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THE DIFFERENCE IN KINEMATIC CHAIN BEHAVIOR BETWEEN PRONATION / SUPINATION OF CALCANEUS AND ROTATION OF SHANK IN STANDING POSITION BY INDIVIDUAL, AGE, GENDER AND RIGHT AND LEFT: ANALYSIS OF KINEMATIC USING OPTICAL THREE DIMENSIONAL MOTION ANALYSIS SYSTEM

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ABSTRACT

Background: Although the kinematic coupling of calcaneus and shank is important for optimizing the pathological movement of the lower extremity, it is not sufficiently clarified. The objective of this study was to represent the kinematic coupling behavior of calcaneal pronation/supination and shank rotation quantitatively while standing and to identify the extent of the individual, age, gender and laterality differences in these measurements.

Methods: This study was a cross-sectional study that subjects were 25 healthy young people (17 men and eight women) and 29 healthy elderly people (15 men and 14 women). 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 3D motion analysis system during pronation and supination of both feet while standing. Individual differences in the KCR, which is an outcome, were also investigated with regard to differences in age, gender, and laterality.

Results: The mean KCR in all subjects was 1.00 ± 0.23. In addition, the coefficient of variation (CV) was 22.9%, with individual results varying from a maximum of 1.6 to a minimum of 0.4. The KCR was also larger in men than in women ($p<0.001$), while the CV for both men and women was in the 20% range.

Conclusion: We should focus attention on individual difference of kinematic coupling rather than assessing the movement by the attributes of the subject. Because, individual differences in KCR are larger than age, gender and laterality differences.

Keywords: Kinematic chain, calcaneus, shank, individual difference, gender difference, motion analysis.

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INTRODUCTION

The coupling in foot supination and pronation during standing associated with external and internal shank rotation [1,2] is a kinematic chain generated through the talocrural joint and subtalar joint between the calcaneus and shank (from now on 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, and is therefore 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]. In other words, this kinematic chain is important for reducing mechanical stress in the lower limbs and in producing smooth body movement. Idiosyncratic behavior in this chain may result in the accumulation of mechanical stress in lower limb joints and contribute to the development of degenerative diseases and ligament injury.

Reports have shown individual differences in KCCS kinematics [5]. Nawoczenski et al. (1998) [6] reported that subjects with hollow feet exhibited greater shank rotation during walking. The authors [7] have also shown that subjects with a smaller range of motion in the subtalar joint exhibited greater shank rotation. However, since the foot strike position and the angle of plantar flexion/dorsiflexion vary greatly when recording kinematics during exercises such as walking and running, such measurements cannot be used to distinguish whether the kinematic chain causes coupling between calcaneal supination/pronation and shank rotation. It is for this reason that KCCS kinematics has not yet to be expressed quantitatively. In light of this, we devised a technique of evaluating the essential kinematics of the KCCS that limits movement during exercise analysis to supination and pronation of the calcaneus and associated rotation of the shank. The validity and reproducibility of this technique were confirmed by a previous study [8].

However, reference data on healthy lower limbs are needed to elucidate the relationship between idiosyncrasies in KCCS kinematics and the pathological movements exhibited by patients with lower limb joint diseases. Thus, the objective of this study was to identify an individual, age, gender and laterality differences of KCCS kinematics and obtain fundamental data on lower limb kinematics in healthy young people and healthy elderly people.

The kinematic terminology used to refer to the foot in this article conforms to the definitions of the International Society of Biomechanics [9], and supination/pronation refer to movement on the frontal plane.

METHODOLOGY

▪ Subjects

The study included a total of 54 subjects (108 legs), comprised of 25 young people (50 legs) (young group) and 29 elderly people (58 legs) (elderly group) with no previous history involving the lower limbs. The young group was comprised of 17 men and eight women aged 26.4 ± 3.7 years, measuring 167.4 ± 8.3 cm in height and 59.0 ± 9.2 kg in weight. The elderly group was comprised of 15 men and 14 women aged 73.5 ± 3.3 years, measuring 156.7 ± 7.6 cm in height and 54.2 ± 9.2 kg in weight.

The objectives and methods of this study were explained to all subjects who participated both orally and in writing, and signed consent forms were obtained from all subjects before 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).

