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VALIDITY AND REPRODUCIBILITY OF MEASURING THE KINEMATIC COUPLING BEHAVIOR OF CALCANEAL PRONATION/SUPINATION AND SHANK ROTATION DURING WEIGHT BEARING USING AN OPTICAL THREE-DIMENSIONAL MOTION ANALYSIS SYSTEM

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ABSTRACT

Background: It's important to understand the kinematic coupling of calcaneus and shank to optimize the pathological movement of the lower extremity. However, the quantitative indicator to show the kinematic coupling hasn't been clarified. We measured the angles of calcaneal pronation-to-supination and shank rotation during pronation and supination of both feet in standing position and devised a technique to quantify the kinematic coupling behavior of calcaneal pronation/supination and shank rotation as the linear regression coefficient (kinematic chain ratio: KCR) of those measurements. Therefore, we verified the validity and reproducibility of this technique.

Methods: This study is a non-comparative cross-sectional study. The KCR, which is an outcome, was measured using an optical three-dimensional motion analysis system in 10 healthy subjects. The coefficient of determination (R^2) was calculated for the linear regression equation of the angle of calcaneal pronation-to-supination and angle of shank rotation, and the intraclass correlation coefficient (ICC [1,1]) was calculated for the KCR during foot pronation and foot supination and for the KCR measured on different days. And also, skin movement artifacts were investigated by measurement of the displacement of bone and body surface markers in one healthy subject.

Results: The linear regression equation of calcaneal pronation/supination and the angle of shank rotation included $R^2 \geq 0.9$ for all subjects. The KCR on foot pronation and supination had an ICC(1,1) of 0.95. The KCR measured on different days had an ICC(1,1) of 0.72. Skin movement artifacts were within the allowable range.

Conclusion: The validity and reproducibility of this technique were largely good, and the technique can be used to quantify kinematic coupling behavior.

Keywords: kinematic chain, calcaneus, shank, validity, reproducibility, motion analysis.

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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 and subtalar joints between the calcaneus and shank (from now on referred to as the kinematic chain between the calcaneus and shank; KCCS). The KCCS is considered to be a converter of planes of motion between the foot and shank and is important for the generation of smooth body movement since it acts to reduce mechanical stress in the lower limbs [3,4].

Although KCCS kinematics are often limited to descriptions regarding the direction of coupling between the calcaneus and shank, individual differences in KCCS kinematics have been shown to exist. Nawoczenski et al. analyzed kinematic coupling behavior during walking and showed that subjects with hollow feet exhibited greater shank rotation [5]. The authors also obtained results showing that subjects with a small range of motion in the subtalar joint exhibited greater shank rotation [6]. The clinical significance of these findings is substantial, since they identify a substantial individual difference in the ratio of calcaneal pronation-to-supination to shank rotation, as was described by Pinto [7]. Nevertheless, it would not be appropriate to determine and investigate individual differences in KCCS kinematics on a quantitative basis by measuring kinematics during movements such as walking or running. During walking and running, it is impossible to distinguish whether the interaction between calcaneal supination/pronation and shank rotation occurs as a result of the KCCS since foot strike position and the angle of plantar flexion/dorsiflexion vary greatly from moment to moment during these exercises. While it is possible to ascertain the movement of the calcaneus and shank during these exercises, it will not demonstrate the essential behavior of the KCCS.

We have therefore devised a technique of evaluating the essential behavior of the KCCS that limits movement during exercise analysis to supination and pronation of the calcaneus and rotation of the shank. The purpose of this study is to confirm the validity and reproducibility of this method of evaluating kinematic behavior.

The kinematic terminology used to refer to the foot in this article conforms to the definitions of the International Society of Biomechanics [8], and supination/pronation refers to movement on the frontal plane.

METHODS

- **Design:** Non-comparative cross-sectional study
- **Setting**: This study was conducted between April and October 2012 at IMS Katsushika Heart Center (Investigation 1) and Bunkyo Gakuin University (Investigation 2, 3 and 4).
- **Participants**: Ten healthy young people participated in this study.

▪ Method of measuring kinematic coupling behavior

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 three-dimensional (3D) motion analysis system consisting of eight MX-T infrared cameras (Vicon Motion Systems, Oxford, UK). Markers were attached to 18 sites in total on the subjects' feet. These sites were the fibular head, medial tibial condyle, medial malleolus, lateral malleolus, posterior surface of the heel, medial surface of the heel, the lateral surface of the heel, head of the first metatarsal, and head of the fifth metatarsal, on both feet (Figure 1).

Measurements were taken during active pronation/supination of both feet in a standing position. Starting from a comfortable standing position, subjects were asked 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. Subjects were instructed to repeat this exercise six times and to move at their optimum velocity to fully pronate or supinate the foot, and to maintain a constant movement velocity.

The 3D positional coordinate data obtained from the reflective markers were 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 (Figure 1). Angles of calcaneal pronation/supination relative to the shank and angles of shank rotation relative to the foot were then calculated using Euler angles. Incidentally, the rotation angle of the shank was determined as an angle concerning the long axis of the foot rather than against the calcaneus for clinical usefulness.

