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ORIGINAL ARTICLE

Intra-Foot Coordination and Its Variability During Walking in Males With and Without Chronic Ankle Instability

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BACKGROUND: Investigating the kinematics of copers, who are individuals with no recurrent ankle sprains, is necessary to prevent the development of chronic ankle instability (CAI). Since the “giving way” of the ankle joint (episodes of excessive inversion of the rearfoot, which do not result in an acute lateral ankle sprain) usually occurs during walking, investigating the intra-foot

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coordination during walking is necessary. This study aims to identify intra-foot coordination and its variability in copers while walking.

METHODS: The study included 12 copers, 13 CAIs, and 10 controls. The participants were required to walk on a treadmill at a fixed speed of 1.3 m/s. Using the modified vector coding technique, the coupling angle between the intra-foot joints, representing inter-joint coordination, was calculated and categorized into four coordination patterns. The coupling angle standard deviation represented the coordination variability during the stance phase.

RESULTS: The coordination between the rearfoot and midfoot in the frontal plane showed a significantly lower proportion of anti-phase with proximal dominance in the coper group than in the CAI and control groups during mid-stance ($p < .05$). Regarding coordination between the midfoot and forefoot in the sagittal plane, the coper group also showed a significantly lower proportion of in-phase coordination with distal dominancy than the CAI group during mid-stance ($p < .05$). For coordination between the midfoot and forefoot in the frontal plane, the coper group also showed a significantly lower proportion of anti-phase with distal dominance than the CAI group during the late stance ($p < .05$).The coordination variability between the sagittal midfoot and forefoot in the coper group was significantly lower than that in the CAI group and similar to that in the control group during mid-stance ($p < .050$).

CONCLUSIONS: These differences may explain why copers do not experience ankle sprain recurrence.

Lateral ankle sprain (LAS) is a common injury with a high prevalence and recurrence[1,2]. Forty percent of LAS patients develop chronic ankle instability (CAI) after an initial ankle sprain[3]. CAI is characterized by recurrent sprains, subjective ankle instability, and “giving way”[4]. Notably, not all individuals with LAS demonstrate CAI. Despite the high recurrence rate of LAS, copers are individuals who have not had a recurrence in > 12 months[5]. The mechanism underlying how copers do not experience recurrence is unclear.

It has been reported that copers have different walking and running biomechanics, including altered kinematics, compared with individuals with CAI. Studies have shown that during the stance phase of walking and running, copers have an ankle joint (rearfoot) in a less inverted position than individuals with CAI[6,7]. This is similar to the ankle joint motion of healthy participants[8]. The abnormal motion of the rearfoot can affect the distal joints due to the coupling motion within the foot during walking[9]. De Ridder et al.[10] reported that the copers and individuals with CAI showed increased medial forefoot inversion compared to controls during the stance phase of walking. However, there was no difference between copers and individuals with CAI. Notably, many studies have investigated the differences in individual joint kinematics; however, only a few have examined the coupling between the two joint motions in copers and individuals with CAI. Modified vector coding techniques can quantify the coordination between two joints based on the direction and amplitude of joint movements. In a cross-sectional study investigating intra-foot coordination during running in the coper and CAI groups, the coper group reported greater midfoot amplitude than the rearfoot during the late stance phase of running compared to the CAI group[11]. It has also been reported that the proportion of forefoot dominant coordination was lower in the coper group than in the CAI group in the early phase of the running stance[11]. Increasing the midfoot-dominant coordination pattern reduces stress on the soft tissues around the rearfoot. Therefore, intra-foot coordination has high power to detect differences between groups and may be beneficial for estimating stress around the rearfoot, such as the lateral ankle ligaments.

Walking is the most frequent movement during low-impact activities, and changes in intra-foot coordination during walking may lead to chronic LAS symptoms. Previous studies have reported that walking can cause “giving way”[12], defined as the regular occurrence of uncontrolled and unpredictable episodes of excessive inversion of the rearfoot, which do not result in an acute lateral ankle sprain[4]. The kinematic coupling has been reported to change task-dependently[13] and differs between walking and running in healthy participants[9]. This suggests that the data coordination for running may not necessarily apply to walking, and intra-foot coordination during walking must be investigated to clarify coper-specific kinematics. Understanding intra-foot coordination in copers and individuals with CAI during walking can explain the underlying mechanism that prevents copers from a re-sprain.

Changes in coordination variability are associated with the presence of lower-limb musculoskeletal injuries[14]. In a previous study[15], healthy participants were reported to have moderately high variability. However, a coordination variability that is too high compared with that of healthy participants indicates joint motion instability. High variability may exhibit behavior that leads to a “giving way”. Therefore, individuals with CAI may have increased variability compared with the coper and control groups. A previous study investigating intra-foot variability during running showed no differences between copers, individuals with CAI, and controls[11]. However, the coordination variability during walking in copers and individuals with CAI is unknown. In coordination of the shank and rearfoot, individuals with CAI demonstrated higher coordination variability than controls during walking and lower variability during running[16]. Therefore, the different constraints needed for walking and running may result in different coordination variability. Moreover, changes in coordination variability have been related to the sensorimotor equivalence that arises from the abundance of motor system degrees of freedom that characterize the human body[17]. Individuals with CAI have been reported to have lower sensorimotor function than copers and health individuals[18]. Walking has a longer stance phase than running and may be more affected by dysfunction; coper-specific intra-foot coordination may be detectable during walking.

This study examined the coordination and variability of the rearfoot, midfoot, and forefoot while walking in copers, individuals with CAI, and healthy controls. We hypothesized that: 1) copers exhibit to higher proportion of midfoot amplitude in the coordination between the rearfoot and midfoot than individuals with CAI; 2) copers exhibit a proportion of higher midfoot amplitude in the coordination between the midfoot and forefoot than individuals with CAI; and 3) copers show lesser variability than individuals with CAI and have a similar variability compared with controls in the variability of each pair of joint rotations.

Material and Methods

Participants

A total of 35 physically active male college students participated in this study. Notably, all participants had been involved in sporting activities for > 10 years (basketball and soccer). Participants were grouped as the CAI group, copers, and controls (healthy individuals without LAS) (Table 1), based on the inclusion and exclusion criteria published by the International Ankle Consortium[4]. Previous reports show that female have changes in general joint laxity due to female hormones, and it is necessary to investigate this variable if they are to be recruited for this experiment[19]. Therefore, only male participants were included in this study. Written informed consent was obtained from the participants before participation. This study was approved by the Niigata University of Health and Welfare internal review board (No. 18641-210618).