▪ Measurement method

The method used to quantify kinematic coupling behavior was the method described below, the validity and reproducibility of which was confirmed in a previous study by the authors [8].

The position of infrared light-reflecting markers attached to the lower limbs of subjects 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). Markers were attached to 18 sites in total on subject 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, and the rotation of shanks occurs with that. Starting from a comfortable standing position, subjects 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. Subjects were instructed to move at the optimum velocity to fully pronate or supinate the foot and to maintain a constant movement velocity.

▪ Data Processing

The 3-dimensional positional coordinate data obtained from the reflective markers were processed using Nexus 1.7.1 (Vicon Motion Systems) data processing software. After a 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 (Figure 1), then angles of calcaneal pronation/supination relative to the shank and angles of shank rotation relative to the foot were calculated using Euler angles.

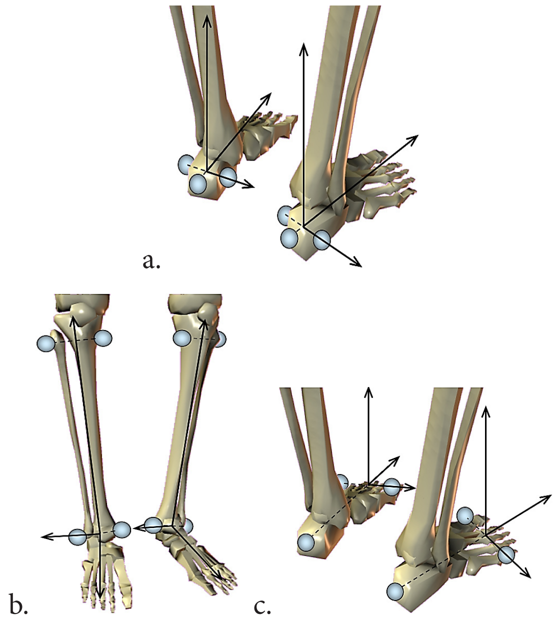

Figure 1: Marker placement and local coordinate system

a: Calcaneus b: Shank c: Foot

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, since the scatter diagram of the flexion angle of the angle of calcaneal pronation-to-supination and angle of shank rotation is in a linear relationship, the linear regression coefficient of both 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.

▪ **Statistical tests**

Kinematic chain ratio (KCR) normality was confirmed using the Shapiro-Wilk test. Additionally, after confirming equality of variance using Levene's test, differences in KCR due to age, gender, and laterality were investigated using the three-way ANOVA. Individual differences in KCR were also investigated using the coefficient of variation (CV), taking age, gender, and laterality into account as factors affecting the CV. The significance level used in the tests to show significance was a hazard ratio of 5% ($p<0.05$). The software used for statistical analysis was IBM SPSS Statistics 21 (IBM Co., Armonk, NY, USA).

RESULTS

The measurement result of KCR in the representative example is shown in Figure 2. The mean KCR among all subjects was 1.00 ± 0.23. Also, the CV was 22.9%, with individual differences ranging from a maximum of 1.6 to a minimum of 0.4.

Results of the three-way analysis of variance for the KCR using age, gender, and laterality as factors revealed that gender was the only factor ($p<0.001$) with an effect, with 1.08 ± 0.22 for men and 0.88 ± 0.18 for women. No other factor or interaction was significant (Table 1). The CV in each group when grouping according to age, gender and laterality was about 20 to 25% (Table 2).

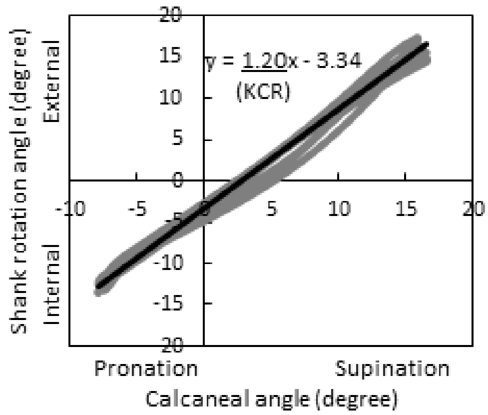

Figure 2: Indicators definition of the behavior of KCCS (KCR) (Representative example)

