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Original Article

Factors that determine kinematic coupling behavior of calcaneal pronation/supination and shank rotation during weight bearing: ananalysis based on foot bone alignment using radiographic images

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Abstract. [Purpose] This study aimed to identify factors that determine the kinematic coupling behavior of calcaneal pronation/supination and shank rotation in a standing position. [Participants and Methods] Study participants included 15 healthy adults (30 legs). Kinematic coupling behavior was quantified as the linear regression coefficient (kinetic chain ratio [KCR]) of the angle of shank rotation against the angle of calcaneal pronation-to-supination measured using a 3-dimensional motion analysis system during pronation and supination of both feet while standing. The relationship between the KCR and the foot bone alignment was also analyzed using 35 parameters that were evaluated based on plain radiography. [Results] Greater the height of the medial longitudinal arch, and greater the backward tilt of the long axis of the talus and the backward tilt of the talar articular surface of the calcaneus, larger the KCR. This alignment differed between the genders. [Conclusion] This study suggested that the KCR increases as the subtalar joint axis approaches the long axis of the shank secondary to the lifting of the medial longitudinal arch of the foot and decreases as the subtalar joint axis approaches the long axis of the foot secondary to the lowering of the medial longitudinal arch of the foot.
Key words: Kinematic chain, Foot alignment, Subtalar joint

INTRODUCTION

Foot supination while standing causes external shank rotation, and foot pronation while standing causes internal shank rotation[1, 2]. This coupling is a kinematic chain generated through the talocrural joint and subtalar joint between the calcaneus and shank (hereinafter referred to as the kinematic chain between the calcaneus and shank; KCCS). The KCCS acts to convert planes of motion between the foot and shank. Therefore, the KCCS is thought to play a role in absorbing the rotational stress that arises in the lower limbs during walking by converting it to foot pronation and supination[3], and conversely to utilize foot pronation and supination to trigger lower limb rotation[4]. These functions are better accomplished when calcaneal pronation and supination are accompanied by more pronounced shank rotation. Conversely, we expect that legs with little shank rotation relative to calcaneal pronation and supination, probably impose mechanical stress on the knee joint and ankle joint because those lower limbs cannot absorb rotation stress of the lower limbs and cannot efficiently transmit calcaneal pronation

and supination to the lower leg rotation.

The KCCS acts to convert motion between foot pronation/supination and shank rotation. Thus far, we have captured this function quantitatively by limiting movement during exercise analysis to calcaneal pronation/supination and associated shank rotation[5]. This analysis has identified quite substantial individual differences in this converting function of the KCCS, and a less prominent converting function in females as compared with males—that is, we observed less shank rotation associated with calcaneal pronation and supination in females than in males[6]. This kind of gender difference in kinematic coupling behavior is probably related to the fact that ligament injuries of the knee joint[7, 8] and degenerative disorders of the knee joint[9–11] are more common in females than in males. Further analysis of the anatomical factors that determine kinematic coupling behavior is required to elucidate the relationship between kinematic coupling behavior and the pathological movements displayed by patients with lower limb joint disease.

Nawoczenski et al.[12] reports greater shank rotation by participants with hollow feet while walking, and greater calcaneal pronation/supination by participants with flat feet. The authors[13] have also shown that participants with a smaller range of motion in the subtalar joint exhibited more pronounced shank rotation relative to calcaneal pronation/supination. Such reports suggest that kinematic coupling behavior is affected by foot alignment, though which anatomical factors determine kinematic coupling behavior remains unknown. The study was therefore designed to identify the relationship between kinematic coupling behavior and foot alignment, and to demonstrate which factors determine kinematic coupling behavior. We hypothesized that the shank rotation is large in the participant with the high medial longitudinal arch of foot, and besides, that kinematics is closely related to the alignment of the crus, talus and calcaneus bones that make up the KCCS.

The kinematic terminology used to refer to the foot in this article conforms to the definitions of the International Society of Biomechanics[14], and supination/pronation refer to movement on the frontal plane.