The copers met the following criteria[20]: (i) at least one episode of severe LAS with inflammatory symptoms (pain and swelling) occurring > 12 months before participation requiring the use of external ankle support for at least 1 week; (ii) a return to moderate levels of weight-bearing physical activity without repeated ankle injury in the past 12 months; (iii) a Cumberland Ankle Instability Tool (CAIT) score of ≥ 28 and an Identification of Functional Ankle Instability (IdFAI) score of ≤10[5]; and (iv) no recurrent LAS or perception of the ankle "giving way". The individuals with CAI met the following criteria[4]: (i) at least one episode of severe LAS occurring > 12 months before participation; (ii) recurrent sprains, the ankle "giving way," or "feeling of instability" in the affected ankle, and a CAIT score < 24; and (iii) an IdFAI score > 11[5]. The control group met the following criteria[21]: (i) no LAS in their lifetime; (ii) a CAIT score of 30 and an IdFAI score of 0; and (iii) no recurrent LAS or perception of the ankle "giving way". The exclusion criteria for all participants were: (i) lower extremity fracture or surgery and (ii) experience of acute musculoskeletal trauma in the past 3 months. "Giving way" is defined as the regular occurrence of uncontrolled and unpredictable episodes of excessive inversion of the rear foot (usually experienced during initial contact during walking or running), which do not result in an acute lateral ankle sprain[4].

Experimental protocol

Reflective markers (9.5 mm in diameter) were fixed to the right shank and foot at the tibial tuberosity, fibular head, medial malleolus, lateral malleolus, Achilles tendon attachment, sustentaculum tail, peroneal tubercle, navicular bone, cuboid, first metatarsal base, first metatarsal head, second metatarsal base, second metatarsal head, fifth metatarsal head, and head of the proximal phalanx of the hallux according to the Rizzoli foot model (RFM)[22] (Fig. 1). Reflective markers were affixed to the posterior superior iliac spine (PSIS) to define initial contact and toe-off. This model's reproducibility was confirmed in another study[23]. Static data were collected in the anatomical position before measurement during walking. Barefoot walking was performed to analyze intra-foot kinematics in the three groups, as there were no differences in intra-foot coordination under the sandal and barefoot conditions[24]. Since speed influences coordination[25], the walking speed was fixed on a treadmill (BW-SRM16: BARWING, Japan). Differences in ankle kinematics between copers and individuals with CAI are more detectable with increasing walking speed[6]; therefore, the treadmill speed was set to 1.3 m/s.

Furthermore, > 10 steps of data are required to measure coordination variability[26]; therefore, data were continuously collected for 100 full strides for three-dimensional kinematic analysis to increase accuracy since the setup allowed continuous data acquisition on the treadmill. All data were measured using a three-dimensional motion analysis system (Vicon, Oxford, UK; MX 13, MX 13+, and MX T20-S) with 12 infrared cameras at a sampling rate of 100 Hz.

Data analysis

Coordination and its variability were used in the analysis by randomly selecting 50 out of 100 strides because the accuracy increased as the number of steps increased. Raw marker trajectory data during walking were filtered using a second-order, zero-lag Butterworth low-pass filter with a 6 Hz cut-off frequency[27] using Vicon Nexus software (version 2.8.1; Vicon, Oxford, UK). The rearfoot, midfoot, forefoot, and shank segments were created from reflective markers attached to bony landmarks based on the RFM[22]. The three-dimensional joint angles were calculated at the distal joint segment. They were expressed relative to the adjacent proximal segment using a right-handed orthogonal Cardan Zxy rotation (sequence of plantarflexion/dorsiflexion, eversion/inversion, and abduction/adduction) [22]. Joint angles were calculated using Visual 3D (C-Motion, Germantown, MD, USA) for the rearfoot with respect to the shank (rearfoot angle), midfoot with respect to the rearfoot (midfoot angle), and forefoot with respect to the midfoot (forefoot angle). After calculating each joint angle during walking, the data were time-normalized to the stance phase (102 points) since the coupling angle was set to 101[28].

Initial contact and toe-off were defined based on a previous study[29]. The initial contact was defined as the maximum anterior-posterior component of the calcaneus and PSIS markers. The toe-off was defined as the minimum anterior-posterior component of the second metatarsal head and PSIS markers.

Coordination data were calculated from the angle-angle diagram (Fig. 2). Proximal and distal joint angles were represented on the horizontal and vertical axes, respectively[30]. The coordination was inferred from the coupling angle (γ) (Table 2). In the present study, the coupling angle was calculated using the modified vector coding technique[30] (Equation 1).

$$\gamma_{j,i} = \tan^{-1}\left(\frac{y_{j,i+1}-y_{j,i}}{x_{j,i+1}-x_{j,i}}\right) \qquad (1)$$

where $0° \leq \gamma \leq 360°$, xj,i and yj,i represent the proximal and distal joint angles, respectively, and i represents the percentage of the jth stride stance.

Coupling angles were performed using circular statistics (Equations 2 and 3)[31]. where i represents the percentage of the jth stride stance.

$$\bar{x}_i = \frac{1}{n}\sum_{j=1}^{n}\left(\cos\gamma_{j,i}\right) \qquad (2)$$

$$\bar{y}_i = \frac{1}{n}\sum_{j=1}^{n}\left(\sin\gamma_{j,i}\right) \qquad (3)$$

$$\bar{\gamma}_i = \begin{cases} arctan\,(\bar{y}_i/\bar{x}_i) & if\ \bar{x}_i > 0 \\ 180 + arctan\,(\bar{y}_i/\bar{x}_i) & if\ \bar{y}_i < 0 \end{cases} \qquad (4)$$

The intra-foot joint couplings of interest included (1) rearfoot vs. midfoot sagittal, (2) rearfoot vs. midfoot frontal, (3) midfoot vs. forefoot sagittal, and (4) midfoot vs. forefoot frontal[27]. The coupling angle represents an instantaneous spatial relationship, from which four coordination patterns can be identified: (i) in-phase with proximal joint dominancy (the same direction and greater angular amplitude of the proximal segment); (ii) in-phase with distal dominancy (the same direction and greater angular amplitude of the distal segment); (iii) anti-phase with proximal dominancy (the opposite direction and greater angular amplitude of the proximal segment); and (iv) anti-phase with distal dominancy (the opposite direction and greater angular amplitude of the distal segment)[32].

Coordination variability was calculated as the circular standard deviation of the coupling angle across 50 strides (Equation 5).

$$\mathrm{Variability}_i = \sqrt{2 \cdot (1 - \bar{\gamma}_i)} \qquad (5)$$

where $\bar{\gamma}_i$ represents the coupling angle at the ith frame. The equations 4 and 5 are multiplied by 180/π to convert the units from radians to degrees.

Coordination patterns and variability were classified into three phases of walking: early- (0–33%), mid- (34–67%), and late-stance (68–100%), based on previous studies on walking coordination[27,30]. In this study, each coordination patterns were calculated as the percent of each gait cycle phase spent in a particular pattern.

