Gait & Posture 70 (2019) 130–135

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

# Tibial and calcaneal coupling during walking in those with chronic ankle instability

Mark W. Cornwall*, Tarang Jain, Taylor Hagel

*Department of Physical Therapy and Athletic Training, Northern Arizona University, Flagstaff, AZ 86011, United States*

ARTICLE INFO

*Keywords:*
Ankle instability
Gait
Segment coupling

ABSTRACT

*Background:* It is estimated that nearly 2 million individuals sprain their ankle each year in the US. A majority of these are recurrent injuries, which often results in chronic ankle instability. To better understand the cause of instability, previous research has looked at the coupling or coordination between leg and foot motion during locomotion.

*Research Question:* Determine the coupling between the tibia and the calcaneus during the stance phase of walking in those without a history of ankle instability compared to those with either moderate or severe instability.

*Methods:* Fifty-four individuals between the age of 18-30 years (15 males; 39 females) participated in this study. Each participant's history of ankle sprains and score on the Cumberland Ankle Instability survey was used to assign them to either a no, moderate or severe instability group. Electromagnetic sensors attached to the tibia and calcaneus recorded three-dimensional movement of their tibia and calcaneus during the stance phase of barefoot over ground walking. The kinematic data was referenced to the subject's standing position and time normalized to each subject's stance phase duration. The relative phase (RP) angle and RP variability between tibia internal/external rotation and calcaneal inversion/eversion motion was then calculated. A one-way analysis of variance test was used to determine if significant differences existed between the three groups of subjects on mean RP angle or variability. An alpha level of .05 was used to determine statistical significance.

*Results:* A significant increase in RP angle and variability was found during the mid-stance phase of walking for those with severe ankle joint instability compared to those with moderate or no instability. Significance. The observed decreased coordination and increased coupling variability observed for those with severe ankle instability suggests either residual ligamentous damage, inadequate sensorimotor control, or both.

## 1. Introduction

The ankle joint is among the most common body regions injured during athletics and physical activity. In the USA, it is estimated that close to 2 million individuals sustain an ankle sprain each year [1]. About 59% of individuals with an acute ankle sprain develop chronic instability (CAI) [2]. CAI is described as a feeling of the ankle "giving way" and feelings of acute ankle joint instability, which is secondary to reduced intrinsic support from a history of multiple ankle sprains [3].

During walking, internal and external rotation of the leg is accompanied by inversion and eversion of the calcaneus. This relationship is referred to as "talocrural coupling" [4]. Since talocrural coupling is dependent upon the integrity of the ligaments supporting the ankle, their injury could result in decreased coordination between the tibia and calcaneus and resultant feelings of instability [4,5].

The coordination, or coupling between tibio-calcaneal motion has been investigated by several authors using a variety of methods. A common analysis technique used to investigate this coordination is vector coding (VC) [6,7]. This technique involves using an angle-angle diagram of the two segments and determining the orientation relative to the horizontal of the vector difference between two points [8].

Using VC, Herb and associates showed that those with CAI had greater relative frontal plane movement of the calcaneus compared with transverse movement of the shank during early and late swing phase of walking [6]. In addition, they found that those with CAI had less variability during late stance and early swing phase. They attributed the reduced variability to less adaptability to constraints by the sensor sensorimotor system. Lilley and associates used the VC technique to investigate the coordination between sagittal plane movement of the knee and frontal plane movement of the ankle [7]. They reported

* Corresponding author.
*E-mail address:* Mark.Cornwall@nau.edu (M.W. Cornwall).

https://doi.org/10.1016/j.gaitpost.2019.02.021
Received 17 September 2018; Received in revised form 30 January 2019; Accepted 22 February 2019

increased coupling variability from 51 to 66% and from 81 to 88% of the gait cycle in those with CAI. They speculated that the increased variability may be related to instances of instability and long-term joint degeneration.

Another analysis technique looking at inter-segment coordination is continuous relative phase (CRP) analysis [9]. Since receptors exist that control both the position and velocity of a segment, CRP analysis has been advocated because it contains both temporal and spatial information, yielding a more detailed analysis of movement behavior [10,11]. CRP also provides a continuous measure of segmental coordination throughout the activity of interest. A CRP angle of 0° indicates that the movement of the two segments are perfectly in-phase, while an angle of 180° indicates that the two segments are perfectly out-of-phase [12,13]. Using CRP analysis, Drews and colleagues studied the coupling between transverse plane rotation of the shank and frontal plane movement of the rearfoot in seven individuals with and seven without CAI [12]. They reported that those with CAI had significantly greater CRP values from 94 to 97% of the gait cycle compared to the control group, indicating that the two segments were more out-of-phase.

