

Difference in Ratio of Evertor to Invertor Activity Between the Dominant and Nondominant Legs During Simulated Lateral Ankle Sprain

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Context: The dominant and nondominant legs respond asymmetrically during landing tasks, and this difference may occur during an inversion perturbation and provide insight into the role of ankle-evertor and -invertor muscle activity. **Objective:** To determine if there is a difference in the ratio of evertor to invertor activity between the dominant and nondominant legs and outer-sole conditions when the ankle is forced into inversion. **Design:** Repeated-measures single-group design. **Setting:** University laboratory. **Participants:** 15 physically active healthy volunteers with no previous history of an ankle sprain or lower extremity surgery or fracture. **Interventions:** An outer sole with fulcrum was used to cause 25° of inversion at the subtalar joint after landing from a 27-cm step-down task. Participants performed 10 fulcrum trials on both the dominant and nondominant leg. **Main Outcome Measures:** The ratio of evertor to invertor muscle activity 200 ms before and 200 ms after the inversion perturbation was measured using electromyography. This ratio was the dependent variable. Independent variables included outer-sole condition (fulcrum, flat), leg (dominant, nondominant), and time (prelanding, postlanding). The data were analyzed with separate 2-way repeated-measures ANOVA, 1 for the prelanding ratios and 1 for the postlanding ratios. **Results:** For the postlanding ratios, the fulcrum outer sole had a significantly greater ($P < .05$) ratio than the flat outer sole, and the nondominant leg had a significantly greater ($P < .05$) ratio than the dominant leg. **Conclusions:** These results indicate that a greater evertor response is produced when the ankle is forced into inversion, and a greater response is produced for the nondominant leg, which may function better during a postural-stabilizing task than the dominant leg.

Keywords: electromyography, landing, bilateral asymmetry

The lateral ankle sprain is one of the most frequently occurring injuries in sports,¹ particularly in volleyball and basketball, because of the constant jumping and landing on 1 foot.²⁻⁴ Athletes are at a greater risk for a lateral ankle sprain in these sports because of the frequent opportunity to land from a jump onto the foot of another player.^{2,3} Often this landing mechanism will force the ankle into excessive inversion and plantar flexion, damaging the lateral structures of the ankle.^{2,3}

When the foot/ankle complex is unexpectedly forced into inversion, such as when landing from a jump onto the foot of another person, the relationship between the primary evertors of the foot/ankle, which are the peroneus longus (PL) and peroneus brevis (PB), and one of the primary invertors, which is the tibialis anterior (TA), is crucial to ankle stability.³ The PL and PB play a large role in the dynamic stability of the ankle.⁵ There is debate in the literature over whether the PL and PB can provide a timely enough response after an inversion perturbation

to prevent a lateral ankle sprain, with some researchers arguing it can occur quickly enough⁶ and others arguing it cannot.⁷ If it can occur quickly enough, a greater PL and PB response may reduce the likelihood of or potentially help limit the potential severity of a lateral ankle sprain by limiting the amount of inversion caused by the perturbation.^{3,5} Conversely, a greater TA response may increase the likelihood of a lateral ankle sprain by increasing the amount of inversion at the foot/ankle.³ If the TA response is greater than the response of the PL and PB, then the TA may contribute to the inertial inversion moment created by the landing mechanics after the individual lands on his or her foot. This increased TA response may also increase the amount of dorsiflexion at the talocrural joint, as the TA is also a dorsiflexor of this joint,³ which may potentially be beneficial if the ankle is forced into a combination of inversion and plantar flexion. When the ankle is in dorsiflexion, it is in a more close-packed position, which would limit the amount of inversion and potentially place the ankle in a more stable position.⁸ Previous research has examined the ratio of evertor to invertor activity during the 200 milliseconds before and the 200 milliseconds after landing.³ The current study used a similar time frame to evaluate muscle activity,

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and the ratios were analyzed as separate prelanding and postlanding events because the prelanding muscle activity is mainly generated in a feed-forward control manner and the postlanding muscle activity is generated in a feedback control manner.³

