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Differences In Kinematic Control of Ankle Joint Motions in People with Chronic Ankle Instability

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Abstract
Background
People with chronic ankle instability display different ankle joint motions compared to healthy people. The purpose of this study was to investigate the strategies used to control ankle joint motions between a group of people with chronic ankle instability and a group of healthy, matched controls.
Methods
Kinematic data were collected from 11 people with chronic ankle instability and 11 matched control subjects as they performed a single-leg land-and-cut maneuver. Three-dimensional ankle joint angles were calculated from 100 ms before, to 200 ms after landing. Kinematic control of the three rotational ankle joint degrees of freedom was investigated by simultaneously examining the three-dimensional co-variation of plantarflexion/dorsiflexion, toe-in/toe-out rotation, and inversion/eversion motions with principal component analysis.

Findings
Group differences in the variance proportions of the first two principal components indicated that the angular co-variation between ankle joint motions was more linear in the control group, but more planar in the chronic ankle instability group. Frontal and transverse plane motions, in particular, contributed to the group differences in the linearity and planarity of angular co-variation.

Interpretations
People with chronic ankle instability use a different kinematic control strategy to coordinate ankle joint motions during a single-leg landing task. Compared to the healthy group, the chronic ankle instability group's control strategy appeared to be more complex and involved joint-specific contributions that would tend to predispose this group to recurring episodes of instability.

Keywords
Ankle sprain, Motor control, Landing biomechanics

1. Introduction
Chronic ankle instability (CAI) is often a result of repeated ankle sprains (Hertel, 2002). CAI can be characterized by a subjective feeling of instability or reported tendency for the ankle to ‘give way’ during activity (Hertel, 2002). From a functional standpoint, CAI is associated with neuromechanical changes in the performance of motor tasks, such as walking and running gait or jump landing tasks, which are thought to contribute to the recurrent episodes of instability (Brown, 2011, Brown et al., 2008, Delahunt et al., 2006a, Delahunt et al., 2006b, Drewes et al., 2009). Perhaps most significant is the fact that people with CAI present with articular lesions and joint degeneration in the ankle, both of which have been associated with post-traumatic osteoarthritis (Hinterrmann et al., 2002, Valderrabano et al., 2006). If pathological neuromechanics are associated with CAI and thus the development post-traumatic osteoarthritis at the ankle, rehabilitation protocols that target and restore normal neuromechanical control are needed. In order to best guide such rehabilitation protocols, the mechanisms responsible for pathological neuromechanics need to be determined.

While neuromechanical changes manifest in the periphery (e.g., impaired muscle force or proprioception), it has recently been posited that central mechanisms are also associated with altered motor control in people with CAI (Hass et al., 2010, Hertel, 2002, Hertel, 2008). The pragmatic implications of these arguments is that the presence of any central reorganization of motor control in people with CAI would indicate that rehabilitation protocols should treat CAI as not solely a peripheral injury, but also a central injury (Hass et al., 2010, Hertel, 2002, Hertel, 2008). While altered central control strategies in people with CAI have been implicated as a contributing factor to re-injury, it remains to be determined how any such changes manifest to influence kinematic outcomes during dynamic movements.

It is generally believed that joint kinematics during dynamic movements are controlled through a task-dependent reduction in the redundancy of the degrees of freedom within the musculoskeletal system (Courtine and Schieppati, 2004, Courtine et al., 2006, Ivanenko et al., 2007, Ivanenko et al., 2008). One way for the central
nervous system to effectively reduce degrees of freedom and simplify motor control is by constraining and controlling the covariation of limb segments and joint angles. Kinematic covariation among limb segments can be observed across a variety of gaits and tasks and is thought to emerge from interaction of spinal neural networks (Ivanenko et al., 2007, Ivanenko et al., 2008). Studying the covariation among joint segments therefore provides insight into how the central nervous system controls joint kinematics during dynamic movements (Ivanenko et al., 2003, Ivanenko et al., 2008).

