value at the point of $RCOF_{res}$.

5. Conclusion

Older adults walk with a lower $RCOF_{res}$ owing to a shorter step length, resulting in a lower slip risk, when compared with the findings in young and middle-aged adults. However, in older adults, the $RCOF_{ML}$ is higher owing to a wider step width, resulting in slips more laterally. Thus, the gait observed in older adults causes slips in a more lateral direction. Our results indicate the need for shoes with increased slip resistance in the ML direction in addition to the AP direction to prevent lateral slips among older adults, and this will provide new guidelines of shoe sole pattern design for older adults.

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.

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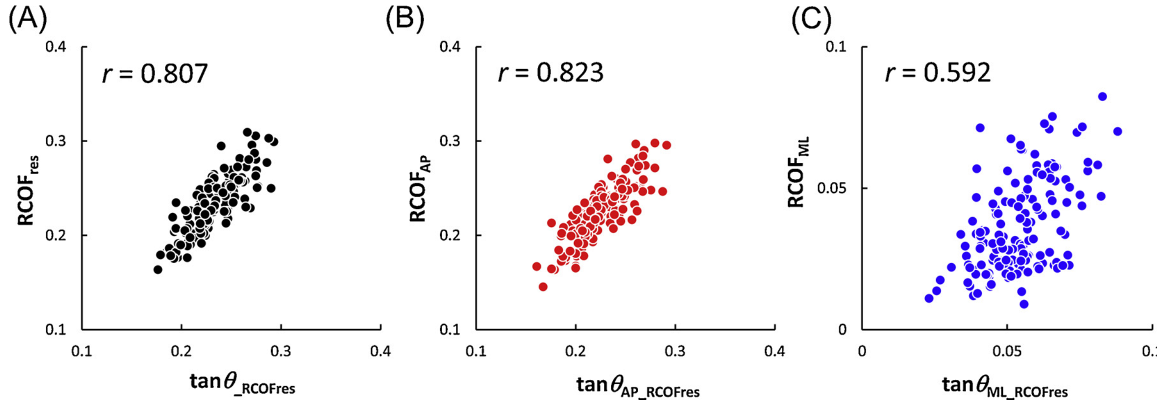

Fig. 4. Relationships between (A) $\tan\theta_{\_RCOFres}$ and $RCOF_{res}$, (B) $\tan\theta_{AP\_RCOFres}$ and $RCOF_{AP}$, and (C) $\tan\theta_{ML\_RCOFres}$ and $RCOF_{ML}$. The number of points for each graph is 188.$RCOF_{res}$, resultant required coefficient of friction; $RCOF_{AP}$, anteroposterior required coefficient of friction; $RCOF_{ML}$, mediolateral required coefficient of friction; $\tan\theta_{\_RCOFres}$, $\tan\theta$ value at the point of the $RCOF_{res}$; $\tan\theta_{AP\_RCOFres}$, $\tan\theta_{AP}$ value at the point of the $RCOF_{res}$; $\tan\theta_{ML\_RCOFres}$, $\tan\theta_{ML}$ value at the point of the $RCOF_{res.}$

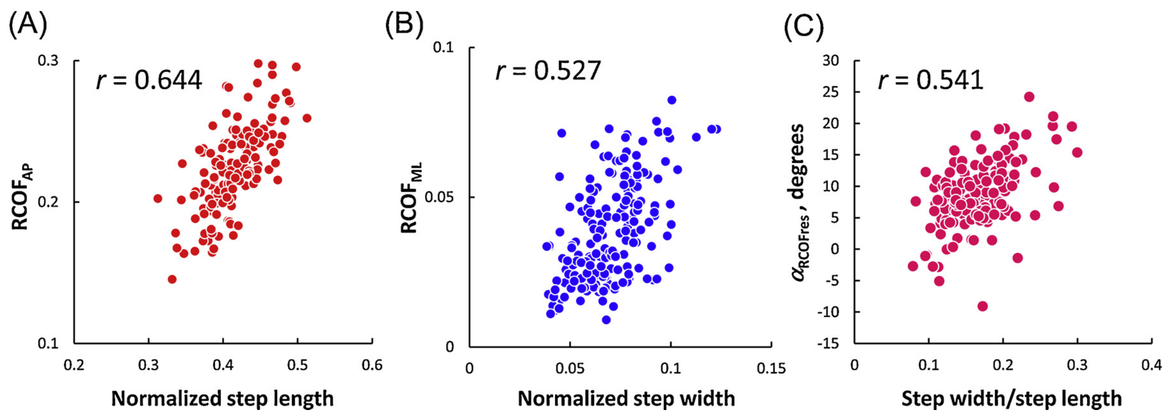

Fig. 5. Relationship between (A) the normalized step length and $RCOF_{AP}$, (B) the normalized step width and $RCOF_{ML}$, and (C) the ratio of step width to step length and $\alpha_{RCOFres}$. The number of points for each graph is 188.
$RCOF_{AP}$, anteroposterior required coefficient of friction; $RCOF_{ML}$, mediolateral required coefficient of friction.

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