Understanding the magnitude and variability of kinematic coupling between the tibia and the calcaneus may help to explain the perceived instability and subsequent degeneration that is frequently seen following repeated ankle sprains. Unfortunately, previous studies have reported conflicting results and have not always looked at the same planes of movement. A further limitation of past research is that the magnitude of ankle instability has not been studied. Individuals with mild symptoms of ankle instability may be similar to uninjured individuals [14]. As such, looking at the magnitude of instability may demonstrate changes in inter-limb coordination that would otherwise not be evident. The purpose of the current study was to investigate tibial rotation and rearfoot eversion/inversion coupling during walking using CRP in those without ankle instability compared to those with either moderate or severe instability. It was theorized that those with severe instability would demonstrate less coordination between the tibia and calcaneus during walking compared to those with either no or moderate instability.

## 2. Methods

### 2.1. Subjects

A total of 54 subjects between the age of 18–30 years (15 males; 39 females) were recruited from a university community and were excluded from participation if they had a current injury to their lower extremities or had a history of injury, disease, or condition, with the exception of ankle sprains, that could possibly alter their foot posture, gait, or mobility. Those who met the inclusion criteria were then asked about their history of ankle sprains, including frequency, severity and whether they had any signs or symptoms of ankle instability. Eighty percent of the subjects in this study were physically active at least three days per week and none of them reported that their activity was limited by signs or symptoms of ankle instability. The Cumberland Ankle Instability (CAIT) [15] survey was used to assess the presence and magnitude of ankle instability. Subjects were then assigned to one of three different groups based on this information. Group 1 (CONTROL) consisted of individuals with a history of less than 2 ankle sprains and a CAIT score of $> 25$ [16]. Group 2 (MODAI) consisted of individuals with a history of 2 or more ankle sprains and a CAIT score of $\leq 25$, but $> 19$. Group 3 (SEVAI) consisted of individuals with a history of 2 or more ankle sprains and a CAIT score $\leq 19$. Prior to initiation of data collection, participants provided written informed consent. The study was approved by Northern Arizona University's institutional review board.

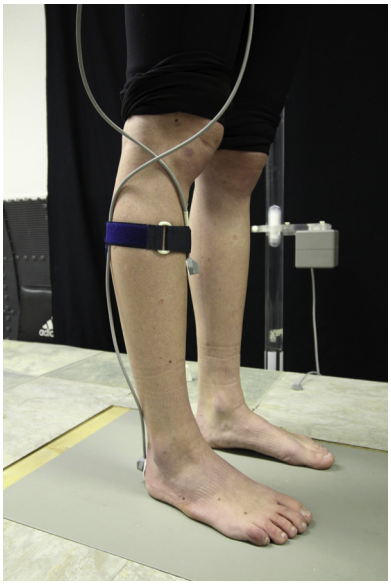

**Fig. 1.** Photograph of subject standing in the reference position (facing positive *Y* axis) with electromagnetic sensors attached.

### 2.2. Data collection

Motion of the shank and rearfoot of each subject was measured using an electromagnetic system based upon the Fastrak tracking device (Polhemus, Colchester, Vermont). The electromagnetic transmitter was positioned at the midway point of a 6-m raised walkway and 34-cm from its supporting surface. The walkway was raised 44.5-cm from the floor to avoid any possible distortion of the electromagnetic fields caused by metal reinforcement in the laboratory's concrete floor. The sensors measured 2.8 × 2.3-cm and weighed 17-g. The signals from each sensor were input to a digital signal processor that computed the sensor's position and orientation relative to the transmitter, which is sufficient for analyzing the stance phase of walking [17]. Within this range, it has an accuracy of 0.8 mm and 0.15° RMS [18].

Two electromagnetic sensors were used to collect the angular orientation of the shank and rearfoot. The sensors were attached to the posterior aspect of the calcaneus and to the anteriomedial tibia, approximately one-third of the distance from the subject's tibial tubercle (see Fig. 1). These locations were selected to minimize movement between the skin and sensor and to define the anatomical segments being analyzed. The sensors were attached using two-sided adhesive tape. Prior to collecting data, the segment endpoints of the shank and foot were defined by digitizing the medial and lateral joint lines of the knee, the medial and lateral malleoli and the tip of the second toe.