Statistical analysis

Statistical analyses were performed to detect differences in the coordination patterns and average variability for each phase among these groups. The Shapiro–Wilk test was used to assess the distribution of all parameters. If data were normally distributed, one-way analysis of variance (ANOVA) was performed to compare these groups and Tukey–Kramer tests were performed when significant main group effects were observed. The Kruskal-Wallis and Steel-

Dwass tests were performed if the data were inconsistent with a normal distribution. Partial eta squared (η^2_p) was used to calculate the effect size (ES) for the statistically significant results. Small, medium, and large effect sizes were indicated by η^2_p values > 0.01, 0.06, and 0.14, respectively[33]. All statistical analyses were performed using R Studio (version 4.0.4; The R Foundation for Statistical Computing, Vienna, Austria), and the level of statistical significance was set at $p < .050$. Post-hoc power analyses were performed for significance and non-significance using the G*Power 3.1 program (Universität Düsseldorf, Düsseldorf, Germany). Post-hoc power was given by the formula 1–ß in the Results and Appendix..

Results

Coordination between rearfoot and midfoot

The time-series data of the coupling angle and variability between the rearfoot and midfoot in the three groups are presented in Fig. 3. The waveform patterns of the coupling angles of the three groups were different during the early stance, in the sagittal plane (Fig. 3a), and in the frontal plane during the mid-stance (Fig. 3b). During the early stance, in the sagittal plane, the coper and CAI groups showed a significantly lower proportion of anti-phase with midfoot dominancy than the control group (control = 8.2 ± 2.1%, coper = 3.3 ± 0.5%, CAI = 3.8 ± 1.4%, $p < .05$, ES = 0.20 [Large]) (Fig. 5a). During the mid-stance in the frontal plane, the coper group showed a significantly lower proportion of anti-phase with rearfoot dominancy than the CAI and control groups (control = 26.8 ± 3.0%, coper = 9.1 ± 2.5%, CAI = 23.7 ± 4.4%, $p < .05$, ES = 0.38 [Large]) (Fig. 5b).

Coordination between midfoot and forefoot

The time-series data of the coupling angle and variability between the midfoot and forefoot in the study groups are presented in Fig. 4. During the mid-stance phase, in the sagittal plane (Fig. 4c), the coupling angle of the coper group was approximately 0º`. During the mid-stance phase, in the sagittal plane, the coper group showed a significantly higher proportion of anti-phase with midfoot dominancy than the control group (control = 26.4 ± 3.7%, coper = 46.2 ± 4.7%, $p < .05$, ES = 0.29 [Large]) and significantly lower proportion of in-phase with forefoot dominancy than the CAI group (coper = 4.4 ± 1.9%, CAI = 8.6 ± 1.9%, $p < .05$, ES = 0.15 [Large]) (Fig. 5c). During the early stance, in the frontal plane, the CAI group showed a significantly lower proportion of in-phase with forefoot dominancy than the control group (control = 31.5 ± 4.6%, CAI = 15.3 ± 4.3%, $p < .05$, ES = 0.22 [Large]). The CAI group also showed a significantly higher proportion of anti-phase with midfoot dominancy than the control group (control = 15.2 ± 2.3%, CAI = 27.7 ± 3.6%, $p < .05$, ES = 0.20 [Large]) (Fig. 5d). During the late-stance, the coper group showed a significantly lower proportion of anti-phase with forefoot dominancy than the CAI group (Coper = 14.6 ± 2.2%, CAI = 23.9 ± 3.8%, $p < .05$, ES = 0.20 [Large]) (Fig. 5d).

Coordination variability

During the mid-stance phase, for the midfoot and forefoot in the sagittal plane, the coper group showed a significantly lower coordination variability than the CAI group (coper = 17.4 ± 9.5%, CAI = 25.3 ± 8.6%, $p < .05$, ES = 0.17 [Large]). For the midfoot and forefoot in the sagittal plane, the coper group showed no significant difference in coordination variability compared with the control group (Fig. 6c).

Table A1 (Appendix A) summarizes the results for coordination patterns and their variability. Only coordination among the rearfoot, midfoot, and forefoot in the frontal plane has been presented in an accepted article (Biomechanism 26, Society of Biomechanisms Japan).

Discussion

In this study, we investigated the coordination and variability of the rearfoot, midfoot, and forefoot while walking in copers, individuals with CAI, and healthy controls. Our study partially supports the hypothesis that copers exhibit an increased midfoot amplitude in coordination with the rearfoot, midfoot, and forefoot. During the mid-stance the midfoot and forefoot sagittal plane coordination variability was significantly lower in the copers than in the CAI group. Previous studies have not revealed differences in the intra-foot kinematics between the coper and CAI groups during walking[10]. Midfoot and forefoot characteristics are potentially involved in the mechanisms of ankle sprain[34]. It is necessary to indicate the difference in intra-foot kinematics between the coper and CAI groups. This study is the first to clarify the intra-foot kinematics of the coper and CAI groups during walking.

In the rearfoot and midfoot frontal planes, the coper group showed a significantly lower proportion of anti-phase rearfoot dominance than the CAI and control groups during mid-stance. In the midfoot, forefoot sagittal, and frontal planes, the coper group showed a significantly lower proportion of forefoot dominance than the CAI group during mid- and late stances. These results support the hypothesis that copers have an increased proportion of patterns with large midfoot amplitudes during intra-foot coordination. In a cross-sectional study investigating intra-foot coordination during running in coper and CAI groups, the coper group reported greater midfoot amplitude than the rearfoot during the late stance phase of running compared to the CAI group[11]. The rearfoot-dominant coordination pattern may stress the soft tissues around the talocrural and subtalar joints, consequently leading to progressive ligament dysfunction. Therefore, the coper groups may have increased the proportion of midfoot-dominant coordination patterns. It has also been reported that, in the early phase of the running stance, the proportion of forefoot dominant coordination was lower in the coper group than in the CAI group[11]. A similar trend was observed in the present study. As for the coordination between the midfoot and forefoot, this may be a characteristic of copers who move the midfoot relatively more by limiting forefoot motion. However, it is unclear how this pattern is related to mechanical stress. Furthermore, the anti-phase is considered to be soft tissue stress due to the torsion between joints[30]. In the present study, coper exhibited increased and decreased patterns of anti-phase. Therefore, we cannot conclude that the anti-phase was negative based on the results of this study. Prospective studies should be conducted in the future.

Coordination may be influenced by the stiffness of the soft tissues around the joint[35]. The rearfoot, midfoot, and forefoot contain extrinsic foot muscles (e.g., the peroneus longus and tibialis posterior) and intrinsic foot muscles (e.g., the abductor hallucis and flexor digitorum brevis)[36]. Patients with acute ankle sprain and CAI have been reported to have decreased ankle plantar flexion, inversion, eversion, hallux, and lesser toe flexion strength than the coper and control groups[37]. These strengths involve the extrinsic and intrinsic foot muscles, which may affect the intra-foot coordination. Therefore, to achieve coordination, training of the extrinsic and intrinsic foot muscles may be necessary. However, this study did not investigate muscle strength in each group. In future studies, it is necessary to investigate the relationship between muscle strength and intra-foot coordination.