PARTICIPANTS AND METHODS

Study participants were 15 healthy adults (30 legs) with no previous history involving the lower limbs. Participants included nine males and six females aged 25.9 ± 3.3 years measuring 167.7 ± 9.1 cm in height and 58.1 ± 9.3 kg in weight. The objectives and methods of this study were explained to all participants who participated both orally and in writing, and signed consent forms were obtained from all participants prior to starting the study. This study was performed after obtaining approval from the ethics review committee of International University of Health and Welfare (approval number: 11-156).

The method used to quantify kinematic coupling behavior was the method described below, the validity and reproducibility of which was confirmed in an authors' previous study[5].

The position of infrared light-reflecting markers attached to the lower limbs of participants was measured at a sampling wavelength of 200 Hz using an optical 3-dimensional motion analysis system consisting of 8 MX-T infrared cameras (Vicon Motion Systems, Oxford, UK). Markers were attached to 18 sites in total on participant feet. These sites were the fibular head, medial tibial condyle, medial malleolus, lateral malleolus, posterior surface of the heel, medial surface of the heel, lateral surface of the heel, head of the first metatarsal, and head of the fifth metatarsal on both feet.

Measurements were taken during active pronation/supination of both feet in a standing position. Starting from a comfortable standing position, participants were made to supinate both their feet simultaneously to a maximally supinated position, then pronate both their feet to a maximally pronated position, then supinate their feet again to a maximally supinated position, and repeat this exercise 6 times. Participants were instructed to move at the optimum velocity to fully pronate or supinate the foot, and to maintain a constant movement velocity.

The 3-dimensional positional coordinate data obtained from the reflective markers was processed using Nexus 1.7.1 (Vicon Motion Systems, Oxford, UK) data processing software. After a second-order Butterworth low pass filter with a 6 Hz cutoff frequency was applied, a local coordinate system was created using the "Body Builder Language" programming language to define the calcaneus, shank, and foot. Then, angle of calcaneal pronation/supination relative to the shank and angle of shank rotation relative to the foot were calculated using Euler angle.

The analysis period of angle data was from the first maximum value measured for the angle of calcaneal supination to the sixth maximum value measured for the angle of calcaneal supination. In addition, the linear regression coefficient for the angle of calcaneal pronation-to-supination and angle of shank rotation was defined as the kinematic chain ratio (KCR) and was used as an indicator of kinematic coupling behavior. The KCR is the ratio of angular variation during shank rotation relative to calcaneal pronation-to-supination (angle of shank rotation/angle of calcaneal protonation-to-supination), where the larger the KCR the greater kinematics is dominated by shank rotation, and the smaller the KCR the greater kinematics is dominated by calcaneal pronation/supination.

Plain radiographic images of both feet (dorsal-planter view and lateral view) were captured while the participant was in a standing position using the UD150L-40E (Shimadzu, Kyoto, Japan) X-ray high voltage generator for diagnostic use. Imaging data was processed using the Kodak Direct View CR975 (Kodak, Rochester, NY, USA) computed radiography (CR) system, and the foot alignment was measured using the ImageJ 1.45l (National Institutes of Health, Bethesda, MD, USA) image analysis software. The measured foot alignment parameters were set to 35 items that comprehensively list items that are commonly used (Table 1).

In the statistical analysis the normality of all data was confirmed using the Shapiro-Wilk test. The relationship between the

Table 1. Measurement parameters for foot bone alignment, and correlation coefficient between the parameters and KCR