The angular covariation of multiple limb segments can be computed from the covariance matrix of time-varying joint angles (Borghese et al., 1996). To this end, a principal component analysis is typically used to extract the eigenvectors and eigenvalues from such a covariance matrix (Borghese et al., 1996). The first two principal components (i.e., eigenvectors) typically determine the axes of a plane that captures the three-dimensional covariation (Courtine and Schieppati, 2004). In addition, greater variance along the first principal component indicates more linear covariation whereas greater variance along the second indicates a more planar covariation (Courtine et al., 2006). An increase in the planarity is associated with an increase in the complexity of a task as well as the strategy that is used to control the kinematic degrees of freedom of the system during that task (Ivanenko et al., 2007, Ivanenko et al., 2008).

The purpose of this study was to use the planar covariation framework to investigate the kinematic control strategies of ankle joint motions between a group of people with CAI and healthy, matched controls during a single-leg land-and-cut maneuver. It was hypothesized that aspects related to the control strategy of ankle motions would differ between these groups and that differences in these aspects would reflect pathological joint kinematics related to the (re)injury mechanism for people with CAI.

2. Methods
Twenty two people (11 with CAI (5 males and 6 females) and 11 healthy controls (5 males and 6 females)) were recruited to participate in this study. Inclusion into the CAI group was based on a questionnaire (McVey et al., 2005) that assessed the severity and history of ankle sprains to establish the presence of CAI. Control subjects were then recruited and matched to people with CAI based on sex, age, height, and weight (CAI group: 22.4(3.2) years; 1.68(0.11) m; 69.0(19.1) kg; Control group: 22.6(4.2) years; 1.74(0.11) m; 66.8(15.5 kg)). The initial matching criteria were set to 10% of all respective anthropometric variables. Subjects then completed the Foot and Ankle Disability Index (CAI group: 90.3(9.4); Control group: 100.0(0.0)) along with the Foot and Ankle Disability Index — Sport (CAI group: 88.6(9.1); Control group: 100.0(0.0)) version to help define the level of self-reported function and disability in the CAI group (Hale and Hertel, 2005). In addition, all subjects were recreationally active, and the activity levels between groups were similar (CAI group: 5.3(1.2) Tegner Score; Control group: 5.3(1.0) Tegner Score). Each person signed an institutionally approved consent form before the beginning of data collection.

Biomechanical data were collected during the execution of a single-leg land-and-cut task. People with CAI were asked to land on their affected leg during the task. In the case that both ankles were affected by CAI, a person was asked to use the leg he/she felt was more affected or unstable. Each matched control was then asked to use the same leg, regardless of leg dominance. The task required each person to jump over a 15-cm box, land on the pre-determined leg and perform a 90 degree side-cut away from the landing leg (McLean and Samorezov, 2009). The forward jump distance was normalized to the individuals’ leg length, measured as the distance from the greater trochanter to the lateral malleolus. Each person completed five trials. During the task, subjects landed on a force plate (AMTI, Watertown, MA, USA), within the field of view of a high-speed motion analysis system (ViconMx, Lake Forest, CA, USA). During each trial, the positions of 11 reflective markers were collected. Markers were attached to the 2nd metatarsal, base of the 5th metatarsal, mid-foot, heel, lateral and medial
malleoli, distal and proximal tibia, tibial tuberosity, as well as the medial and lateral epicondyles of the knee (Kipp and Palmieri-Smith, 2012). Marker and force plate data were acquired at 240 and 1200 Hz, respectively. All data were low-pass filtered with a cubic-spline at 12 Hz (Woltring et al., 1985). The filtered position data were then used as inputs to a two segment (foot and shank) kinematic model in Visual 3D (C-Motion, Rockville, Maryland, USA) that calculated ankle rotations based on Cardan-rotation sequences of the distal (foot) segment with respect to the proximal (shank) segment, and expressed relative to a neutral standing position (McLean and Samorezov, 2009). Since aberrant movement mechanics during lateral sprains appear noticeable up to 180 ms after touchdown (Gehring et al., 2013, Kristianslund et al., 2011), the joint angle time-series data were trimmed from 100 ms before to 200 ms after touchdown (Fig. 1), which was defined as the point when the vertical ground reaction force exceed 10 N. Joint angles at touchdown along with peak stance angles during the trimmed 200 ms window were extracted and analyzed.