The sensors were connected to a computer by means of a 30-foot cable. An AMTI (Advanced Mechanical Technology, Inc., Watertown, MA) force plate positioned flush within the walkway and adjacent to the electromagnetic transmitter was used to record the initiation (onset of vertical force) and cessation (return to baseline) of the subject's stance phase. Joint coordinate angles were determined using a Cardan angle system (X'Y"Z"' sequence). Dorsiflexion/plantar flexion corresponded to rotation of the calcaneus about the lab's *x*-axis relative to the tibia. Inversion/eversion was rotation of the calcaneus about the lab's *y*-axis relative to the tibia. Finally, internal/external rotation was rotation of the tibia about the lab's *z*-axis relative to the calcaneus.

### 2.3. Procedure

After signing the informed consent, each subject's age, height, weight and foot posture index was recorded. Foot posture was assessed by the same individual (MWC) using the Foot Posture Index (FPI) [19],

which has been shown to have high intra-rater reliability and moderate inter-rater reliability [20]. Since the FPI is predictive of dynamic rearfoot motion [21], it was used to help ensure that foot posture was not significantly different between the three groups. The subject's limb with the greatest symptoms of instability was selected for analysis.

Subjects walked barefoot across the walkway and force plate for a minimum of 5 trials at their self-selected speed. Subjects were monitored during each trial and if they did not make complete contact with the force plate or they appeared to "target" the force plate, the trial was repeated.

### 2.4. Data processing

The sensor and vertical ground reaction force data were collected at 240 Hz and filtered with a 6 Hz low-pass, zero lag digital filter using *The Motion Monitor* software (Innovative Sports Training, Inc, Chicago, IL). All motion data was referenced to when the subject was standing with their feet shoulder width apart, the feet parallel to each other and facing along the positive y axis (See Fig. 1). The kinematic data were then time normalized to each subject's stance phase duration.

### 2.5. Continuous relative phase technique

Using proprietary MatLab version 17b scripts (MathWorks, Natick, MA), the continuous relative phase angle (CRP) between the shank ($z$) and rearfoot ($y$) was calculated as the difference in the phase angles of the two segments. The phase angles were determined from the position vs. velocity ($x$ vs. $x$') phase-planes. From the resulting phase-planes, the phase angle at each point ($\phi(t)$) was calculated relative to the right horizontal using the following equations described by previous investigators [9,10,22]. Prior to calculating the phase angles, the phase planes were normalized [9]. The continuous relative phase was then calculated by subtracting the two phase angles. In addition to determining the CRP angles between the two segments, the between-trial coupling variability of those phase angles at each point during the motion was calculated.

### 2.6. Statistical analysis

The stance phase was divided into 4 periods, similar to that proposed by Ferber et al. [23]. PERIODS 1, 2, 3 and 4 were defined as from 0–20% (loading response), 20–50% (mid-stance), 50–80% (terminal stance), and 80–100% (push-off), respectively. In addition to descriptive statistics, a one-way analysis of variance (ANOVA) was used to determine if statistically significant differences existed between the three groups of subjects relative to their mean CRP angle or mean CRP angle variability in each of the functional periods as well as the entire stance phase. If the ANOVA was statistically significant, a bonferroni post hoc correction was used to determine which conditions were significantly different. All statistical tests were performed using SPSS v24.0 (IBM Corp.) with a 5% level of statistical significance of 5%.

## 3. Results

The demographic information for subjects is shown in Table 1. The subjects in this study tended to be young females with an average FPI of 2.7, which is considered to be within the range of normal foot posture [24]. There was no statistical difference ($p > .05$) between the three groups on any of the demographic variables including the FPI.

**Table 2**
Mean continuous relative phase angles and continuous relative phase angle variability for each group during each functional period of the stance phase.

| Period | Control | MODAI | SEVAI | *F* value |
|---|---|---|---|---|
| Continuous relative phase angle | | | | |
| 1 | 43.2 (27.2) | 33.2 (32.0) | 50.9 (25.9) | 1.16 |
| 2 | 38.6 (19.9) | 28.6 (23.9) | 51.2[b] (22.0) | 3.18[a] |
| 3 | 44.7 (19.3) | 33.5 (21.2) | 44.0 (17.3) | 1.60 |
| 4 | 63.3 (25.5) | 48.2 (29.9) | 76.0 (34.5) | 2.80 |
| Total | 46.3(16.2) | 34.9 (24.2) | 53.9 (17.1) | 3.17[a] |
| Continuous relative phase angle variability | | | | |
| 1 | 14.7 (8.0) | 11.2 (8.8) | 17.3 (10.6) | 1.47 |
| 2 | 10.2 (5.7) | 7.9 (5.4) | 21.0[b,c] (20.4) | 5.65[a] |
| 3 | 8.12 (4.4) | 6.2 (3.3) | 10.2 (5.3) | 2.38 |
| 4 | 7.8 (4.0) | 6.4 (3.7) | 10.7[b] (5.1) | 3.18[a] |
| Total | 10.0 (3.8) | 7.7 (4.6) | 15.0[b,c] (9.5) | 5.21[a] |

Values in parentheses are standard deviations.
[a] Overall significance; $p < 0.05$.
[b] Different from MODAI; $p < 0.05$.
[c] Different from control; $p < 0.05$.