No.	Measurement parameters	Correlation with KCR		Gender difference		
		Correlation coefficient	Test name	Male	Female	Test name
1	Posterior tilt angle of the calcaneus relative to floor	−0.07	P			
2	Anterior tilt angle of the talus relative to floor (talus-floor angle)	−0.37	* P	23.7 ± 4.5	28.6 ± 4.6	**t
3	Anterior tilt angle of the tibia relative to floor	0.28	P			
4	Plantar flexion angle of long axis of the talus relative to long axis of the tibia (talus-tibia angle)	−0.46	* P	107.0 ± 5.7	113.9 ± 4.3	**t
5	Anterior tilt angle of anterior superior border of the calcaneus relative to long axis of the tibia (calcaneus-tibia angle)	−0.49	** P	12.6 ± 2.7	15.1 ± 3.5	*t
6	Plantar flexion angle of long axis of the calcaneus relative to long axis of the talus (calcaneus-talus angle)	−0.36	* P	42.6 ± 4.5	49.7 ± 6.0	***t
7	Adduction angle of lateral border of the calcaneus relative to anterior border of the medial and lateral malleolus	0.13	P			
8	Abduction angle of long axis of the calcaneus relative to long axis of the head of talus	−0.11	P			
9	Anterior tilt angle of surface of talocrural joint relative to long axis of the tibia	−0.11	P			
10	Posterior tilt angle of posterior superior border of the calcaneus relative to anterior superior border of the calcaneus (Bohler angle)	−0.36	* P	30.2 ± 4.0	37.9 ± 5.6	***t
11	Posteriar tilt angle of posterior border of the calcaneus relative to line connecting posterior end of the calcaneal tuberosity with the tarsal sinus	0.13	S			
12	Adduction angle of posterior border of the navicular relative to anterior border of the medial and lateral malleolus	0.34	P			
13	Adduction angle of posterior border of the navicular relative to long axis of the head of talus	0.34	P			
14	Posterior tilt angle of inferior border of calcaneus relative to line connecting inferior end of the calcaneal tuberosity with inferior end of the first metatarsal head	−0.01	S			
15	Dorsiflexion angle of long axis of the first metatarsal relative to long axis of the head of talus	−0.41	* P	3.6 ± 6.9	11.5 ± 6.6	**t
16	Dorsiflexion angle of long axis of the first metatarsal relative to long axis of the calcaneus	−0.14	P			
17	Dorsiflexion angle of inferior border of the fifth metatarsal relative to inferior border of the calcaneus	−0.06	P			
18	Anterior tilt angle of long axis of the talus relative to line connecting back end of the first metatarsal base with anterior end of the head of talus	−0.29	P			
19	Anterior tilt angle of line connecting center of the calcaneocuboid joint with posterior end of the calcaneal tuberosity relative to line connecting inferior end of the first metatarsal base with center of the calcaneocuboid joint	0.08	P			
20	Abduction angle of long axis of the second metatarsal relative to anterior border of the medial and lateral malleolus	−0.42	* P	78.0 ± 6.8	86.5 ± 8.4	**t
21	Abduction angle of long axis of the first metatarsal relative to long axis of the head of talus	0.37	* P	−3.0 ± 5.8	−10.5 ± 8.7	**t
22	Abduction angle of line connecting center of anterior border of the medial and lateral malleolus with the second metatarsal head relative to perpendicular drawn from anterior border of the medial and lateral malleolus	0.39	* P	8.9 ± 6.7	3.2 ± 7.5	*t
23	Adduction angle of long axis of the second metatarsal relative to lateral border of the calcaneus	0.4	* P	9.0 ± 6.5	1.3 ± 4.9	**t
24	Adduction angle of long axis of the first metatarsal relative to long axis of the second metatarsal	−0.32	P			
25	Abduction angle of long axis of the fifth metatarsal relative to long axis of the first metatarsal	0.39	* P	27.4 ± 2.5	24.8 ± 2.9	*t
26	The ratio of distance between lateral border of the second and the fifth metatarsal base in dorsal-planter view (A) to distance between inferior border of the second and the fifth metatarsal base in lateral view (B), namely A/B	0.62	** P	1.0 ± 0.2	0.8 ± 0.2	*t

Table 1. Continued.

