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Published online: 06 Feb 2014.


To link to this article: http://dx.doi.org/10.1080/02640414.2013.868917

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Neuromuscular control during stepping down in continuous gait in individuals with and without ankle instability

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(Accepted 20 November 2013)

Abstract
Ankle sprains are a common injury and those affected are at a risk of developing chronic ankle instability (CAI). Complications of an acute sprain include increased risk of re-injury and persistent disability; however, the exact link between ankle sprains and chronic instability has yet to be elucidated. The purpose of this study was to investigate neuromuscular control (including kinematics, kinetics and EMG) during stepping down from a curb, a common yet challenging daily activity, in persons with ankle instability (n = 11), those with a history of ankle sprain without persistent instability, called ankle sprain “copers” (CPRs) (n = 9) and uninjured controls (CTLs) (n = 13). A significant group difference was noted as the CPR group demonstrated increased tibialis anterior activity in both the preparatory (pre-touchdown) and reactive (post-touchdown) phases when compared to healthy and unstable groups (P < 0.05). It follows that the CPR group also demonstrated a significantly less plantar-flexed position at touchdown than the other two groups (P < 0.05). This is a more stable position to load the ankle and this strategy differed from that used by participants with CAI and uninjured CTLs. These findings provide insight into the neuromuscular control strategies of CPRs, which may allow them to more appropriately control ankle stability following sprains.

Keywords: curb-walking, biomechanics, EMG, ankle instability, ankle sprain copers

Introduction
Lateral ankle sprains are the most common musculoskeletal injury in active populations (Fong, Hong, Chan, Yung, & Chan, 2007). Sprains are associated with pain, local inflammation from tissue damage and possible receptor damage in the injured ligament(s) that can interfere with normal neuromuscular control in the acute setting. The magnitude of these changes becomes apparent given the increased relative risk of injury with a previous ankle sprain (Fong, Chan, Mok, Yung, & Chan, 2009). Studies have estimated the rate of subjective instability and re-sprain can range from 34% to 74% (Anandacoomarasamy & Barnsley, 2005; van Rijn et al., 2008). The feeling of the ankle rolling or giving way is the most commonly reported symptom in patients suffering from more than one lateral ankle sprain (Yeung, Chan, So, & Yuan, 1994). Disability can persist with 32% of patients reporting residual chronic pain and swelling 7 years after a sprain (Konradsen, Bech, Ehrenbjerg, & Nickelsen, 2002). However, despite continued symptoms, 84% return to their respective sport (Anandacoomarasamy & Barnsley, 2005). This pattern of injury and return to activity may force patients to develop maladaptive or deficient neuromuscular strategies that ultimately create a cycle of re-injury and continued disability. This persistent cycle may lead individuals to develop chronic degenerative changes such as synovitis, loose bodies and cartilage fibrillation that may be under-reported, based on clinical exam alone (Harrington, 1979; Hintermann, Boss, & Schäfer, 2002; Lee, Hamilton, & Ford, 2011). These arthritic changes may become severe enough for patients to develop post-traumatic osteoarthritis, in addition to the ligamentous injuries that require surgical interventions (Baumhauer & O’Brien, 2002; Colville, 1998).

Biomechanical and electromyographic (EMG) studies can help investigators observe functional movements and muscle activity in participants with chronic ankle instability (CAI). Altered biomechanics are thought to be responsible for the increased strain on ankle cartilage, the increased risk of injury and potential for developing the degenerative joint changes that accompany CAI (Bischof et al., 2010; Caputo et al., 2009). A study of level gait in
participants with CAI found a more inverted ankle throughout loading of the affected ankle and differing patterns from healthy participants in frontal plane ankle joint moment and power (Monaghan, Delahunt, & Caulfield, 2006). Moreover, Delahunt, Monaghan, and Caulfield (2006a) found that their CAI participants demonstrated a decrease in vertical clearance of each step from the floor and had greater peroneus longus (PL) activation following touchdown. Taken together, these findings may indicate that individuals with CAI present with different neuromuscular control strategies than those without CAI. By remaining more inverted throughout the gait cycle, combined with less floor clearance, patients with CAI may be in a more vulnerable position for suffering recurrent ankle sprains.