Fig. 3 shows the kinematic movement of the shank and rearfoot for each group. The results of the ANOVA test on mean CRP angle during walking showed it was statistically increased ($p = .05$) for the entire stance phase as well as during period 2 ($p = .05$) (see Table 2). Post hoc analysis for total stance phase and period 2 showed that mean CRP angle for SEVAI individuals was significantly increased ($p = .047$ and $p = .045$ respectively) compared to those in the MODAI group, but not the CONTROL group. The observed kinematic differences between the three groups during period 2 show that although the tibia in the SEVAI group continues to internally rotate similar to that in the MODAI and CONTROL groups, the rearfoot begins inverting sooner, thus resulting in the significantly increased CRP angle between the two segments (see Fig. 2a and Table 2). No statistical difference was found between those in the CONTROL, MODAI and SEVAI groups for periods 1, 3 or 4. Table 3 shows the effect sizes for each comparison made for mean CRP angle. As is seen, for those means that were found to be statistically significant, the effect size ranged from 1.03 to 1.06, which is considered "Large" [25].

The results of the ANOVA test on mean CRP angle variability showed that it was statistically different ($p = .0087$) for the entire stance phase as well as during period 2 ($p = .0061$) and period 4 ($p = .0497$) (see Fig. 2b and Table 2). Post hoc analysis showed that mean CRP angle variability for those in the SEVAI group during period 2 was significantly increased compared to those in the MODAI ($p = .009$) and CONTROL ($p = .013$) groups. There was no statistical difference seen between the MODAI and CONTROL group. With respect to period 4, the SEVAI group was significantly greater ($p = .05$) than the MODAI group, but not the CONTROL group (see Fig. 2b). For the entire stance phase, the SEVAI group was significantly greater than the MODAI group ($p = .008$) and the CONTROL group ($p = .045$). In addition, there was no statistical significance between the MODAI and

**Table 1**
Demographic information for the subjects in the study.

| Group | *N* | Male (%) | Age (yrs) | Height (cm) | Weight (kg) | FPI | CAIT | Number of sprains |
|---|---|---|---|---|---|---|---|---|
| Control | 31 | 35.5 | 23.9 (2.3) | 169.7 (7.8) | 73.5 (16.7) | 2.4 (2.9) | 29.1 (1.4) | .6 (1.1) |
| MODAI | 13 | 7.7 | 22.3 (3.0) | 172.4 (8.4) | 67.6 (12.7) | 3.9 (4.4) | 22.4 (1.7) | 3.9 (2.2) |
| SEVAI | 10 | 30.0 | 24.6 (1.8) | 171.3 (8.6) | 72.5 (11.8) | 2.0 (2.8) | 15.9 (3.2) | 7.2 (5.2) |
| Total | 54 | 27.8 | 23.6 (2.5) | 170.6 (8.0) | 71.9 (15.0) | 2.7 (3.3) | 25.1 (5.5) | 2.6 (3.6) |

Values in parentheses are standard deviations.