Table 1: Differences in KCR based on age, gender, and laterality

		Young / Men / Right	Elderly / Women / Left	p value
Factor	Age	1.00 ± 0.22	1.00 ± 0.24	n.s.
	Gender	1.08 ± 0.22	0.88 ± 0.18	p<0.001
	Laterality	1.01 ± 0.26	0.99 ± 0.20	n.s.
Interaction	Age vs Gender			n.s.
	Age vs Laterality			n.s.
	Gender vs Laterality			n.s.
	Age vs Gender vs Laterality			n.s.

n=54(108) mean±SD n.s. not significant

Table 2: CV in KCR based on age, gender, and laterality

		Young / Men / Right	Elderly / Women / Left
Factor	Age	22.4	23.6
	Gender	20.8	20.1
	Laterality	25.3	20.4

n=54(108) CV%

DISCUSSION

We expressed KCCS kinematics 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. Measurements revealed a mean KCR of 1.0 among both healthy young and elderly people, with individual differences ranging from 1.6 to 0.4. In other words, individual differences accounted for variation in the angle of shank rotation by up to a factor of 4 when comparing subjects with the same angle of calcaneal pronation-to-supination. We also revealed a gender difference for the KCR, with larger results found in men than in women, though no difference was revealed between young subjects and elderly subjects, and right and left legs.

The KCCS is thought to play a role in absorbing the rotational stress that arises in the lower limbs during walking by converting it into foot pronation and supination [3], and conversely by utilizing foot pronation and supination to trigger lower limb rotation [4]. Since these functions are better accomplished when calcaneal pronation and supination are accompanied by more pronounced shank rotation, we can say that legs with a larger KCR have better KCCS kinematics. Conversely, we expect these functions to occur inefficiently in legs with a small KCR, which is likely to give rise to mechanical stress in the knee joint. This may be a reason for the higher prevalence of ligament injuries of the knee joint [10,11], and for degenerative disorders of the knee joint [12-14] in women.

Since the KCCS is comprised of talocrural joint movement and subtalar joint movement, the individual differences in the KCR revealed by this study may originate from individual differences in the orientation of these joint axes. The angle formed between the subtalar joint and the foot or shank is, in particular, thought to be a major contributor to these individual differences. According to Isman (1968) [15], Manter (1941) [16] and Lundberg et al. (1993) [17], the orientation of the subtalar joint axis has individual differences of about 20 degrees or more in the sagittal plane and the horizontal plane. Based on this, a subtalar joint axis more closely oriented towards the long axis of the shank is expected to produce kinematics dominated by shank rotation (large KCR), while a subtalar joint axis more closely oriented towards the long axis of the foot is expected to produce kinematics dominated by calcaneal pronation and supination (small KCR). The foot arch is also typically lower in women than in men [18,19], and because of this, women have a forward-tilting calcaneus along with a forward-tilting articular surface of the subtalar joint. This is likely to result in an axis of subtalar joint in a subtalar joint axis that is closer to the long axis of the foot. The gender difference in the KCR revealed by this examination can be illustrated by such gender differences in the anatomical structure of the foot. Future research should clarify such reasoning.

Although this study revealed that there was a gender difference in KCR, the CV in grouping based on gender was 20% range in both men and women, and there was not so different from the CV, namely 22.9%, of among all subjects. From this, it is said that the size of the individual differences of KCR in all subjects and the size of individual differences of KCR in men and women are almost same in the subjects of this study. Consequently, kinematic coupling behavior should not be interpreted based on gender; instead, the focus should be on individual differences. While identifying a relationship between KCR, lower limb movement during exercise, and the pathological movements of lower limb joint diseases will be a topic for future research. This study has revealed the large size of individual differences in KCR, which we consider to be fundamental kinematic data on lower limbs.

CONCLUSION

This study revealed that the mean KCR of healthy young and elderly people is 1.0, and also there is a gender difference for the KCR, with larger results found in men than in women. Furthermore, individual differences could be a larger factor, and such differences in KCR may be explained by the foot structure, or rather the direction of the subtalar joint axis. Further studies are needed to identify factors that determine the KCR and to clarify the relationship between KCR and the pathological movements of lower limb joint diseases. The mean, gender difference and individual differences of KCR recognized in this study are important findings as basic data in the kinematics of lower limbs.

Abbreviations or symbols

KCCS: Kinematic chain between the calcaneus and shank
KCR: Kinematic chain ratio

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