The coordination variability between the midfoot and forefoot sagittal planes was significantly lower in the copers than in the CAI group during mid-stance, and there was no significant difference compared with the control group. However, health variability has not yet been determined[38]. Assuming that the variability of the control group is healthy, the coper group is similar to the control group; thus, the copers may have healthy variability. The CAI group has been reported to have decreased spinal reflex excitability compared with the coper and control groups[18]. Additionally, atrophy and weakness of the intrinsic and extrinsic foot muscles have been reported in the CAI group[37,39]. Based on the results of these previous studies, CAI participants may lack sensorimotor, which may be responsible for the increased variability. Coordination variability, which is too high compared to that in healthy subjects, indicates joint motion instability. Because the mid-stance always involves single-leg support, it is considered the phase of walking with the highest postural demands. “Giving way” is defined as the regular occurrence of uncontrolled and unpredictable episodes of excessive rearfoot inversion in individuals with CAI[4]. Several factors contribute to the development of “giving way” after an initial sprain. Because changes in sagittal plane kinematics also occur during the “giving way”[40], changes in the variability of the midfoot-forefoot sagittal plane may also be involved. However, the sensorimotor function was not measured in this study. Therefore, it is necessary to analyze the direct relationship between the results obtained in this study and sensorimotor function in future studies.

This study had several limitations. First, only male participants were included. The incidence of ankle sprain in females is approximately twice that in males[41]. Therefore, it is necessary to investigate coordination in females in the future. Second, this study did not evaluate the mechanical instability in the CAI and coper groups, and the instability of the foot and ankle joints may have influenced our study's results[42]. Future studies should simultaneously investigate mechanical instability and intra-foot coordination to provide a more detailed explanation of the study's results. Third, the intra-foot coordination and its variability can only be measured using a three-dimensional motion analyze system. Applying a stretch strain sensor to the foot makes it possible to measure the kinematics of the rearfoot and forefoot during walking[43]. However, it is unclear whether this sensor can be used to measure intra-foot coordination. In future studies, it is necessary to establish a method to easily evaluate the results obtained in this study in a clinical setting. Fourth, this study had a small sample size and limited statistical power; consequently, it may have been susceptible to a type II error. For example, the coordination was below 0.8 and may have been prone to type II errors. These nonsignificant results should be interpreted with caution.

Conclusion

In this study, the coper group showed a greater midfoot amplitude than the CAI group. This result indicates that interventions focusing on midfoot (mainly transverse tarsal joint) mobility may benefit injured patients after the initial LAS. The coordination variability between the midfoot and forefoot sagittal planes in the coper group was lower than that in the CAI group and similar to that in the control group. Intervention for midfoot and forefoot sagittal plane stability is necessary for injured patients after an initial ankle sprain. The differences in coordination and variability observed in this study may explain the mechanism by which the copers did not experience LAS recurrence.

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References

1. Hootman JM, Dick R, Agel J. Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. *J. Athl. Train.* **42**: 311–319, 2007.
2. McKay GD, Goldie PA, Payne WR, et al. Ankle injuries in basketball: injury rate and risk factors. *Br. J. Sports Med.* **35**: 103–108, 2001.
3. Doherty C, Bleakley C, Hertel J, et al.Recovery From a First-Time Lateral Ankle Sprain and the Predictors of Chronic Ankle Instability: A Prospective Cohort Analysis. *Am. J. Sports Med.* **44**: 995–1003, 2016.

4. Gribble PA, Delahunt E, Bleakley CM, et al. Selection criteria for patients with chronic ankle instability in controlled research: a position statement of the International Ankle Consortium. *J. Athl. Train.* **49**: 121–127, 2014.
5. Hertel J, Corbett RO. An Updated Model of Chronic Ankle Instability. *J. Athl. Train.* **54**: 572–588, 2019.
6. Koldenhoven RM, Hart J, Saliba S, et al. Gait kinematics & kinetics at three walking speeds in individuals with chronic ankle instability and ankle sprain copers. *Gait Posture* **74**: 169–175, 2019.
7. Koldenhoven RM, Hart J, Abel MF, et al. Running gait biomechanics in females with chronic ankle instability and ankle sprain copers. *Sports Biomech.* **21**: 447–459, 2022.
8. Sun D, Fekete G, Mei Q, et al. The effect of walking speed on the foot inter-segment kinematics, ground reaction forces and lower limb joint moments. *PeerJ* **6**: e5517, 2018.
9. Takabayashi T, Edama M, Yokoyama E, et al. Changes in Kinematic Coupling Among the Rearfoot, Midfoot, and Forefoot Segments During Running and Walking. *J. Am. Podiatr. Med. Assoc.* **108**: 45–51, 2018.
10. De Ridder R, Willems T, Vanrenterghem J, et al. Gait kinematics of subjects with ankle instability using a multisegmented foot model. *Med. Sci. Sports Exerc.* **45**: 2129–2136, 2013.
11. Watanabe T, Takabayashi T, Watabe T, et al. Coper has altered foot joint coordination pattern compared to individuals with chronic ankle instability during running. *Gait Posture* **98**: 173–179, 2022.

12. Takeda R, Nakajima K, Anzai E, et al. A “Giving way” captured during walking by gyroscopes and plantar force sensors. *J. Biomech.* **129**: 110754, 2021.
13. Koshino Y, Yamanaka M, Ezawa Y, et al. Coupling motion between rearfoot and hip and knee joints during walking and single-leg landing. *J. Electromyogr. Kinesiol.* **37**: 75–83, 2017.
14. Hamill J, Van Emmerik REA, Heiderscheit BC, et al. A dynamical systems approach to lower extremity running injuries. *Clin. Biomech.* **14**: 297–308, 1999.
15. Hamill J, Palmer C, Van Emmerik REA. Coordinative variability and overuse injury. *Sports Med. Arthrosc. Rehabil. Ther. Technol.* **4**: 45, 2012.
16. Lilley T, Herb CC, Hart J, et al. Lower extremity joint coupling variability during gait in young adults with and without chronic ankle instability. *Sports Biomech.* **17**: 261–272, 2018.
17. Davids K, Glazier P, Araujo D, et al. Movement systems as dynamical systems. *Sports Med.* **33**: 245–260, 2003.
18. Bowker S, Terada M, Thomas AC, et al. Neural Excitability and Joint Laxity in Chronic Ankle Instability, Coper, and Control Groups. *J. Athl. Train.* **51**: 336–343, 2016.
19. Shultz SJ, Levine BJ, Nguyen AD, et al. A comparison of cyclic variations in anterior knee laxity, genu recurvatum, and general joint laxity across the menstrual cycle. *J. Orthop. Res.* **28**: 1411–1417, 2010.
20. Wikstrom EA, Brown CN. Minimum reporting standards for copers in chronic ankle instability research. *Sports Med.* **44**: 251–268, 2014.