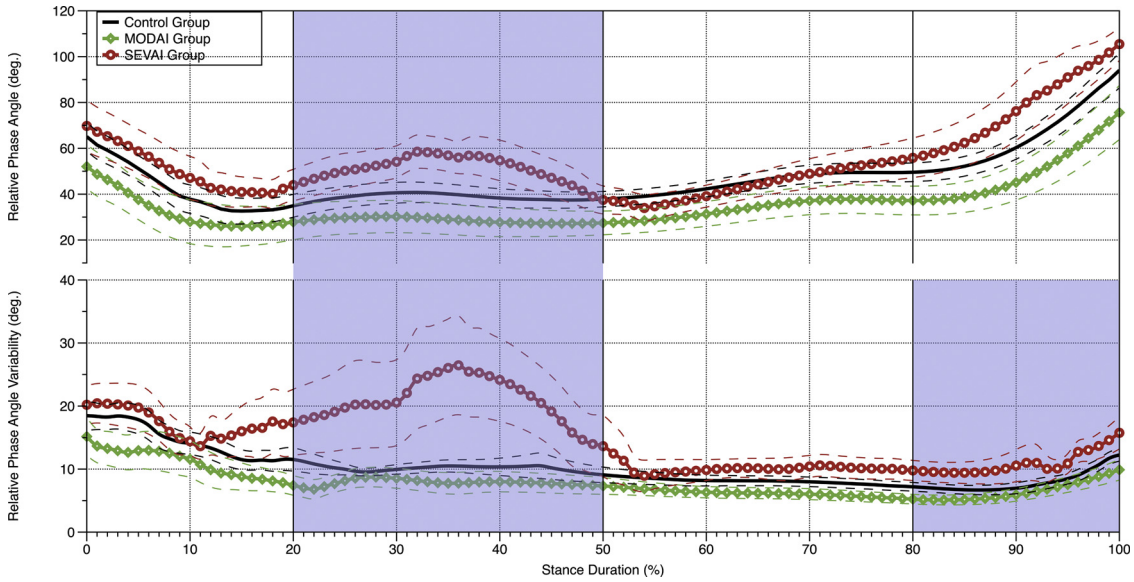


**Fig. 2.** Plot of the mean continuous relative phase angles and mean continuous relative phase angle variability for each group during the stance phase of walking. The shaded area indicates the functional period where statistical difference between the three groups was found. The dashed lines represent +/− one standard error of the mean.

**Table 3**
Magnitude of CRP angles and CRP variability effect sizes for comparison and each functional period of the gait cycle.

| CRP angle | | | CRP variability | | |
|---|---|---|---|---|---|
| Period 1 | | | | | |
| | MODAI | SEVAI | | MODAI | SEVAI |
| Control | .355 | .273 | Control | .403 | .300 |
| MODAI | – | .628 | MODAI | – | .703 |
| Period 2 | | | | | |
| | MODAI | SEVAI | | MODAI | SEVAI |
| Control | .470 | .592 | Control | .231 | 1.08[a] |
| MODAI | – | 1.06[a] | MODAI | – | 1.31[a] |
| Period 3 | | | | | |
| | MODAI | SEVAI | | MODAI | SEVAI |
| Control | .576 | .036 | Control | .443 | .480 |
| MODAI | – | .540 | MODAI | – | .924 |
| Period 4 | | | | | |
| | MODAI | SEVAI | | MODAI | SEVAI |
| Control | .532 | .448 | Control | .339 | .703 |
| MODAI | – | .981 | MODAI | – | 1.04[a] |
| Total | | | | | |
| | MODAI | SEVAI | | MODAI | SEVAI |
| Control | .615 | .410 | Control | .925 | 1.85[a] |
| MODAI | – | 1.03[a] | MODAI | – | .925[a] |

[a] Post-hoc significance; $p < 0.05$.

CONTROL groups. Table 3 shows the effect sizes for each comparison made for mean CRP angle variability. As is seen, for those means that were found to be statistically significant, the effect size ranged from .925 to 1.85, which is considered to be “Very Large” [25].

## 4. Discussion

The purpose of this study was to investigate tibia rotation and calcaneal eversion/inversion coupling during walking in those without ankle instability compared to those with either moderate or severe instability. The results indicate that during the mid-stance phase of walking, tibial rotation and calcaneal eversion are significantly out of phase with each other (increased CRP angle) during mid-stance for those with severe CAI. Previous studies have shown decreased coordination during stance, but not during mid-stance. Using the vector coding analysis technique, Herb, et al. demonstrated decreased coordination during the late and early swing phase [6]. Using the CRP analysis technique, Drewes et al. [12] demonstrated decreased coordination only during the late swing phase of walking. These differences may be related to Herb et al. [26] using the VC analysis technique rather than CRP. Further Research comparing the two techniques is therefore warranted. In addition, it is possible that Herb et al. [26] and Drewes et al. [12] may have studied individuals with less instability than those in the current study. In the case of Drewes et al. [12] a relatively small sample size ($n = 7$) may have also contributed to the difference in results. It is recommended that future research should either study only those with symptoms of severe ankle instability or subdivide subjects based on the severity of their symptoms.