For the purpose of the co-variance plane analysis the trimmed time-series data were then further ‘normalized’ by subtracting each series’ mean and dividing by its standard deviation. This procedure normalizes the amplitude and range of each time-series and ensures that all data are given an equal consideration in said analysis (St-Onge and Feldman, 2003). In addition, this procedure increases the emphasis on the temporal structure (i.e., timing) of the joint rotation as opposed to solely the spatial structure (i.e., magnitude). Eigenvectors and eigenvalues were then extracted from the covariance matrix of all three normalized joint angle
time-series data (Courtine and Schieppati, 2004). The eigenvalues were used to calculate the variance proportion (%) accounted for by each eigenvector (i.e., principal component — PC) (Courtine and Schieppati, 2004). Extraction of PCs continued until the variance proportion explained by the last extracted PC was less than 1%. The variance proportions accounted for by the first two extracted PCs quantify the majority of covariation of all segments or joint angles included in the analysis. More specifically, a larger variance proportion explained by the first PC captures a more ‘linear’ angular covariation, which indicates that the covariation of all angles is tightly coupled and occurs more or less along a line. A large variance proportion explained by the second PC captures a more ‘planar’ angular covariation, which indicates that the covariation is less tightly coupled and occurs within a plane (Courtine and Schieppati, 2004) (Fig. 2). By nature of the orthogonal extraction of PCs, the third PC is perpendicular to the other two PCs and captures the planes' orientation, which is sometimes used to quantify the temporal coupling between segments (Courtine and Schieppati, 2004) or between different movements (Ivanenko et al., 2008). Since each joint angle is a linear combination of the extracted PC, the contribution of each PC to the angle time-series data can also be estimated by calculating the weighing coefficient of each contributing joint angle. Comparisons between matched weighing coefficients therefore indicate how much each joint angle contributes to the respective linearity of planarity of the co-variation plane.

Fig. 2. Principal component analysis of angular co-variation. a) Simulated three-dimensional angle–angle plot for three degrees-of-freedom (DoF) from a single joint. Extracted principal components (PC) from joint angle data where b) a large variance proportion is explained by PC1 and angular co-variation is more ‘linear,’ and c) where a relatively larger variance proportion is explained by PC2 and angular co-variation is more ‘planar’.

The list of dependent variables included touchdown and peak angles, as well as PC variances and PC contributions to the joint angle time-series data. Two-tailed t-tests were used to compare all dependent variables between the CAI and control groups. Data are presented as Mean(SD). Statistical significance was set at $\alpha = 0.05$. Statistical trends were analyzed if the $P$-value was less than 0.10. Effect sizes (ES) were calculated if
statistical significance or trends were found and interpreted according to the convention of Cohen. All statistical analyses were performed in SPSS 19 (IBM Corporation, Armonk, New York, USA).

3. Results
Touchdown and peak joint angles did not differ significantly between groups (Table 1).

Table 1. Mean(SD) touchdown and peak joint angles in the chronic ankle instability (CAI) and control (CON) group.