21. Watabe T, Takabayashi T, Tokunaga Y, et al. Copers adopt an altered dynamic postural control compared to individuals with chronic ankle instability and controls in unanticipated single-leg landing. *Gait Posture* **92**: 378–382, 2022.
22. Leardini A, Benedetti MG, Berti L, et al. Rear-foot, mid-foot and fore-foot motion during the stance phase of gait. *Gait Posture* **25**: 453–462, 2007.
23. Deschamps K, Staes F, Bruyninckx H, et al. Repeatability in the assessment of multi-segment foot kinematics. *Gait Posture* **35**: 255–260, 2012.
24. Eslami M, Begon M, Farahpour N, et al. Forefoot-rearfoot coupling patterns and tibial internal rotation during stance phase of barefoot versus shod running. *Clin. Biomech.* **22**: 74–80, 2007.
25. Bailey JP, Freedman Silvernail J, Dufek JS, et al. Effects of treadmill running velocity on lower extremity coordination variability in healthy runners. *Hum. Mov. Sci.* **61**: 144–150, 2018.
26. Hafer JF, Boyer KA. Variability of segment coordination using a vector coding technique: Reliability analysis for treadmill walking and running. *Gait Posture* **51**: 222–227, 2017.
27. Takabayashi T, Edama M, Nakamura E, et al. Coordination among the rearfoot, midfoot, and forefoot during walking. *J. Foot Ankle Res.* **10**: 42, 2017.
28. Takabayashi T, Edama M, Inai T, et al. Gender differences in coordination variability between shank and rearfoot during running. *Hum. Mov. Sci.* **66**: 91–97, 2019.
29. Zeni JA, Richards JG, Higginson JS. Two simple methods for determining gait events during treadmill and overground walking using kinematic data. Gait Posture **27**: 710–714, 2008.

30. Chang R, Van Emmerik R, Hamill J. Quantifying rearfoot-forefoot coordination in human walking. J. Biomech. **41**: 3101–3105, 2008.
31. Batschelet E. Circular statistics in biology, Mathematics in biology. London, New York: Academic Press; 1981.
32. Needham R, Naemi R, Chockalingam N. Quantification of rear-foot, fore-foot coordination pattern during gait using a new classification. Footwear Sci. **7**: S32–S33, 2015.
33. Cohen J. Statistical power analysis for the behavioral sciences. Routledge; 2013.
34. Morrison KE, Kaminski TW. Foot characteristics in association with inversion ankle injury. J. Athl. Train. **42**: 135–142, 2007.
35. Pohl MB, Messenger N, Buckley JG. Forefoot, rearfoot and shank coupling: effect of variations in speed and mode of gait. Gait Posture **25**: 295–302, 2007.
36. McKeon PO, Hertel J, Bramble D, Davis I. The foot core system: a new paradigm for understanding intrinsic foot muscle function. Br. J. Sports Med. **49**: 290, 2015.
37. Fraser JJ, Koldenhoven RM, Jaffri AH, et al. Foot impairments contribute to functional limitation in individuals with ankle sprain and chronic ankle instability. Knee Surg. Sports Traumatol. Arthrosc. **28**: 1600–1610, 2020.
38. Silvernail JF, Boyer K, Rohr E, et al. J. Running Mechanics and Variability with Aging. Med. Sci. Sports Exerc. **47**: 2175–2180, 2015.
39. Feger MA, Snell S, Handsfield GG, et al. Diminished Foot and Ankle Muscle Volumes in Young Adults With Chronic Ankle Instability. *Orthop J Sports Med* **4**: 2325967116653719, 2016.

40. Li Y, Ko J, Zhang S, et al. Biomechanics of ankle giving way: A case report of accidental ankle giving way during the drop landing test. *J Sport Health Sci* **8**: 494–502, 2019.
41. Doherty C, Delahunt E, Caulfield B, *et al.* The incidence and prevalence of ankle sprain injury: a systematic review and meta-analysis of prospective epidemiological studies. *Sports Med.* **44**: 123–140, 2014.
42. Brown C, Padua D, Marshall SW, et al. Individuals with mechanical ankle instability exhibit different motion patterns than those with functional ankle instability and ankle sprain copers. *Clin. Biomech.* **23**: 822–831, 2008.
43. Sakamoto K, Tsujioka C, Sasaki M, *et al.* Validity and reproducibility of foot motion analysis using a stretch strain sensor. *Gait Posture* **86**: 180–185, 2021.

Table 1: Participant characteristics

Variables	Control	Coper	CAI	*p*-value
N	10	12	13	—
Age (years)	20.7 ±1.6	20.2±0.8	21.0±1.3	0.31
Height (cm)	175.5±6.2	172.9±3.7	178.5±5.9	0.32
Weight (kg)	67.3±6.8	64.1±9.1	69.3±5.3	0.29
CAIT	30.0±0.0	28.3±0.9	18.0±4.3	—
IdFAI	0.0±0.0	8.3±8.3	24.0±4.3	—
Total ankle sprains (times)	0.0±0.0	1.0±0.0	4.0±2.7	—

Data are given as mean ± SD. Abbreviations: CAI, chronic ankle instability; CAIT, Cumberland Ankle Instability Tool; IdFAI, Identification Functional Ankle Instability.

Table 2: Definitions to classify coordination patterns

Coordination pattern	Dominant of joint	Coupling angle definitions
In-phase	Proximal	$0^\circ < \gamma < 45^\circ$, $180^\circ < \gamma < 225^\circ$
	Distal	$45^\circ < \gamma < 90^\circ$, $225^\circ < \gamma < 270^\circ$
Anti-phase	Distal	$90^\circ < \gamma < 135^\circ$, $270^\circ < \gamma < 315^\circ$
	Proximal	$135^\circ < \gamma < 180^\circ$, $315^\circ < \gamma < 0^\circ$

Figure 1: Anterior (a) and medial views (b) of the marker set, and segment construction (c).