During the loading response of walking, the internally rotating tibia coincides with subtalar joint eversion, adduction and plantar flexion of the talus [4]. During this time, talar movement is assisted by the increasing tension in the deltoid ligament, pulling it further into adduction and plantarflexion. This motion of the talus and its relatively tight fit within the ankle mortise works in concert with the subtalar joint configuration to evert the calcaneus. As the foot begins to unload during mid-stance and into terminal stance, the tibia begins to externally rotate. The external rotation of the tibia thus places increasing tension on the anterior tibiofibular ligament, causing the talus to move into abduction and dorsiflexion with subsequent calcaneal inversion. A disruption of the soft tissue about the ankle including the anterior talofibular or distal tibiofibular ligaments [27,28] could result in excess joint movement, allowing inversion rather than eversion of the calcaneus. Such altered movement during mid-stance for those with severe ankle instability was shown in the present study (see Fig. 3). As such, the extent of instability following an ankle sprain appears to be related to the degree of decreased coordination between the tibia and calcaneus. As always, further research regarding this is warranted.

With respect to coupling variability, previous research has reported decreased variability for those with CAI [6]. This is consistent with those in the current study with moderate instability, but not severe instability. Dynamic systems theory considers movement variability to reflect sensorimotor health and the capacity to explore a variety of strategies in order to accomplish a particular task [29,30]. It is suggested that the decreased coupling variability in those with CAI is an indication of less adaptability and a protective mechanism against

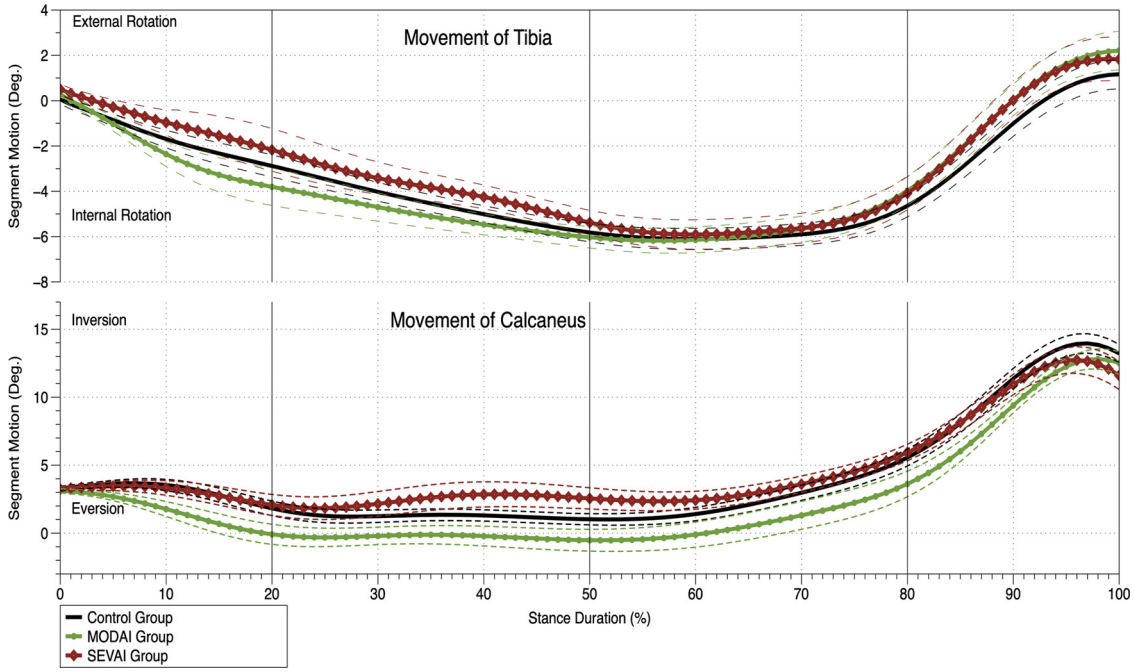


**Fig. 3.** Movement of the Tibia and Calcaneus during the stance phase of walking. Positive values for the Calcaneus are inversion, while positive values for the Tibia are external rotation. The vertical lines represent the division of the stance phase into four functional periods. The dashed lines represent + / − one standard error of the mean.

subsequent injury [7]. The reduced coupling variability in the current study for those with moderate instability could be such a manifestation of this attempt to restrict movement variability and thus prevent injury or reduce symptoms of instability. For those in our study with severe ankle instability, the increased coupling variability might be an indication of their attempt to use a variety of movement strategies in an attempt to reduce their symptoms of instability. On the other hand, the increased variability may simply be the result of a loss in the structural integrity of the ankle and the inability to adequately restrict uncoordinated movement, thus producing symptoms of "giving way". Future research should certainly explore the possible role that each of these two mechanisms may play in chronic instability following ankle sprains.