Not everyone who suffers an ankle sprain develops persistent symptoms typical of CAI. These “copers” (CPRs) are able to recover from the initial injury, with 26% of patients reporting a full functional recovery after an inversion sprain in one study (Anandacoomarasamy & Barnsley, 2005). Recent studies of these individuals have looked at participants who had a history of ankle sprain but have returned to pre-injury activities with no active symptoms of pain, sensation of the ankle “giving way” or re-injury (Brown, Padua, Marshall, & Guskwiewicz, 2008; Wikstrom et al., 2009, 2012). CPRs have been compared to participants with CAI (including both mechanically and functionally unstable ankles) and found to have a decrease in frontal plane displacement during level gait compared to both types of CAI (Brown, 2011). These alterations may represent an adaptive strategy of loading the ankle that may be protective against re-injury. Interestingly, self-reported measures were found to be more accurate than mechanical or sensorimotor tasks at distinguishing CPRs from those suffering from CAI (Wikstrom et al., 2012). This supports the subjective nature of the sensation of the ankle rolling or giving way that is so common in CAI. The rationale for including this CPR group is that they may provide information as to successful adaptation after an ankle sprain.

A challenging, functional task, which may elicit any adaptive, protective or deficient strategies not required, and therefore not observed, in simpler tasks may provide insight into the patho-mechanics of CAI. Specifically, the changes that surround touchdown during functional tasks are thought to play a crucial role in contributing to ankle instability (Gutierrez, Kaminski, & Douex, 2009). Previous works have found deficits in time to stabilisation after jump landings in patients with CAI (Gribble & Robinson, 2010). When tasked with a single leg drop jump, participants with CAI showed a significant decrease in PL activity and a more inverted position of the ankle joint before touchdown (Delahunt, Monaghan, & Caulfield, 2006b). In addition, chronically unstable participants had a less dorsiflexed position of the ankle joint during landing compared to healthy CTLs. CPRs have demonstrated greater sagittal plane displacement at the ankle while stepping up and over an elevated box, greater plantar flexion (PF) when landing during drop jumps and less ankle frontal plane displacement during stop jumps, when compared to mechanically unstable ankles (Brown et al., 2008). CPRs have also been found to exhibit higher frontal plane dynamic postural variability on jump stop manoeuvres than both the uninjured CTL and chronically unstable groups (Wikstrom et al., 2009). Further, Gutierrez et al. (2012) found greater tibialis anterior (TA) muscle activation and a more close-packed position of the ankle during landings on a supinating platform in CPRs compared to persons with CAI and uninjured CTLs – a potentially more appropriate landing strategy on a previously injured ankle. Further investigation of neuromuscular control during functional tasks in those with CAI and CPRs is warranted.

During forward gait, a single step (e.g. a curb) is often encountered in both indoor and outdoor settings. By incorporating vertical displacement, a step demands the utilisation of a different motor strategy that must either overcome gravity and climb the step or dissipate the potential energy gained in stepping down. An increased physical demand is evidenced by the increasing stride time, step length, and relatively higher knee and hip moments generated after touchdown compared to level gait (Van Dieën, Spanjaard, Konemann, Bron, & Pijnappels, 2007). While stepping down from a height, the lead leg can exhibit a strategy of landing on the forefoot (in PF), gaining less kinetic energy and absorbing more potential energy as negative work at the ankle as the joint is initially loaded (Van Dieën, Spanjaard, Konemann, Bron, & Pijnappels, 2008). Stepping down affords researchers the ability to safely observe participants with CAI loading their unstable limb in a situation that incorporates PF and forward propulsion, which are thought to increase the risk of lateral ankle sprains (Wright, Neptune, van den Bogert, & Nigg, 2000).

The purpose of this study was to investigate neuromuscular function during curb-walking in persons with ankle instability (CAI group), those with a history of ankle sprain without persistent instability (CPR group) and uninjured CTLs (CTL group).

Methods
Participants

A total of 33 participants were recruited by flyer and word of mouth and provided informed consent prior
to participation. Participants were excluded if they had suffered an ankle sprain within the past 6 months. The Cumberland Ankle Instability Tool (CAIT), a standardised questionnaire, was administered to all participants. A CAIT score of 24 or less has been shown to be valid and reliable in identifying individuals with ankle instability (Hiller, Refshauge, Bundy, Herbert, & Kilbreath, 2006). Participants were then placed into groups based on history of previous ankle sprains. Participants with a history of ankle sprain were grouped based on their CAIT scores; those with scores greater than 27 were placed in the CPR group (n = 9), while those with scores less than 25 were placed in the CAI group (n = 11). Participants with a history of bilateral ankle sprains were assigned a test limb by lowest CAIT score. The CTL group members (n = 13) had never suffered an ankle sprain and had CAIT scores reflecting a lack of instability with scores greater than 27. Participant group assignment and participant demographics are summarised in Table I. There were no significant group differences in demographics.