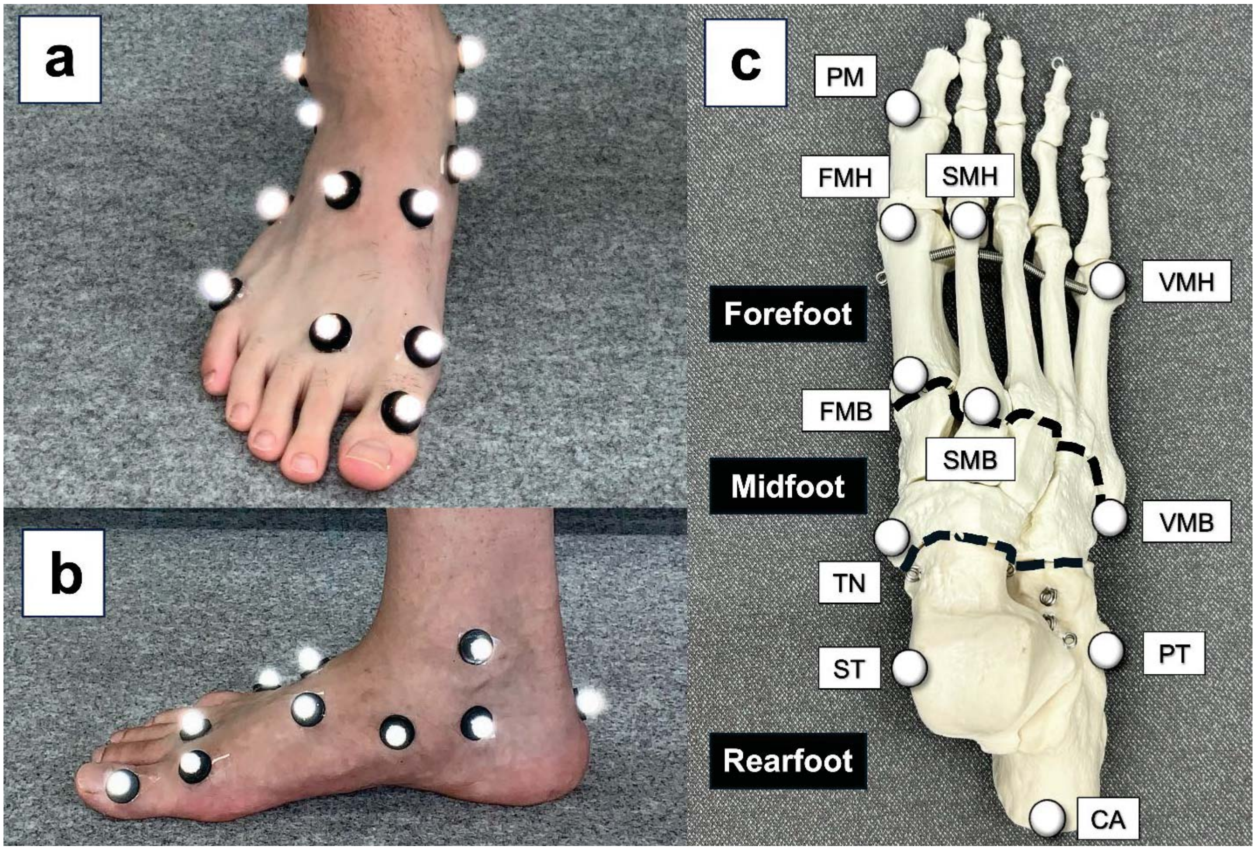

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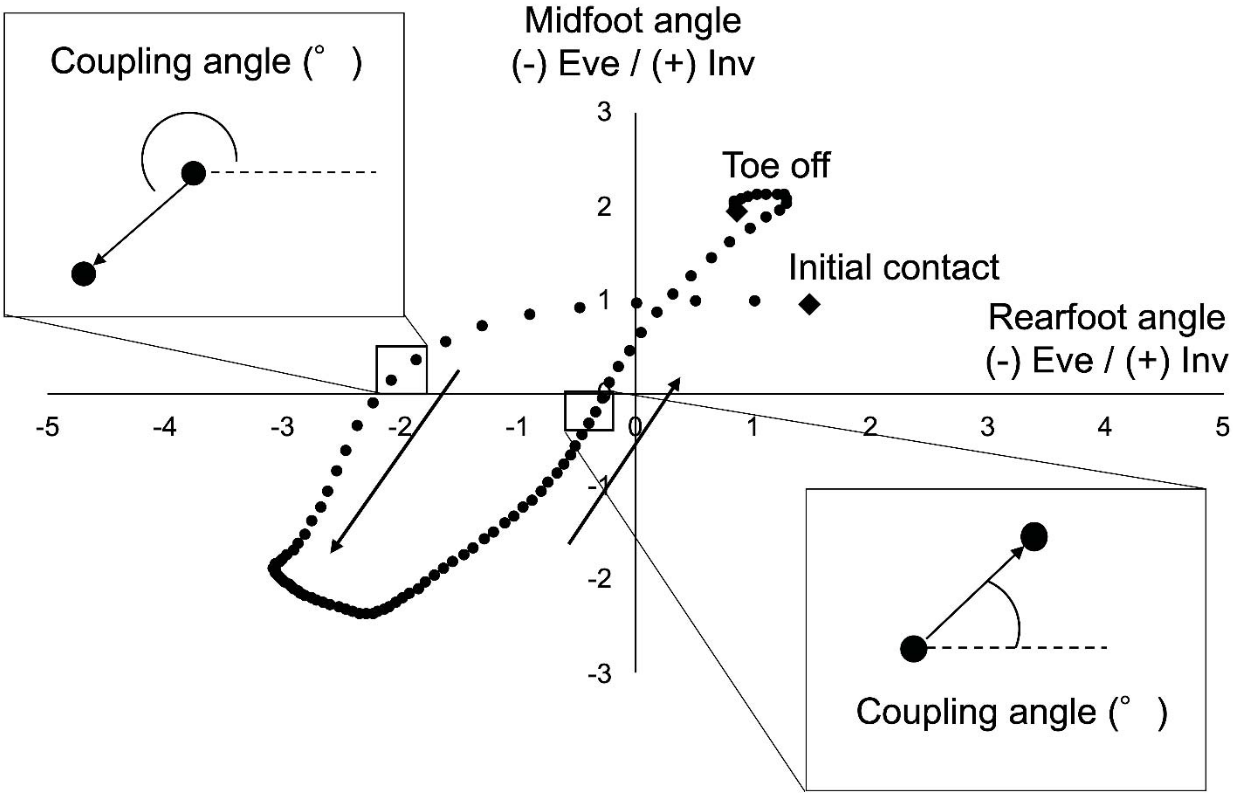
Fig. 2: Inferring coordination: Angle-angle plot of rearfoot and midfoot frontal plane motions. The coupling angle is calculated as the angle between the horizontal plane and the line connecting the points plotted from each time-series angle data.