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. Also, the linear regression coefficient for the angle of calcaneal pronation-to-supination and the 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 the kinematics are dominated by shank rotation, and the smaller the KCR, the greater the kinematics are dominated by calcaneal pronation/supination.

In this study, we performed four investigations of the validity and reproducibility of the kinematic measurement method described above. 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 the start of this study. Approval from the ethics review committee of International University of Health and Welfare was also obtained before initiation (approval number: 11-156).

▪ Investigation 1 (Validity of marker positioning)

The right lower limb was investigated in one healthy subject (age: 28 years, sex: male, height: 183.5 cm, weight: 67.0 kg) with no previous medical history involving the lower limbs.

Computed tomography (CT) images of the lower limbs with markers attached according to the method described in this paper were captured by a clinical radiologist in three different positions (at the midway foot position, maximal foot supination, and maximal foot pronation). The CT imaging conditions did not allow for the subject to be in a standing position, so loading of the feet was simulated by pressing an acrylic board in the direction of the long axis between the soles and lower limbs. Three-dimensional images of the posterior of the calcaneus and horizontal plane images of the lower limbs were extracted from CT imaging data using zioTerm2009 Ver.2.0.0.4 (Ziosoft, Tokyo, Japan) image processing software. Also, the angles described by markers and the angles moved by actual bones during calcaneal pronation-to-supination, and shank rotation was measured using ImageJ 1.45l (National Institutes of Health, Bethesda, MD, USA) image analysis software. The angle of calcaneal pronation-to-supination was measured concerning the method of Seibel [9], and the angle of shank rotation was measured based on the Showa University method [10]. Angle measurements were used to calculate the change in angle between the midway foot position and both the maximally supinated position and maximally pronated position, and deviations in these angles were then investigated.

▪ Investigation 2 (Validity of KCR as indicator of kinematics)

The coefficient of determination (R^2) of the linear regression equation for the angle of calcaneal pronation-to-supination and the angle of shank rotation obtained by the technique described above was calculated for ten healthy subjects (20 limbs) with no previous medical history involving the lower limbs. The subjects included six males and four females aged 25.2 ± 2.9 years, 165.4 ± 10.0 cm in height, and 58.7 ± 9.9 kg in weight.

▪ Investigation 3 (Validity of measurement target)

Angular data on the calcaneus and shank obtained by the method described in this paper from the same subjects mentioned in Investigation 2 were separated into categories of calcaneal pronation data and calcaneal supination data. The KCR was then calculated for pronation and supination, and agreement between these results was investigated using the intraclass correlation coefficient (ICC[1,1]).

Data normality was confirmed with the Shapiro-Wilk test, and the significance level used 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.

▪ Investigation 4 (Reproducibility of devise measurement method)

Kinematic measurements were performed twice by the method described in this paper, with an interval of three days between each measurement in the same subjects mentioned in Investigation 2. The KCR results obtained were investigated for reproducibility using the ICC(1,1).

The method used to confirm data normality, the significance level, and the statistical analysis software used were the same as Investigation 3.

RESULTS

▪ Investigation 1 (Validity of marker positioning)

The change in angle as shown by markers as a percentage of the change in angle of the actual bones is shown in Table 1. This investigation showed the calcaneal markers evaluated the angle of supination as 5% greater than actual, and the angle of pronation as 21% greater than actual. It also showed that shank markers evaluated external shank rotation during foot pronation as 13% smaller than actual, and internal shank rotation during foot supination as 9% greater than actual.

▪ Investigation 2 (Validity of KCR as indicator of kinematics)

The measurement result of KCR in the representative example is shown in Figure 2. The average of KCR in all subjects was 0.93 ± 0.15, with large variation ranging from 0.64 to 1.27.

The R^2 for the linear regression equation of the angle of calcaneal pronation-to-supination and angle of shank rotation was ≥0.9 for all subjects.

▪ Investigation 3 (Validity of measurement target)

The KCR during foot pronation and foot supination had an ICC(1,1) of 0.95 (Figure 3).

▪ Investigation 4 (Reproducibility of devise measurement method)

The KCR results obtained from measurements performed on different days had an ICC(1,1) of 0.72.

DISCUSSION

▪ Investigation 1 (Validity of marker positioning)

Skin movement artifacts [11] that cause surface markers to inaccurately depict bone movement can arise due to the changing relative position of skin and bone during exercise and must be considered when surface markers are used to analyze 3D motion. The largest skin movement artifacts to arise with the measurement method used in this study occurred at the location of the calcaneus markers during foot pronation, followed by shank markers during foot supination and shank markers during internal shank rotation. However, since the angle moved by the actual calcaneus during supination was very small at just 1.89°, and since the evaluation of shank markers showed internal shank rotation during both foot pronation and foot supination, we can say that the effects of skin movement artifacts on the linear progression coefficient of the calcaneal angle and shank angle are small. Although this result cannot generally be applied, since only one subject was included in the investigation, for the above reasons, we inferred that there were no major problems with the marker attachment positioning used for the devised measurement method.