<table>
<thead>
<tr>
<th></th>
<th>CAI</th>
<th>CON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Touchdown</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DF/PF</td>
<td>−30.6(2.6)</td>
<td>−30.6(1.7)</td>
</tr>
<tr>
<td>TO/TI</td>
<td>9.2(2.4)</td>
<td>7.9(2.1)</td>
</tr>
<tr>
<td>IN/EV</td>
<td>6.7(1.9)</td>
<td>9.3(1.4)</td>
</tr>
<tr>
<td>Peak</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DF/PF</td>
<td>15.9(1.8)</td>
<td>18.1(2.0)</td>
</tr>
<tr>
<td>TO/TI</td>
<td>11.5(3.3)</td>
<td>13.8(2.1)</td>
</tr>
<tr>
<td>IN/EV</td>
<td>7.3(1.7)</td>
<td>9.5(1.4)</td>
</tr>
</tbody>
</table>

DF/PF = dorsi-flexion(+) / plantar-flexion(−).
TO/TI = toe-out(+) / toe-in(−).
INV/EV = inversion(+) / eversion(−).

The variance proportion accounted for by the individual PCs differed between the groups. The variance proportion of the first PC (PC1) was smaller in the CAI than the CON group (78.1(11.0)% vs. 89.7(6.8)%; \( P = 0.010, \text{ES} = 1.08 \)). Conversely, the variance proportion accounted for by the second PC (PC2) was greater in the CAI (15.3(7.9)% vs. 6.5(4.0)%; \( P = 0.005, \text{ES} = 1.15 \)) than the CON group. The variance proportions explained by the third PC (PC3) did not differ between groups (CAI: 4.4(2.9)%; CON: 3.0(1.2)%; \( P = 0.272 \)). The differences in the variance proportions explained by PC1 and PC2 indicate that the eigenvectors within the covariance plane differ in length, which identifies differences in the linearity and planarity of angular covariation (Fig. 3).
Fig. 3. Representative ankle joint angles (degrees) for one trial from an individual subject in the a) chronic ankle instability and b) healthy control group. Note that the angular co-variation appears more linear for the healthy person in b) and more planar for the person with chronic ankle instability in a). The differences in these figures illustrate that the angular changes in joint motions at the ankle were more tightly coupled in healthy people, but were less tightly coupled in people with chronic ankle instability.

The contribution of each angle to the PCs differed between groups (Table 2). The analysis indicated that groups differed in the contributions of ankle plantarflexion/dorsiflexion \( (P = 0.054, \text{ES} = 0.70) \) and inversion/eversion \( (P = 0.026, \text{ES} = 0.84) \) angles to PC1, toe-in/toe-out rotation \( (P = 0.030, \text{ES} = 0.82) \) to PC2, and plantarflexion/dorsiflexion \( (P = 0.064, \text{ES} = 0.79) \) and inversion/eversion \( (P = 0.071, \text{ES} = 0.77) \) angles to PC3. These findings indicate that the aforementioned differences in linearity/planarity are driven by specific differences in joint-specific contributions.

Table 2. Mean(SD) contribution of each angle to shaping each principal component (PC) in the chronic ankle instability (CAI) and control (CON) group.

<table>
<thead>
<tr>
<th>PC</th>
<th>Angle</th>
<th>CAI</th>
<th>CON</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC1</td>
<td>DF/PF†</td>
<td>8.0(0.5)</td>
<td>8.3(0.2)</td>
</tr>
<tr>
<td></td>
<td>TO/TI</td>
<td>4.5(3.6)</td>
<td>1.9(7.6)</td>
</tr>
<tr>
<td></td>
<td>IN/EV*</td>
<td>6.2(2.0)</td>
<td>7.7(1.1)</td>
</tr>
<tr>
<td>PC2</td>
<td>DF/PF</td>
<td>0.3(1.2)</td>
<td>−0.3(1.2)</td>
</tr>
<tr>
<td></td>
<td>TO/TI*</td>
<td>2.2(3.3)</td>
<td>−0.3(2.2)</td>
</tr>
<tr>
<td></td>
<td>IN/EV</td>
<td>−0.5(3.7)</td>
<td>−0.6(1.7)</td>
</tr>
<tr>
<td>PC3</td>
<td>DF/PF†</td>
<td>0.3(1.8)</td>
<td>−0.9(0.7)</td>
</tr>
<tr>
<td></td>
<td>TO/TI</td>
<td>−0.1(2.0)</td>
<td>−1.2(1.6)</td>
</tr>
<tr>
<td></td>
<td>IN/EV†</td>
<td>0.5(2.4)</td>
<td>−1.2(0.8)</td>
</tr>
</tbody>
</table>