The limitations of the present study include the measurement of only walking as well as only analyzing the stance phase. Despite this, the authors do not feel that this is a significant limitation since all subjects reported having some degree of instability during walking and that such symptoms would be most likely reported during a closed-chained movement such as the stance phase. Admittedly, the study is limited by the relatively small number of individuals with moderate or severe ankle instability. The calculated effect sizes, however, indicate that the observed changes were real, regardless of the number of subjects tested. Finally, the activity of the muscles about the ankle were not recorded in this study, which may have provided insights as to the nature and cause of the observed decreased coordination between the tibia and calcaneus as well as the increased coupling variability. Future research should include such analysis.

## 5. Conclusion

Individuals with a history of multiple ankle sprains and symptoms of severe ankle instability show decreased coordination between the tibia and calcaneus during the mid-stance phase of walking. In addition, coordination variability was significantly increased during the mid-stance and push-off phases. This increased variability may indicate the inability to successfully restrict segmental movement in order to minimize symptoms or prevent subsequent injury.

## Author's contribution

Mark W. Cornwall: Conception and design of study, acquisition, analysis and interpretation of data, drafting and revising of manuscript, and final approval of the version submitted.

Tarang Jain: Design of study, acquisition and interpretation of data, drafting and revising of manuscript, and final approval of the version submitted.

Taylor Hagel: Acquisition of data, drafting and revising of manuscript, and final approval of the version submitted.

## Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

## Conflict of interest

None of the authors have any financial or personal relationship with other people or organizations what could inappropriately influence this work.

## References

[1] B.R. Waterman, B.D. Owens, S. Davey, M.A. Zacchilli, P.J. Belmont, The epidemiology of ankle sprains in the United States, J. Bone Joint Surg. [Am.] 92 (2010) 2279–2284, https://doi.org/10.2106/JBJS.I.01537.

[2] R.M. van Rijn, A.G. van Os, R.M.D. Bernsen, P.A. Luijsterburg, B.W. Koes, S.M.A. Bierma-Zeinstra, What is the clinical course of acute ankle sprains? A systematic literature review, Am. J. Med. 121 (2008) 324–326, https://doi.org/10.1016/j.amjmed.2007.11.018.

[3] J. Hertel, Functional anatomy, pathomechanics, and pathophysiology of lateral ankle instability, J. Athl. Train. 37 (2002) 364–375.

[4] A. Huson, M.H. Jahss, Functional Anatomy of the Foot Disorders of the Foot and Ankle: Medical and Surgical Management vol. 2, W.B. Saunders, Philadelphia, 1991, pp. 409–431.

[5] P. Kjærsgaard-Andersen, J.-O. Wethelund, P. Helmig, S. Nielsen, Effect of the calcaneofibular ligament on hindfoot rotation in amputation specimens, Acta Orthop. Scand. 58 (2009) 135–138, https://doi.org/10.3109/17453678709146459.

[6] C.C. Herb, L. Chinn, J. Dicharry, P.O. McKeon, J.M. Hart, J. Hertel, Shank-rearfoot joint coupling with chronic ankle instability, J. Appl. Biomech. 30 (2014) 366–372,