▪ **Investigation 2 (Validity of KCR as indicator of kinematics)**

Since the R^2 of the linear regression equation for the angle of calcaneal pronation-to-supination and the angle of shank rotation was ≥0.9 for all subjects, the relationship between the angle of calcaneal pronation-to-supination and the angle of shank rotation can be described as linear. The KCR, which is the linear regression coefficient of the calcaneal and shank angles, was therefore judged to be a valid indicator of kinematic coupling behavior.

▪ **Investigation 3 (Validity of measurement target)**

The KCR results of foot pronation and foot supination were confirmed to be highly repeatable (almost perfect) [12], with an ICC(1,1) of 0.95. Based on this, we determined that KCCS behavior was strongly interlinked and not affected by the direction of ankle movement and that there were no problems with calculating KCR using a combination of supination and pronation behavior as in the devised method.

▪ **Investigation 4 (Reproducibility of devise measurement method)**

The KCR results of measurements taken on different days were confirmed to be highly reliable (substantial) [12], with an ICC(1,1) of 0.72. Although various criteria exist for interpreting ICC, a value of ≥0.7 is thought to demonstrate high reproducibility [12,13]. Based on this result, we judged the reproducibility of the devised method to be largely good. We speculate that any discrepancies observed in the KCR results obtained by our method were mainly caused by differences in marker placement and between-subject differences in movement performance. Therefore, it is expected that more excellent reproducibility can be obtained by specifying the marker pasting position and the foot width at the time of measurement operation in more detail.

CONCLUSION

We devised a technique that captured the essential behavior of the KCCS quantitatively. This technique involved using the linear regression constant of calcaneal pronation-to-supination and shank rotation during supination and pronation of either foot as an indicator of the kinematic coupling behavior of the KCCS. We investigated the validity and reproducibility of this technique and confirmed both were largely good and determined that this technique can be used to analyze kinematic coupling behavior.

We believe that the measurement method we devised can be used to evaluate individual differences in the essential behavior of KCCS. Therefore, this study can be described as a foundation for a clear identification of the clinical significance of KCCS.

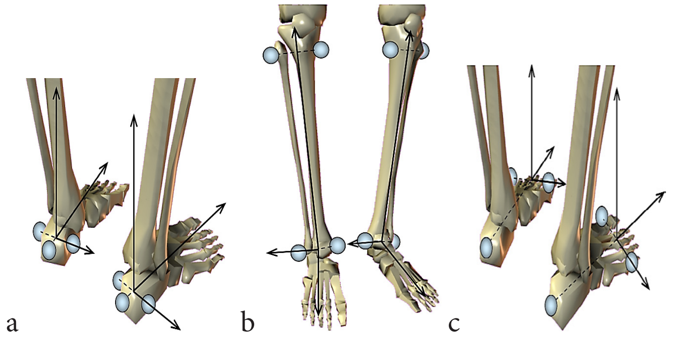


Figure 1: Marker placement and local coordinate system

a: Calcaneus b: Shank c: Foot

Table 1: Comparison of angle as shown by markers to angle of the actual bones

	Change amount of angle during supination of the foot		Change amount of angle during pronation of the foot	
	Calcaneus angle	Shank angle	Calcaneus angle	Shank angle
Angle of the actual bones (degree)	16.60	21.53	-1.89	-5.92
Angle as shown by markers (degree)	17.44	18.82	-2.29	-6.46
Angle as shown by markers to angle of the actual bones (%)	105.06	87.41	121.16	109.12
Calcaneus angle; supination (+), Shank angle; external rotation (+)				

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

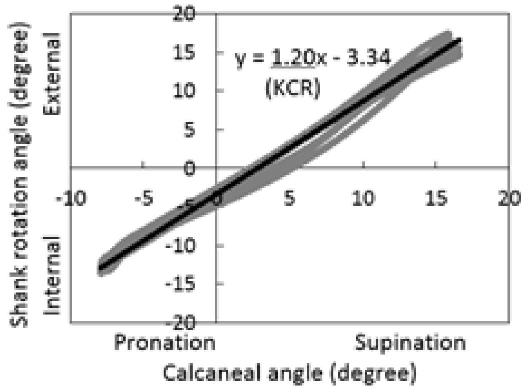
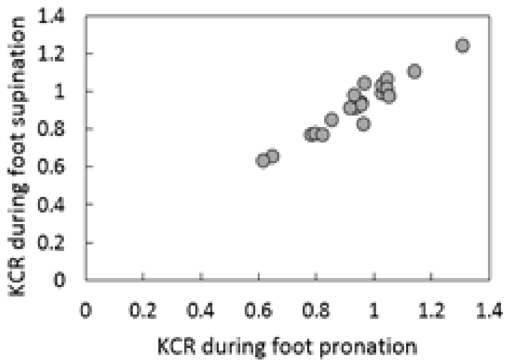


Figure 3: Relationship between KCR during supination and pronation of the foot



Abbreviations or symbols

KCCS: Kinematic chain between the calcaneus and shank

KCR: Kinematic chain ratio

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