DF/PF = dorsi-flexion/plantar-flexion.
4. Discussion
The purpose of this study was to investigate the kinematic control strategies of ankle joint motions between a group of people with CAI and healthy, matched controls during a single-leg land-and-cut maneuver. It was hypothesized that aspects related to control of ankle motion would differ between these groups and that differences in these aspects would reflect pathological joint kinematics related to the (re)injury mechanism for people with CAI. The results of this study confirmed these hypotheses in that the CAI group used a different strategy to control the co-variation of the kinematic degrees of freedom at the ankle joint during the single-leg land-and-cut task. In addition, the joint-specific contributions to the co-variation of ankle joint motions in the CAI group were more consistent with the mechanism of injury for ankle sprains. These findings may point to different control at the level of the central nervous system, which may be predispose the CAI group to recurring episodes of ankle instability.

The variance proportion accounted for by the first and second principal components differed between the CAI and CON group. Specifically, the variance proportion of the first principal component was smaller in the CAI group; conversely the variance proportion of the second principal component was greater in this group. A greater variance proportion of the first principal component indicates a greater linearity in the co-variation among joint angles, which implies that joint angles lie and co-vary along a line (Courtine and Schieppati, 2004). Conversely, greater variance proportion of the second principal component indicates a greater planarity in the co-variation among joint angles, which implies that joint angles lie and co-vary within a plane (Courtine and Schieppati, 2004). In combination, the smaller variance of the first principal component and greater variance of the second principal component indicates that the joint angles in the CAI group co-varied more within a plane, whereas the joint angles in the control group lay more along a line. Differences in joint angle co-variation (i.e., linear vs. planar) are usually considered to reflect different kinematic control strategies (Ivanenko et al., 2008). For example, increases in task difficulty, such as switching from normal walking to either walking while blindfolded or walking on a slippery surface, are associated with change from linear to planar co-variation among limb segments (Cappellini et al., 2010, Courtine and Schieppati, 2004). Conversely, processes associated with motor learning appear to shift the angular covariation in the opposite direction (Ivanenko et al., 2008). Based on these previous results, the greater planar co-variation exhibited by people in the CAI group would therefore indicate that they used a different strategy to control the kinematic degrees of freedom at the ankle joint during the single-leg land-and-cut maneuver. This conclusion is particularly interesting because the touchdown and peak angles did not differ between groups. It thus appears that while both groups exhibit similar kinematic profiles, they differ in how they coordinate the degrees-of-freedom that contribute to these motions.

Although there were no group differences in touchdown and peak angles, the extent with which each angle contributed to shaping the principal components differed between groups. The most substantial group differences were found in how much ankle inversion/eversion angles contributed to the first principal component, and in how much ankle toe-in/toe-out angles contributed to the second principal component. These results consequently indicate that the aforementioned group differences in linearity and planarity of angular co-variation are driven by a combination of frontal and transverse plane rotations. It is important to note that motions in these two planes manifest as multi-planar rear-foot supination, which is thought to be a primary mechanism of injury during lateral ankle sprains (Hertel, 2002, Hertel, 2008). Although not a primary aim of this study, it is interesting to briefly reflect on a slight group difference in the standard deviation of the toe-in/toe-out rotation angle contribution for the first principal component. This group difference is of potential...
clinical interest because greater variability in movement kinematics has been purported as a predisposing factor of compromised joint stability and the recurrence of ankle sprains in people with CAI (Brown et al., 2008, Drewes et al., 2009). Collectively, these findings therefore implicate that how joint-specific differences relate to the observed group difference in kinematic control, could predispose people with CAI to further ankle sprains and ‘giving-away’ episodes.