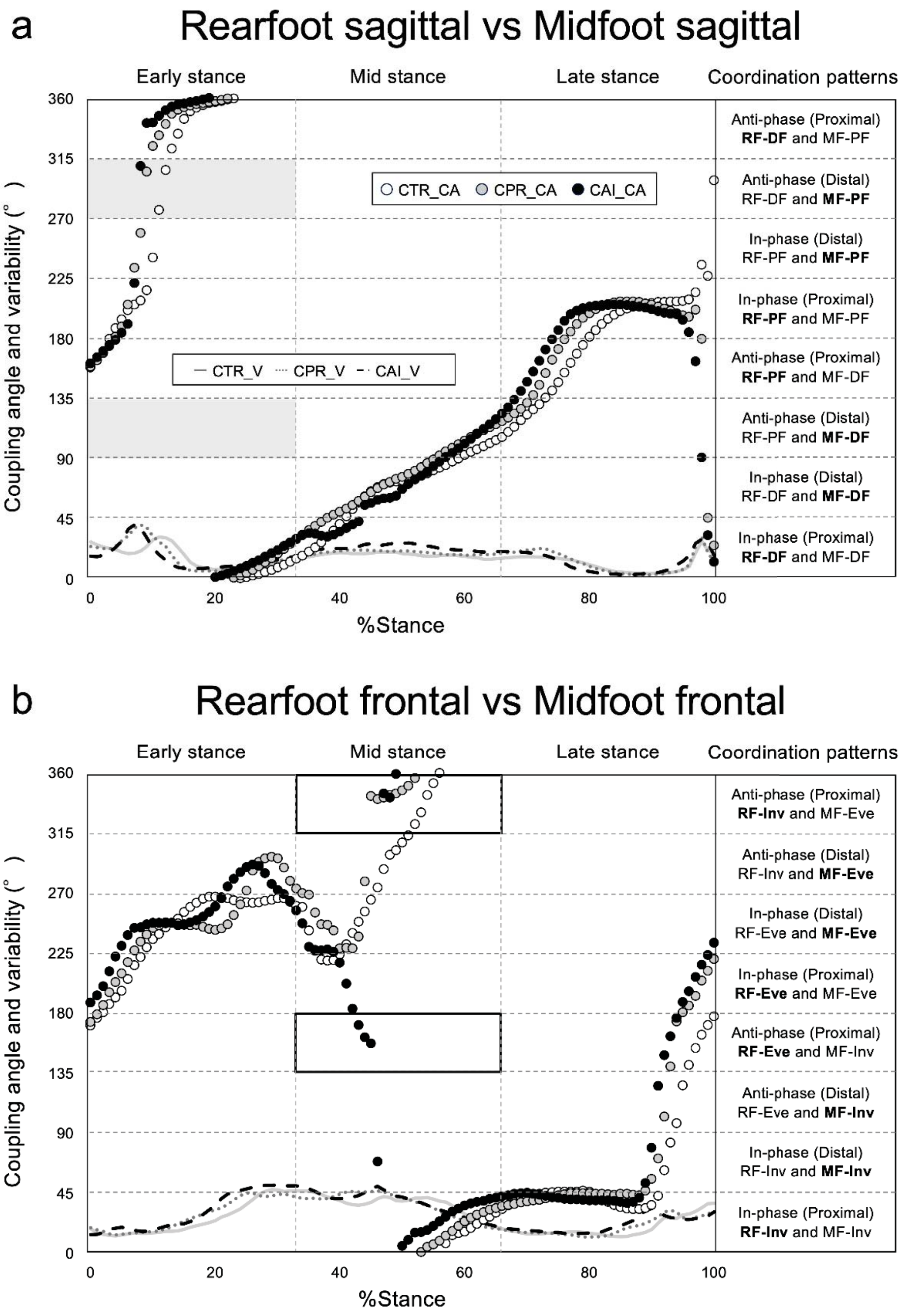


Fig. 3: Time-series data of the mean coupling angle and its variability among the rearfoot and midfoot: (a) rearfoot and midfoot sagittal planes, (b) rearfoot and midfoot frontal planes, during walking in control (CTR), coper (CPR) and chronic ankle instability groups (CAI). Shading indicates statistically significant differences among groups. Abbreviations: CA, coupling angle; V, variability.

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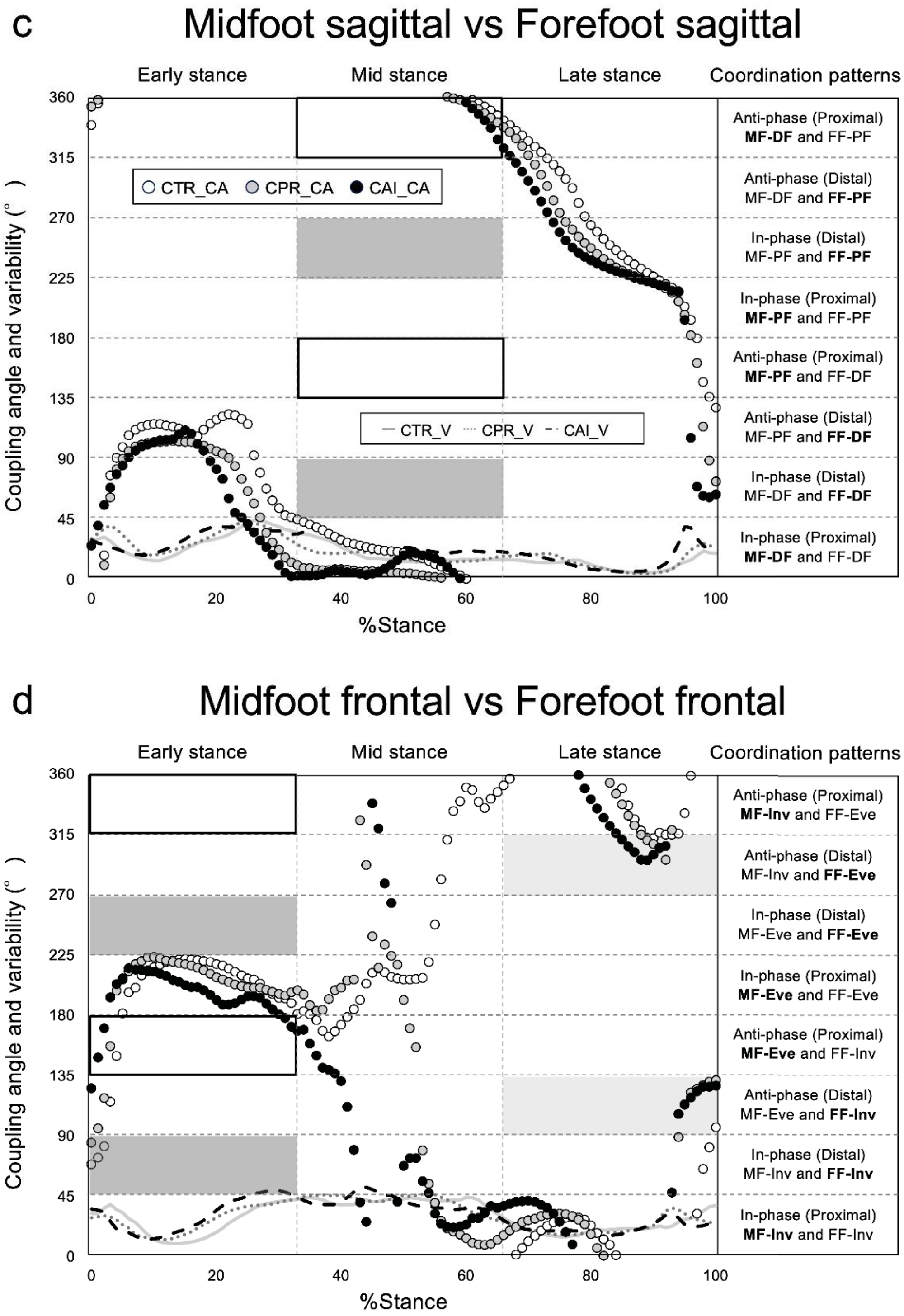

