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Movement coordination patterns between the foot joints during walking
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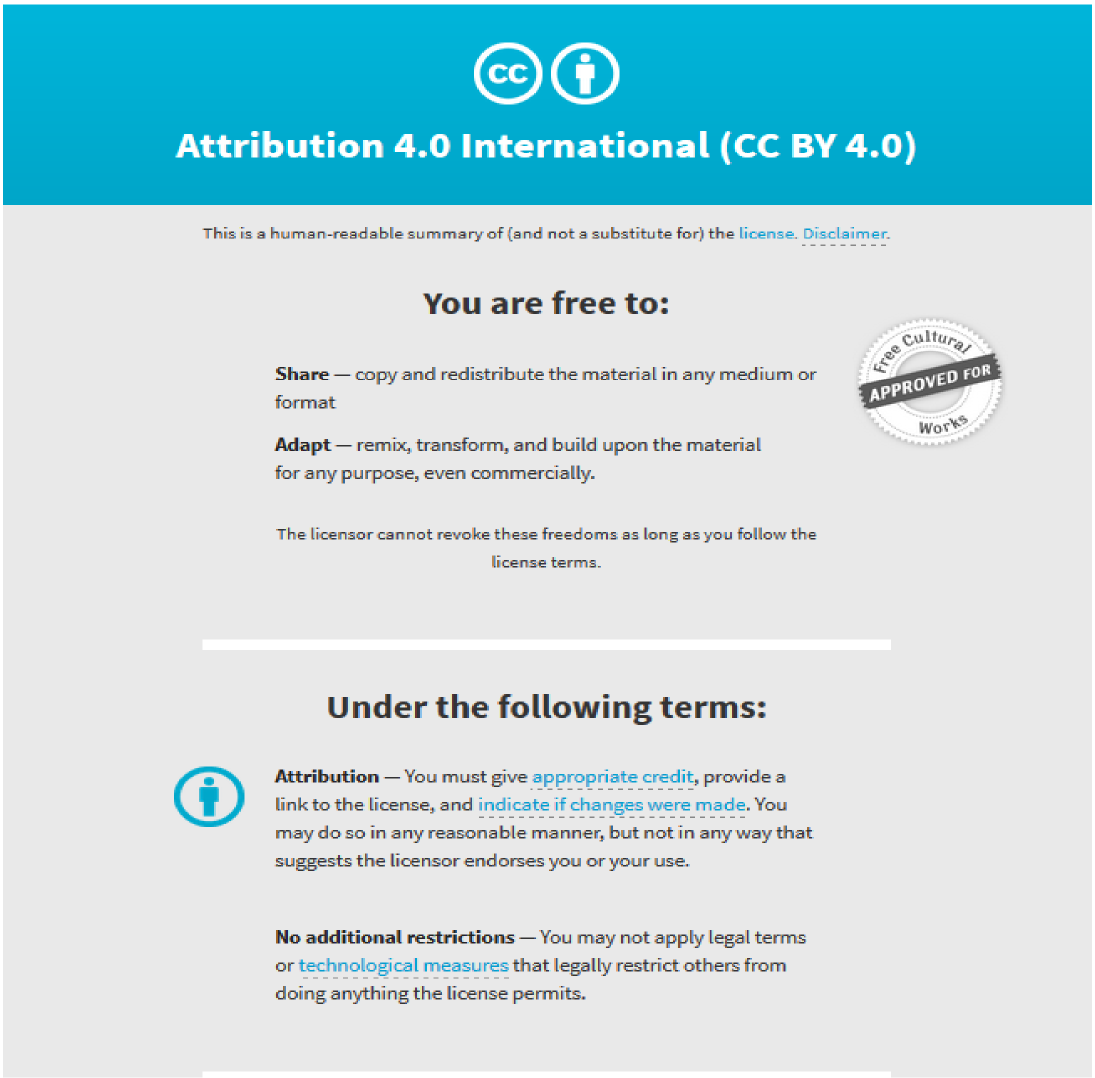

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Fig. 2 Left (**a**-**d**), mean temporal profiles of pairs of foot joints rotations (±1 standard deviation band) normalized to stance duration across all walking trials of all subjects. Right (**a1**-**d1**), angle-angle trajectories (i.e. coupling angle) for the pairs of joints rotations on the left. Where: ShCa (y) is the coronal-plane rotation of the midfoot with respect to the calcaneus; CaMi (x) and CaMi (y) are the sagittal and coronal-plane rotations of the midfoot with respect to the calcaneus; MiMe (y) is the coronal-plane rotation of the metatarsus with respect to the midfoot, and MeHa (x) is the sagittal plane rotation of the hallux with respect to the metatarsus. The trajectory initial point (0% stance) is highlighted by the '+' symbol

a shift to distal phase coordination pattern was detected due to rapid midtarsal plantarflexion (Fig. 3b).