https://doi.org/10.1123/jab.2013-0085.
[7] T. Lilley, C.C. Herb, J. Hart, J. Hertel, Lower extremity joint coupling variability during gait in young adults with and without chronic ankle instability, Sports Biomech. 55 (2017) 1–12, https://doi.org/10.1080/14763141.2017.1287215.
[8] W.A. Sparrow, E. Donovan, R. van Emmerik, E.B. Barry, Using relative motion plots to measure changes in intra-limb and inter-limb coordination, J. Mot. Behav. 19 (1987) 115–129, https://doi.org/10.1080/00222895.1987.10735403.
[9] P.F. Lamb, M. Stöckl, On the use of continuous relative phase: Review of current approaches and outline for a new standard, Clin. Biomech. 29 (2014) 484–493, https://doi.org/10.1016/j.clinbiomech.2014.03.008.
[10] J. Hamill, R. van Emmerik, B.C. Heiderscheit, L. Li, A dynamical systems approach to lower extremity running injuries, Clin. Biomech. 14 (1999) 297–308.
[11] R.H. Miller, S.A. Meardon, T.R. Derrick, J.C. Gillette, Continuous relative phase variability during an exhaustive run in runners with a history of iliotibial band syndrome, J. Appl. Biomech. 24 (2008) 262–270.
[12] L.K. Drewes, P.O. McKeon, G. Paolini, P. Riley, D.C. Kerrigan, C.D. Ingersoll, et al., Altered ankle kinematics and shank-rear-foot coupling in those with chronic ankle instability, J. Sport Rehabil. 18 (2009) 375–388.
[13] J. Hamill, J.M. Haddad, W.J. McDermott, Issues in quantifying variability from a dynamical systems perspective, J. Appl. Biomech. 16 (2000) 407–418.
[14] C.J. Wright, B.L. Arnold, Fatigue's effect on eversion force sense in individuals with and without functional ankle instability, J. Sport Rehabil. 21 (2012) 127–136.
[15] C.E. Hiller, K.M. Refshauge, A.C. Bundy, R.D. Herbert, S.L. Kilbreath, The Cumberland ankle instability tool: a report of validity and reliability testing, Arch. Phys. Med. Rehabil. 87 (2006) 1235–1241, https://doi.org/10.1016/j.apmr.2006.05.022.
[16] C.J. Wright, B.L. Arnold, S.E. Ross, S.W. Linens, Recalibration and validation of the Cumberland Ankle Instability Tool cutoff score for individuals with chronic ankle instability, Arch. Phys. Med. Rehabil. 95 (2014) 1853–1859, https://doi.org/10.1016/j.apmr.2014.04.017.
[17] K. Mannon, T. Anderson, P. Cheetham, M.W. Cornwall, T.G. McPoil, A comparison of two motion analysis systems for the measurement of two-dimensional rearfoot motion during walking, Foot Ankle 18 (1997) 427–431.
[18] Fastrak User's Manual, Polhemus, Inc, Colchester, VT, 1993.
[19] A.C. Redmond, J. Crosbie, R.A. Ouvrier, Development and validation of a novel rating system for scoring foot posture: Foot Posture Index, Clin. Biomech. 21 (2006) 89–98.
[20] M.W. Cornwall, T.G. McPoil, M. Lebec, B. Vicenzino, J. Wilson, Reliability of the modified Foot Posture Index, J. Am. Podiatr. Med. Assoc. 98 (2008) 7–13.
[21] V.H. Chuter, Relationships between foot type and dynamic rearfoot frontal plane motion, J. Foot Ankle Res. 3 (2010) 9, https://doi.org/10.1186/1757-1146-3-9.
[22] B.T. Peters, J.M. Haddad, B.C. Heiderscheit, R.E.A. Van Emmerik, J. Hamill, Limitations in the use and interpretation of continuous relative phase, J. Biomech. 36 (2003) 271–274.
[23] R. Ferber, I.M. Davis, D.S. Williams, Effect of foot orthotics on rearfoot and tibia joint coupling patterns and variability, J. Biomech. 38 (2005) 477–483, https://doi.org/10.1016/j.jbiomech.2004.04.019.
[24] A.C. Redmond, Y.Z. Crane, H.B. Menz, Normative values for the Foot Posture Index, J. Foot Ankle Res. 1 (2008) 1–9.
[25] L.E. Cohen, Statistical Power Analysis for the Behavioral Sciences, 2nd ed., Academic Press, 1988.
[26] C.C. Herb, J. Hertel, Shank-rearfoot joint coupling in young adults with chronic ankle instability: a cross-correlation analysis, J. Sports Med. Therap. 55 (2015) 639–646.
[27] F.W. Roemer, N. Jomaah, J. Niu, E. Almusa, B. Roger, P. D'Hooghe, et al., Ligamentous injuries and the risk of associated tissue damage in acute ankle sprains in athletes: a cross-sectional MRI study, Am. J. Sports Med. 42 (2014) 1549–1557, https://doi.org/10.1177/0363546514529643.
[28] Y.P. Khor, K.J. Tan, The anatomic pattern of injuries in acute inversion ankle sprains, Orthop. J. Sports Med. 1 (2013), https://doi.org/10.1177/2325967113517078 232596711351707–5.
[29] A.T.A. DeLeo, T.A.T. Dierks, R.R. Ferber, I.S.I. Davis, Lower extremity joint coupling during running: a current update, Clin. Biomech. 19 (2004) 983–991, https://doi.org/10.1016/j.clinbiomech.2004.07.005.
[30] P.O. McKeon, C.D. Ingersoll, D.C. Kerrigan, E. Saliba, B.C. Bennett, J. Hertel, Balance training improves function and postural control in those with chronic ankle instability, Med. Sci. Sports Exerc. 40 (2008) 1810–1819, https://doi.org/10.1249/MSS.0b013e318170f92.