Instrumentation

Participants were equipped with clusters of three markers on the first metatarsal, calcaneus, and shank and with single markers on the pelvis (4), thigh (2), and lateral knee (1) on both legs. Kinematic data, with an individual's two-legged stance set as neutral with all angles calculated relative to this static position, were acquired at 120 Hz using five ProReflex cameras (Qualisys, Gothenburg, Sweden). EMG electrodes (DE-2.1, Delsys Inc, Boston, MA, USA) were placed on the belly of the TA and PL muscles according to standard guidelines (Perotto, 1994). EMG data were collected at 1200 Hz using a Bagnoli 8 channel EMG system (Delsys, Inc., Boston, MA). Kinetic data were obtained using force plates (Kistler Instruments, Amherst, NY, USA) embedded into the walkway sampling at 1200 Hz. Ground reaction force data were also used to identify the instant of touchdown.

Procedures

Participants walked on a custom 8.5 m walkway, with a 15 cm step in the centre of the platform to simulate a street curb, at a self-selected speed. Participants were asked to walk barefoot on the elevated walkway, step down with their test leg onto the ground-level walkway and keep walking until the end of the platform. Trials were discarded if participants actively targeted the force plates, if they did not make clean contact with the force plates, or if they failed to maintain their self-selected speed (±5% of each participant’s individual average after three practice trials). Three acceptable trials per participant were collected and used for analysis. A representative participant walking on the walkway, with all equipment, is depicted in Figure 1.

Table I. Demographics of our participants by group [x ± s]. Participants were placed into groups based on history of previous ankle sprain and then further divided by their Cumberland Ankle Instability Tool (CAIT) scores greater than 27 as stable in the copers (CPRs) and controls (CTLs) and less than 25 as unstable in those with chronic ankle instability (CAI).

<table>
<thead>
<tr>
<th>CAI</th>
<th>CPR</th>
<th>CTL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of subjects</td>
<td>11</td>
<td>9</td>
</tr>
<tr>
<td>Age (years)</td>
<td>26 ± 4</td>
<td>26 ± 3</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.70 ± 0.11</td>
<td>1.73 ± 0.09</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>76.77 ± 20.42</td>
<td>69.31 ± 12.74</td>
</tr>
<tr>
<td>Number of sprains</td>
<td>5.2 ± 3.2</td>
<td>2.1 ± 1.6</td>
</tr>
<tr>
<td>Ankle pain during sport*</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>Episodes of “Giving Way”ǂ</td>
<td>7</td>
<td>n/a</td>
</tr>
<tr>
<td>CAIT score</td>
<td>18 ± 5</td>
<td>28 ± 2</td>
</tr>
</tbody>
</table>

Notes: *Indicates the number of individuals that reported pain during sports/exercise participation. ǂIndicates the number of individuals that reported regular episodes of the ankle giving way (defined as weekly). The remaining individuals in the CAI group did report that their ankle gives way, just not “regularly”.

Figure 1. A representative participant demonstrating the experimental set-up with markers and electrodes placed on both lower extremities.
Data analysis. Data were collected and tracked in Qualisys Track Manager (Qualisys, Gothenburg, Sweden) software and imported into Visual 3D (C-Motion, Inc., Germantown, MD, USA) for analysis. Participant-specific models were created prior to data collection and applied to all trials. The EMG data were bandpass filtered (second-order Butterworth; \( f_c = 10–300 \) Hz), rectified, smoothed (second-order Butterworth; \( f_c = 7 \) Hz) and normalised to the maximal activation for each muscle during the gait trials. Preparatory and reactive EMG activity was calculated as the area under the processed EMG signal 200 ms before and after touch-down, respectively. The following kinematic, kinetic and EMG-dependent variables were calculated: ankle PF angle at touchdown, ankle inversion angle at touchdown, peak sagittal plane ankle power, knee flexion (FLX) angle at touchdown, peak sagittal plane knee power and preparatory and reactive and EMG activity in the TA and PL muscles. Statistical analysis was conducted utilising two separate one-way (group) MANOVAs – one for EMG variables and one for kinematic/kinetic variables, as those represent separate constructs. Tukey post hoc tests were utilised when appropriate. The level of significance (\( \alpha \)) was set at 0.05, \( \alpha \)-a-priori. Effect sizes were calculated using partial \( \eta^2 \) statistic, in which \( <0.06 \) is a small effect, \( 0.06 < x <0.14 \) is a medium effect, and \( >0.14 \) is a large effect (Cohen, 1988).