Proximal phase coordination between ShCa (y) and MiMe (y) was found in early and middle stance (Fig. 3c and Table 1), primarily due to the limited mobility of the tarso-metatarsal joint relative to the more mobile ankle joint (Fig. 2c). Similar to coronal plane motion at the midtarsal joint, a shift to in-phase coordination was observed in late stance due to simultaneous inversion of tarso-metatarsal and ankle joints.

Anti-phase coordination between ShCa (y) and MeHa (x) was prominent in early stance, due to simultaneous ShCa eversion and MeHa plantarflexion (see Fig. 2d and Fig. 3d). This pattern shifts to proximal phase coordination

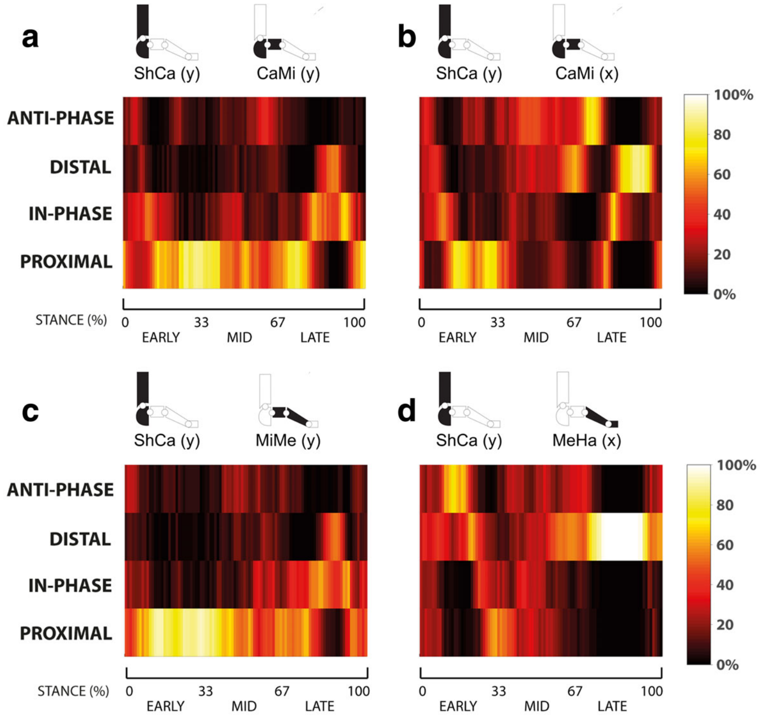

Fig. 3 For each pair of joints rotations (**a**-**d**), color maps of the frame-by-frame percentage of walking trials in each coupling state during normalized stance duration. Where dark colors indicate lower percentages of walking trials in each coupling state and bright colors indicate larger percentages

Table 1 Median frequency (# of frames) spent in each of the four coordination phases during early, middle and late stance. Values are presented as median [interquartile range]

	CaMi (y) - ShCa (y)	CaMi (x) - ShCa (y)	MiMe (y) - ShCa (y)	MeHa (x) – ShCa (y)
Early (1–33%)				
Anti-Phase	3 [3.5]	5 [4.5]	3 [4]	10.5 [5.5]
Distal	2 [2]	4.5 [4]	1 [2]	10 [7.5]
In-Phase	7 [6]	6 [6]	2 [4]	5 [5.5]
Proximal	19.5 [8]	17 [7.5]	25 [6]	6.5 [6]
Mid (34–66%)				
Anti-Phase	4.5 [7.5]	11 [11.5]	4 [5.5]	6.5 [6]
Distal	2 [4]	9 [9]	2 [4.5]	11 [12.5]
In-Phase	5 [4.5]	3.5 [7.5]	4 [6]	5.5 [8]
Proximal	19 [7.5]	5 [7.5]	20 [9.5]	7 [8]
Late (67–100%)				
Anti-Phase	1 [2]	8 [6.5]	1 [2.5]	3 [3]
Distal	5 [7]	16 [7.5]	4 [8]	28 [3.5]
In-Phase	12.5 [8]	6 [6.5]	14 [11]	1 [2]
Proximal	13 [5.5]	4 [3.5]	12 [11]	1 [1]

as the ankle continues to evert once the hallux reaches the supporting surface. During late stance, a large gradient of 1st metatarso-phalangeal joint dorsiflexion compared to that of ankle inversion results in a strong distal phase coordination pattern (Table 1).