Fig. 4: Time-series data of the mean coupling angle and its variability among the midfoot and forefoot: (c) midfoot and forefoot sagittal planes, (d) midfoot and forefoot frontal planes, during walking in control (CTR), coper (CPR) and chronic ankle instability groups (CAI). Shading indicates statistically significant differences among groups. Abbreviations: CA, coupling angle; V, variability.

Fig. 5: Stacked graph for the proportion of intra-foot coordination during each stance of walking: (a) rearfoot and midfoot sagittal planes, (b) rearfoot and midfoot frontal planes, midfoot and forefoot sagittal planes, (c) midfoot and forefoot sagittal planes, and (d) midfoot and forefoot frontal planes coordination patterns during the walking stance phase. The asterisk (*) indicates a significant change between each group (p<0.05). (**) indicates a significant change between each group (p<0.01). (***) indicates a significant change between each group (p<0.001). Abbreviations: In (Prox); In-phase with proximal dominance, In (Dis); In-phase with distal dominance, Anti (Dis); Anti-phase with distal dominance, Anti (Prox); Anti-phase with proximal dominance. Abbreviations: CAI, chronic ankle instability group.

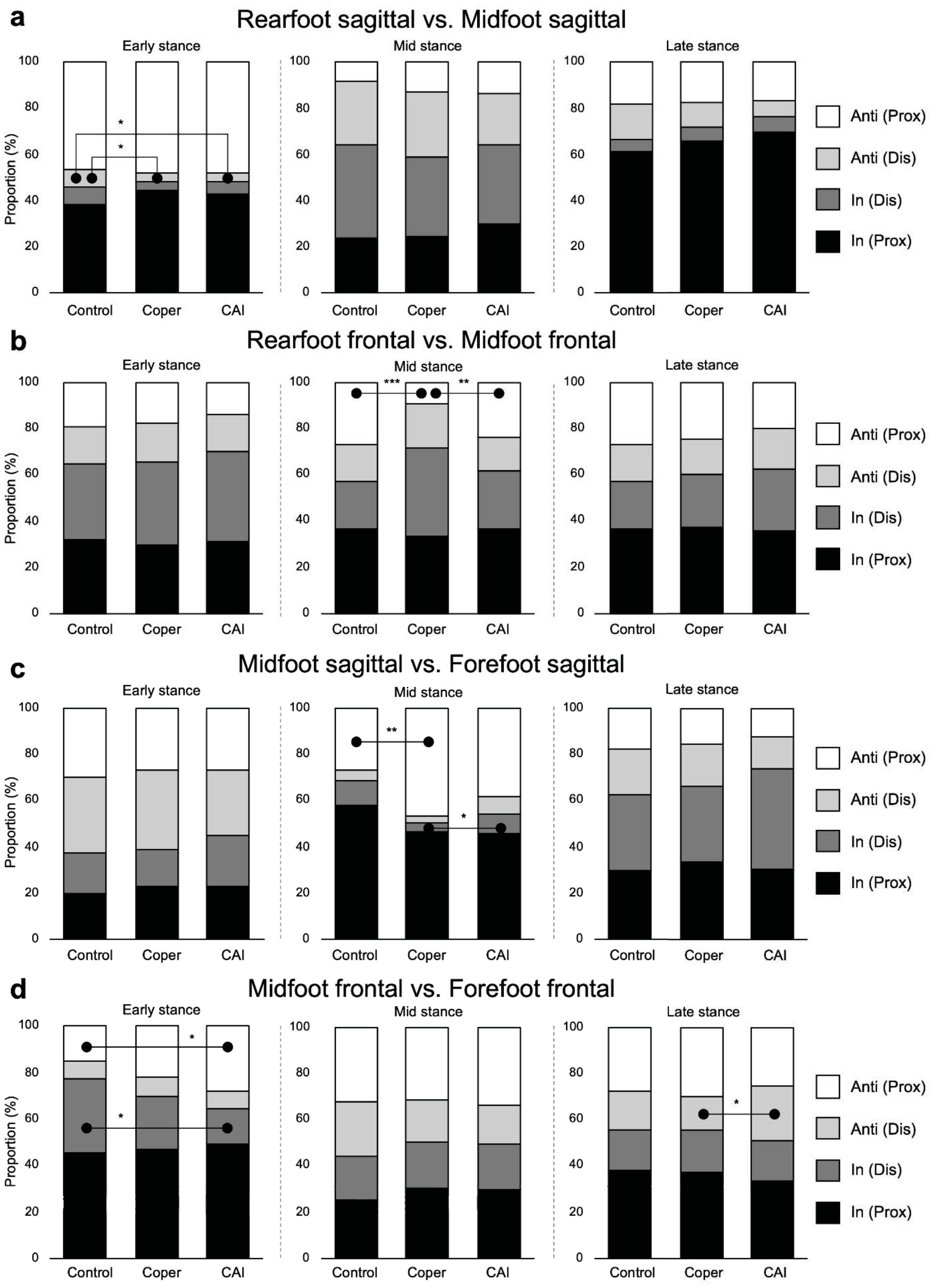
a
Rearfoot sagittal vs. Midfoot sagittal
b
Rearfoot frontal vs. Midfoot frontal
c
Midfoot sagittal vs. Forefoot sagittal
d
Midfoot frontal vs. Forefoot frontal
Early stance
Mid stance
Late stance
Proportion (%)
0
20
40
60
80
100
Control
Coper
CAI
*
**
***
Anti (Prox)
Anti (Dis)
In (Dis)
In (Prox)

Fig. 6: Stacked graph for intra-foot coordination variability during walking. (a) Plots for rearfoot and midfoot sagittal planes, (b) rearfoot and midfoot frontal planes, (c) midfoot and forefoot sagittal planes, (d) midfoot and forefoot frontal planes coupling angle variability during the walking stance phase. Abbreviations: CAI, chronic ankle instability. The asterisk (*) indicates a significant change between copers and CAI (*p*<0.05).