Results

To ensure that stride length did not influence the other outcomes, we conducted a one-way ANOVA and found no significant differences in stride length among the groups (\( x \pm s \); CAI group = 80.7 ± 7.8 cm, CPR group = 80.8 ± 6.5 cm, and CTL group = 82.6 ± 4.1 cm; \( F_{2,30} = 0.198; P = 0.822 \)).

A significant group main effect was noted in the EMG MANOVA (\( F_{4,24} = 3.421; P = 0.021; \text{partial } \eta^2 = 0.328 \)). Univariate tests revealed differences in TA activation in both the preparatory (\( P = 0.029 \); partial \( \eta^2 = 0.210 \)) and reactive (\( P = 0.050 \); partial \( \eta^2 = 0.181 \)) phases. Tukey post hocs on both the preparatory and reactive phases revealed the CPR group demonstrated significantly greater TA activity compared to both CTL (\( P = 0.04 \)) and the chronically unstable (\( P = 0.05 \)) groups (Figure 2). No statistically significant differences were found between groups in PL activation.

A significant group main effect was noted in the kinematic/kinetic MANOVA (\( F_{5,27} = 3.421; P = 0.024; \text{partial } \eta^2 = 0.365 \)). Univariate tests revealed differences in ankle PF angle at touchdown (\( P = 0.028 \); partial \( \eta^2 = 0.212 \)). Tukey post hocs revealed that the CPR group demonstrated a significantly less plantar-flexed ankle at touchdown compared to both CTL (\( P = 0.04 \)) and chronically unstable groups (\( P = 0.02 \)) (Figure 3). No significant differences were noted in ankle inversion angle, FLX angle or power absorption at the knee or ankle joints (Figures 3 and 4).

Discussion

This study was performed to assess how participants with and without CAI negotiated a single step-down during continuous gait. The CPR group had a unique pattern of increased activation of the TA before and after touchdown (partial \( \eta^2 < 0.18 \), indicating a large effect size) that may represent an adaptive and protective mechanism after an initial lateral ankle sprain. Prior to touchdown, the

![Figure 2. Electromyographic (EMG) activity prior to (Preparatory) and following (Reactive) touchdown in the tibialis anterior (TA) and peroneus longus (PL) muscles. Error bars represent \( s \); *denotes statistically significant differences (\( P < 0.05 \)). \( x \pm s \) presented in the table beneath figure.](https://example.com/figure2.png)
increased TA activation resulted the ankle joint being in a less plantar-flexed (~4.5° > CTL group, ~10° > CAI group; partial $\eta^2 < 0.21$ indicating a large effect size) and therefore more stable position of the ankle at touchdown due to the configuration of the ankle mortise. This suggests that a motor strategy is enacted before the foot actually contacts the ground, which could be a protective strategy for the previously injured ankle. We postulate that this compensatory strategy employed by CPR participants includes keeping the ankle less plantar-flexed (more close-packed) prior to touchdown to control ankle movement in the frontal plane, while possibly absorbing power at more proximal joints (the knee or hip). This is supported by the fact that the CPR group did demonstrate slightly (non-significant) greater power absorption at the knee. While it was not a statistically significant result of greater power absorption at the knee, the effect size (partial $\eta^2 = 0.08$) indicates a medium effect which could be significant in a study with a larger sample size. These changes in the mechanical loading pattern of the lower extremity could make inversion at the ankle less likely. Further, this is consistent with studies that have shown alterations in unilateral knee kinematics from jump landings in participants with CAI (Gribble & Robinson, 2009). Not only do proximal ipsilateral changes occur, such as quadricep facilitation, but bilateral inhibition of the hamstrings during maximal voluntary isometric contractions is also observed in participants with CAI (Sedory, McVey, Cross, Ingersoll, & Hertel, 2007).

Previous investigators have found differences when comparing participants similar to the chronically unstable group with uninjured CTLs, but this study suggests that studying those who have successfully recovered from an ankle sprain may provide valuable insight into the mechanism behind continued disability in CAI. Previous studies in CAI have noted that dorsiflexion was limited during gait, compared to uninjured CTLs (Delahunt et al., 2006a). We also found increased PF (reduced dorsiflexion) in the chronically unstable group relative to the CTL group (~6°), but those differences were not
significant ($P = 0.20$) in our study. The current data suggest that a successful compensatory strategy utilised by CPRs to manage that limitation may include increased TA activation with concomitant reductions in PF prior to ground contact. As stated, the CPR group exhibits a strategy of protecting the previously injured ankle using a different neuromuscular control strategy to take advantage of the anatomy of the joint, while shifting the load to proximal joints with larger musculature (i.e. the knee). The results of this study show changes in the sagittal plane that are consistent with previous works involving ankle sprain CPRs. Gutierrez et al. (2012) found similar results in a comparable group of CPRs, including increased preparatory and reactive TA activation and reduced PF during drop landings on a supinating platform. Brown et al. (2008) did not find sagittal plane differences at touchdown in CPRs, but did note an increase in the sagittal plane displacement (specifically, greater dorsiflexion) throughout the movement while stepping down from a box. It should be noted that we did not observe the decrease in frontal plane displacement shown by Brown et al., but the differences in testing procedure (stepping up and over a 32 cm box compared to stepping down from a ~18 cm height during continuous gait) may account for the observed differences in results. This represents the first study to evaluate stepping down during continuous gait in those with CAI, CPRs and CTLs, so direct comparisons are difficult. Future studies on neuromuscular control in ankle sprain CPRs during a variety of tasks will be useful in eliciting the adaptations after an ankle sprain that promote healthy recovery and possibly identify other deficient strategies present in participants with CAI.