Discussion

Foot joints mobility and coordination is achieved via interaction of intrinsic and extrinsic muscles acting across several joints under the constraint of soft tissues and ligaments. However, traditional kinematic analysis does not allow to capture the complexity of coordination between foot joint rotations. This study aimed at applying a modified vector coding technique for the analysis and representation of patterns of coordination between foot joints, comprising calcaneus, midfoot, metatarsus and hallux segments, in order to provide more insight into foot function during walking.

The main difference to previous analyses of foot joint coordination based on the vector coding technique is the inclusion of other foot joints, such as the midtarsal and first metatarsophalangeal joints, and the assessment of coordination patterns across different planes according to known anatomical and functional relationships in the foot. This study also used the proximal segment rather than the global coordinate system as the reference for joint rotations. From a biomechanical perspective, the present definition of proximal phase implies that while the proximal joint rotates the distal joint follows. The authors believe that this definition is more appropriate to describe the coordinative behaviour between foot joints as "proximal phase" and better reflects the idea of the proximal joint leading the motion of the distal one. With the previous definition such behaviour would be characterized as *in-phase*, which implies a synergistic mechanism [10].

Good qualitative consistency was found for kinematics of the foot joints with comparable results from previous studies [6, 17, 18, 24]. For coordinative patterns, similar to what was reported by Chang et al. [10], late stance in-phase coordination pattern between coronal-plane motion of the ankle and tarso-metatarsal joints was detected. The same coordination pattern was also found for the midtarsal joint. This suggests that late stance in-phase coordination may be present also in other foot joints. This seems in contrast to the classic view of simultaneous opposite rotations assisting foot stability during push-off [25]. Moreover, the presence of a predominantly distal coordination pattern, due to the rapid midtarsal joint plantarflexion in late stance, further reflects the complex interaction between joints in the foot across multiple planes of motion. Unlike what reported in previous studies [10], an increased frequency of proximal coordination between ankle and tarso-metatarsal joints was detected, associated to a less frequent distal coordination pattern (Table 1 and Fig. 3c). This difference is likely due to differences between foot models across studies, with less tarso-metatarsal motion probably biasing the pattern toward proximal coordination, as highlighted by the rather flat angle-angle relationship (Fig. 2 c1).

In addition to the intrinsic limitations of kinematic analysis based on skin markers, and to the relatively small sample size used here, it should also be pointed out that the vector coding technique is sensitive to small joint rotations and rotation velocities [10]. We attempted to mitigate this limitation by using kinematic measures from an established and reliable foot model [26], and by excluding further coupling relationships which could have been more susceptible to errors [24]. Methods for presenting detailed coordination profiles along with additional data on segmental dominancy and variability are also emerging [14]. Since this was the first study reporting coordination patterns using the vector coding technique for all joints within the Rizzoli Foot Model, we adopted an established technique specifically designed for foot analysis [10]. Future studies can benefit from using different techniques to reveal additional details about coordination of foot joint motion during walking and other activities [14].

Conclusions

This study has identified and classified coordination patterns across a number of joints in the foot during walking. Identifying coordination patterns of foot joint motion offers a different perspective in the analysis of multi-segment foot kinematics, and may be used for the objective quantification of alterations in foot joint coordination patterns thus assisting in the clinical interpretation of foot and lower limb pathologies.

Abbreviations

CaMi (x) and CaMi (y): sagittal- and coronal-plane rotations of calcaneus - midfoot joint; MeHa (x): sagittal-plane rotation of first metatarso-phalangeal joint; MiMe (y): coronal-plane rotation of midfoot-metatarsus joint; ShCa (y): coronal-plane rotation of shank - calcaneus joint

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Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Authors' contributions

JBA designed the study, acquired the kinematic data, performed the data analysis, and helped with the interpretation of the results and the preparation of the manuscript. PC assisted with the interpretation of the results and the preparation of the manuscript. FF performed the data analysis, assisted with the interpretation of the results and preparation of the manuscript. DT assisted with designing the study, preparation of the manuscript and interpretation of the results. AL helped with the interpretation of the results and the preparation of the manuscript. All authors read and approved the final manuscript.

Ethics approval and consent to participate

The Human Research Ethics Committee of the University of South Australia (protocol 24,952) gave approval to conduct the study. All participants gave written informed consent.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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