No.	Measurement parameters	Correlation with KCR		Gender difference		
		Correlation coefficient	Test name	Male	Female	Test name
27	Tangent of A and B (tanα=A/B)	0.61	** P	43.8 ± 5.6	37.1 ± 7.5	**t
28	Height of center of the first lisfranc joint relative to line connecting inferior end of the calcaneal tuberosity with inferior end of the first metatarsal head	0.41	* P	18.2 ± 2.0	16.7 ± 1.2	*W
29	Height of center of the medial cuneonavicular joint relative to line connecting inferior end of the calcaneal tuberosity with inferior end of the first metatarsal head	0.4	* P	24.3 ± 3.0	22.2 ± 2.0	*t
30	Height of center of the talonavicular joint relative to line connecting inferior end of the calcaneal tuberosity with inferior end of the first metatarsal head	0.29	P			
31	Height of center of the tarsal sinus relative to line connecting inferior end of the calcaneal tuberosity with inferior end of the first metatarsal head	0.09	P			
32	Height of center of the talocrural joint relative to line connecting inferior end of the calcaneal tuberosity with inferior end of the first metatarsal head	0.24	P			
33	Height of inferior border of the first metatarsal base relative to line connecting inferior end of the calcaneal tuberosity with inferior end of the first metatarsal head	−0.02	P			
34	Height of inferior border of the cuboid relative to line connecting inferior end of the calcaneal tuberosity with inferior end of the first metatarsal head	0.09	P			
35	Height of anterior inferior edge of the calcaneus relative to line connecting inferior end of the calcaneal tuberosity with inferior end of the first metatarsal head	0.02	P			

p value (*p<0.05, **p<0.01), Correlation analysis (P: Pearson's, S: Spearman's), t: Two-sample t-test, W: Welch's t-test.

kinematic chain ratio (KCR) and foot alignment was investigated by calculating the Pearson's product-moment correlation coefficient or Spearman's rank-correlation coefficient, and then calculating the partial correlation coefficient to control for confounding effects. In addition, to demonstrate whether the gender difference in the KCR revealed by the authors' previous study[6] results from gender differences in foot structure, the correlation between KCR and foot alignment was analyzed. For the foot alignment parameters demonstrated to be significantly correlated with the KCR, equality of variance was confirmed using Levine's test, and then the gender difference of these parameters was confirmed using a two-sample t-test and Welch's adjusted two-sample t-test. Left and right leg data were handled independently during analysis, and the significance level used in tests was a hazard ratio of 5% (p<0.05). Statistical analysis was performed using IBM SPSS Statistics 21 (IBM Co., Armonk, NY, USA) statistical analysis software.

RESULTS

The measurement result of KCR in the representative example is shown in Fig. 1. The mean KCR among all participants was 0.96 ± 0.20 (maximum 1.58, minimum 0.64).

An analysis of correlation between the KCR and foot alignment revealed significant correlation with 15 foot alignment parameters (Table 1). Out of the 15 alignment parameters, five parameters shown in Table 2 pertained exclusively to the shank, calcaneus, and talus, which constitute the KCCS. In order to identify the anatomical factors that determine the KCR, a partial correlation analysis was performed on the KCR and these five parameters. This analysis showed that when the (4) talus-tibia angle and (5) calcaneus-tibia angle were taken as control variables, that the partial correlation coefficient of the other parameters was at a minimum, and the partial correlation coefficient of all parameters was ≤0.2 (Table 2).

A significant gender difference was found for all foot alignment parameters that were significantly correlated with KCR. More parameters were positively correlated with KCR in males, and more parameters were negatively correlated with KCR in females, with no exceptions for any parameter.

DISCUSSION

We have expressed the KCCS as the linear regression coefficient of the angle of shank rotation against the angle of calcaneal pronation-to-supination, and defined this coefficient as the KCR. This study analyzed the relationship between the KCR and 35 foot alignment parameters. The characteristics of 15 alignment parameters found to correlate positively with
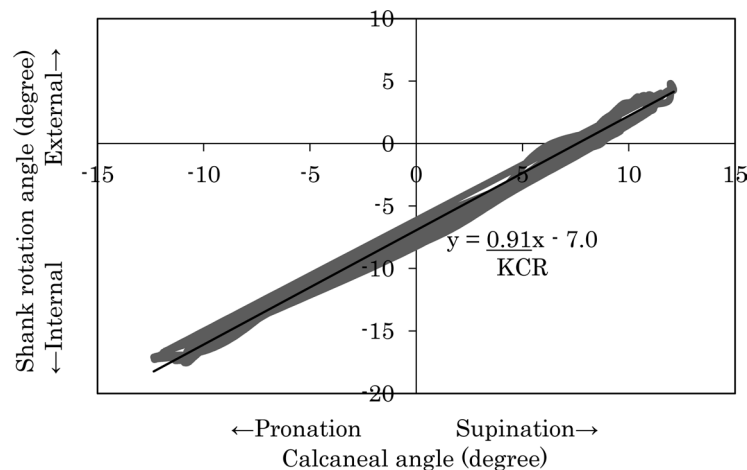
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Fig. 1. Indicators definition of behavior of KCCS (KCR) (Representative example).