Contrary to previously published investigations that found altered neuromuscular patterns during functional activities such as walking, single leg drop jumps and hopping, in those with CAI (Delahunt et al., 2006a, 2006b, 2010), we did not find significant differences in neuromuscular control patterns between the chronically unstable and CTL groups. In those studies, participants with CAI tended to contact the ground in a more inverted position compared to healthy CTL participants, which may be related to an activation deficit before ground contact. Those authors utilised different criteria to identify individuals with CAI, which may explain the difference in findings, considering the highly subjective nature of CAI. Ankle instability research is hindered by inconsistencies regarding inclusion criteria across studies, but a recent review suggests that the subjective feeling of the ankle giving way 1 year after the initial sprain as a possible definition and suggests the use of standardised questionnaires to aid in determining group assignment (Delahunt et al., 2010). It is also possible that the differences in methodology may explain the different findings. Specifically, the tasks being tested were different (level ground gait, jumping and hopping vs. stepping down), which may have elicited differing neuromuscular control patterns. Further research is required to identify the source of the differing results and properly identify the patho-mechanics of CAI. We speculate that the lack of this adaptive strategy in the chronically unstable group following ankle injury may contribute to the increased risk of re-injury and the sensation of ankle instability commonly perceived by patients. Adaptations to the ankle sprain may include changes that are proximal to the ankle and bilateral in nature and are in need of further evaluation. Previous investigations (Gribble & Robinson, 2009; Sedory et al., 2007), along with the results of this study, suggest that post-ankle sprain rehabilitation should not only focus on the ankle, but also include appropriate distribution of joint loading over both lower extremities, which may contribute to the patho-mechanics of CAI.

Several limitations exist in this study. Grouping of participants was based on ankle injury history and CAIT score, which may not sufficiently dichotomise these three groups. Based on the subjective nature of CAI and the numerous tools available to quantify and categorise persons with CAI, it is distinctly possible that the patterns demonstrated by our groups do not represent those identified in similarly categorised groups in other studies. The design of the study was retrospective, thus it is not known whether the different motor strategies observed were the result of an adaptation to injury or if they were present before the original lateral ankle sprain. We cannot be sure whether the CPR group has lingering damage from their injury and that they may be anatomically different from the CTL group. While there is overlap on CAIT score in the CPR and CTL groups, they have been separated based on sprain history with the CTLs having never sprained either ankle, while the coping group has. Furthermore, we did not screen for participation in rehabilitation following the lateral ankle sprain, so we cannot state whether the CPR group naturally changed their motor strategy or if a rehabilitation program influenced these changes. Also, a lack of arthrometric data does not allow for distinction between mechanical and functionally unstable ankles that may be useful in comparison to previous works as well as in future studies with hopes of classifying subtypes of CAI to better guide treatment. As with any laboratory-based biomechanical study, it is unclear...
whether the movements performed by the participants represent their typical movement patterns.

Conclusions

Little is known about the exact link between suffering an acute ankle sprain and developing CAI. Our results demonstrate that CPRs may be able to adjust their neuromuscular control patterns and exhibit a protective mechanism to compensate after a sprain. Participants with CAI appear to utilise a similar strategy as uninjured persons, and perhaps have not developed this compensatory protective mechanism to prevent continuing disability. Alterations in neuromuscular control and the effects of these changes may be the limiting factor in rehabilitation programmes and prevent patients from successfully recovering healthy function of the ankle joint after an ankle sprain. Insight into these changes may provide new targets for rehabilitation from this common musculoskeletal injury.

Acknowledgements

We would like to acknowledge the participants in the study, who volunteered their time to advance scientific inquiry. No external funding sources were utilised to complete this study.

References