People in the CAI group of the current study reported stereotypical clinical symptoms of either subjective feelings of instability or tendency for the ankle to ‘give way’ during activity. Although it is unclear if kinematic control differed before the injury or whether it is a result of the injury, it could be speculated that these differences reflect a deleterious compensatory strategy that ineffectively alters joint coordination in a way to predispose people with CAI to recurring episodes of ankle instability. For example, it has been purported that an increase in the complexity of motor control strategies during dynamic movements may ‘overload’ a sensorimotor system that is already constrained by the injury itself (McKeon and Hertel, 2008, Wikstrom et al., 2010). This ‘overload’ could even further decrease a person's ability to respond, cope, and control joint motions in the face of changing task and/or environmental demands and contribute to said clinical symptoms associated with CAI.

Since CAI is associated with articular lesions and joint degeneration (Hintermann et al., 2002, Valderrabano et al., 2006), targeted rehabilitation protocols that focus on kinematic control are needed to restore proper control of joint motions in people with CAI. As the current study provides evidence for differences in the kinematic control of joint motions in people with CAI, future research should examine these differences in order to design effective rehabilitation intervention address the underlying mechanisms associated with CAI.

It should be noted that some debate exists on whether the extracted principal components actually represent control strategies or rather capture task-dependent biomechanical constraints imposed on the musculoskeletal system (Tresch and Jarc, 2009). For example, it may be that the principal components, their associated variance proportions, and joint-specific contributions may simply reflect general biomechanical constraints inherent to movement rather than a centrally mediated control strategy. However, even if biomechanical constraints contribute to planar co-variation, the central nervous system must still account for these factors and take them into consideration during the control of movement (Ivanenko et al., 2008). It is therefore likely that the planar co-variation strategy arises from a combination of biomechanical and central constraints (Ivanenko et al., 2008). One approach to address this issue in the future may be to use the co-variation framework to investigate angular co-variation in people with either mechanical or functional ankle instability in order to parse out the influence of biomechanical, or even perhaps ligamentous, constraints.

In addition to the general methods-related limitation addressed in above paragraph, several other limitations warrant brief discussion. First, inclusion into the CAI group was based on subjective self-reports of instability. Second, people in the CAI group were not tested for specific mechanical or ligamentous instability. These inclusion and selection criteria therefore limit the generalizability of the current study's findings, because the umbrella-term ‘chronic ankle instability’ does not differentiate between functional and mechanical instability of the ankle. Research, however, has identified neuromechanical differences between these groups (Brown et al., 2008). As mentioned earlier, replicating a similar study in groups that have either mechanical or functional ankle instability within better defined sub-groups of people with CAI may help further elucidate the mechanisms that contribute to ankle instability. Another consideration that may also facilitate this effort is to extend our analysis to more proximal joints since it is well known that biomechanics at these joint also differ in people with CAI. One last point to consider is that the observed group differences may also reflect greater inter-trial variation in the CAI group. Several studies have identified differences in inter-trial variability between people with CAI and healthy controls (Brown et al., 2008, Drewes et al., 2009, Kipp and Palmieri-Smith, 2012). Greater inter-trial
variability could also arise from a number of sources not considered in this study, such as muscle activation strategies or arthrokinematics.

5. Conclusion
People with CAI use a different kinematic control strategy to coordinate the angular co-variation of ankle joint motions during a single-leg land-and-cut maneuver. Compared to a group of healthy people, the CAI group used a more complex strategy to control the kinematic degrees of freedom at the ankle joint. The contributions of various joints to the observed differences in co-variation of ankle joint motions were also consistent with the mechanism of injury for ankle sprains. These differences may predispose people with CAI to recurring episodes of ankle instability. Since CAI affects long-term musculoskeletal health, the trainability of kinematic control in response to targeted interventions after injury may provide useful clinical insights for the treatment of CAI.

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