Table 2. Partial correlation coefficient between the alignments of calcaneus, talus and shank and KCR

			Partial correlation coefficient with KCR				
			2	4	5	6	10
	2	Talus-floor angle	—	−0.29	−0.37	−0.18	−0.27
	4	Talus-tibia angle	0.02	—	−0.22	−0.08	−0.18
Control variable	5	Calcaneus-tibia angle	−0.15	−0.1	—	−0.16	−0.13
	6	Calcaneus-talus angle	−0.2	−0.31	−0.38	—	−0.11
	10	Bohler angle	−0.28	−0.34	−0.37	−0.1	—

the KCR can be summarized into the following four; that is, the KCR increased with increasing backward tilt of the talus long axis, increasing backward tilt of the calcaneus superior anterior border, increasing metatarsal supination, and increasing forefoot adduction. These characteristics are associated with the elevation of the medial longitudinal arch, which suggests that clinically, the medial longitudinal arch height could be a rough indicator of the KCR.

The results of this study are consistent with the report by Nawoczenski et al.[12], which states that shank rotation is dominant in participants with hollow feet, and that calcaneal pronation/supination is dominant in participants with flat feet. The results of this study also suggest the gender difference in the KCR revealed by our previous study, which shows that the KCR is smaller in females[6]; this can be explained by the finding that females have a lower medial longitudinal arch height[15, 16]. The correlation coefficients obtained in this study—even for alignment parameters that positively correlated with the KCR—were not high at ≤0.62. However, since the results are consistent with previous studies, we consider the results of this study to be useful for elucidating the mechanism of KCCR kinematic coupling behavior.

Because the KCCS is composed of the subtalar joint and talocrural joint, we expect the KCR to be determined by discrepancies in the orientation of the axis of these joints. Individual differences in the orientation of the subtalar joint axis are known to be particularly large[17–19]. Partial correlation analysis was performed on the KCR and five alignment parameters that pertain exclusively to the shank, calcaneus, and talus, which constitute the KCCS. This analysis showed that the partial correlation coefficient of other alignment parameters was at a minimum when the (4) talus-tibia angle and (5) calcaneus-tibia angle were taken into account as control variables. Based on this, we can assume that the angle formed between the calcaneus superior anterior border and tibial long axis and the angle formed between the talus long axis and the tibial long axis along the sagittal plane are directly involved in determining the KCR. Because the articular surface of the subtalar joint is positioned between the talus long axis and calcaneus superior anterior border in the sagittal plane, it can be inferred that forward/backward tilting of these structures indicates forward/backward tilting of the subtalar joint surface. Because the axis of motion of the subtalar joint displays movement from a posteroinferior to an anterosuperior direction on the sagittal plane, forward tilting of the subtalar joint surface would move its plane of motion closer to the long axis of the foot and generate kinematic coupling behavior dominated by foot pronation/supination (small KCR). Meanwhile, backward tilting of the subtalar joint surface would bring its plane of motion closer to the long axis of the shank and generate kinematic coupling behavior dominated by shank rotation (large KCR).

Based on the above discussion, the hypothesis proved that the higher the medial longitudinal arch of the foot, the larger

the KCR. Furthermore, we considered the angle formed between the subtalar joint axis and the shank/foot on the sagittal plane to be the factor that direct determines the KCR. In other words, we can say that KCCS kinematics is dominated by foot pronation/supination (when KCR is small) when the medial longitudinal arch is high, because the subtalar joint axis is oriented closer to the long axis of the shank. This points to the possibility that the KCR can be adjusted by controlling the medial longitudinal arch height. When a lower limb joint disease is caused by a KCR that is too small, increasing the KCR by raising the medial longitudinal arch may be an effective method of correcting pathological movement. Whether the KCR can be controlled or the KCR is involved in lower limb disorders cannot be mentioned sufficiently in this study and should be clarified in the future because these findings are related to clinical value.

Conflict of interest

None.

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