Humans encounter many unexpected, transient perturbations every day. The responses to the perturbations vary from person to person and between situations. Many times these unexpected perturbations will result in a “startle response,” which is characterized by a short-latency muscle response designed to protect the body from injury.⁹ Research has found that a startle response is present during low-speed rear-end collisions.¹⁰ This response presents initially as cocontraction of both the neck flexors and neck extensors.¹⁰ When the ankle is unexpectedly forced into inversion, there may be a cocontraction of the ankle evertors and invertors, and the invertor response could possibly negate the protective mechanism supplied by the ankle evertors, similar to the response of the neck flexors and extensors.^{3,9} This study was an initial attempt to examine the relative activity of the ankle evertors and invertors during repeated exposures to an unexpected inversion perturbation. An increase in evertor muscle response and/or decrease in invertor muscle response may be favorable when the ankle is forced into inversion, as this would help keep the foot/ankle in a more neutral posture or less extreme position and help limit the amount of inversion. As a result, the roles of the PL, PB, and TA in the frontal plane were investigated in the current study. These muscles also contribute to joint actions in the sagittal plane (PL and PB assist with plantar flexion; TA is the primary dorsiflexor), and this must be considered when examining these ratios.

In addition to examining the ratio of evertor to invertor activity, a secondary purpose was to examine if this ratio is different between the dominant and nondominant legs. It has been assumed that the dominant and nondominant legs behave symmetrically during landing movements.¹¹ Sadeghi et al¹² reported that the foot of the dominant leg is used for manipulative activities such as kicking, and the foot of the nondominant leg is used more for stabilization and maintenance of posture. Different demands are placed on the dominant leg in comparison with the nondominant leg during single-leg landing and manipulative tasks.^{11,12} One study reported that soccer players use the dominant leg to kick a ball 80% of the time.¹³ A recent study also found that during a bilateral drop landing, the dominant ankle is likely at greater risk for injury than the nondominant ankle because of greater peak ankle angular velocities and a reduction in EMG activity of the ankle flexors compared with the nondominant leg.¹¹ In an athletic setting, the quadriceps of the dominant leg is injured more frequently than the quadriceps of the nondominant leg in Australian football players,¹⁴ and the knee flexors of the dominant leg have been found to be significantly weaker than the knee flexors of the nondominant leg in soccer players.¹⁵ Previous research using a cross-sectional methodology has indicated that the ankle of the dominant leg is sprained more

frequently than the ankle of the nondominant leg,^{16,17} and the latency of the PL of the dominant leg is significantly longer than the latency of the PL of the nondominant leg.¹⁸ These factors may increase the risk of injury of the ankle of the dominant leg compared with the ankle of the nondominant leg, and the ratio of evertor to invertor activity may be different between the 2 legs.

The purpose of this study was to determine the ratio of evertor to invertor muscle activity during a simulated lateral ankle-sprain mechanism and to determine if this ratio differs between the dominant and nondominant legs and between a forced-inversion landing and normal flat-footed landing. In light of the previous literature,^{3,11,18} we hypothesized that the ratio of evertor to invertor activity would be greater when the ankle is forced into inversion than during a normal, flat landing, and the evertor response would be greater than the invertor response for the nondominant leg.

Methods

Participants

Fifteen healthy volunteers (age 21.07 ± 1.07 y, height 1.69 ± 0.09 m, mass 63.45 ± 11.97 kg) completed the testing. All participants were free from any previous history of an ankle sprain, lower extremity fracture, or lower extremity surgery. All male participants wore a US men’s shoe size 10 to 11, and all female participants wore a US women’s shoe size 8 to 9. Furthermore, all participants were physically active, participating in at least 30 minutes of physical activity 4 d/wk. Any participant who had previously suffered an ankle sprain or lower extremity fracture or surgery or did not meet the shoe-size requirement was excluded from the study. Each participant signed an informed-consent document approved by the authors’ institutional review board.

Instrumentation

Eight detachable outer soles (4 with fulcrum and 4 flat), made of orthoplast, were developed for this project. A left and right outer sole was developed for the average men’s shoe size (US men’s 10–11) and the average female shoe size (US women’s size 8–9). To produce 25° of inversion on landing, a 6-mm-thick and 30-mm-high fulcrum was placed 20 mm from the medial border of the outer sole and ran the length of the outer sole. This methodology has been previously used to force the ankle into inversion and measure the effectiveness of ankle braces¹⁹ and peroneal latency.¹⁸ The outer sole was attached to the athletic shoe of the participants using Velcro straps. All participants were required to wear low-top, flat-soled, nonrunning athletic shoes for testing.

Muscle activity was recorded with a multichannel electromyography (EMG) amplifier/processor unit (MyoClinical, Noraxon USA Inc, Scottsdale, AZ) using wet-gelled bipolar Ag-AgCl disc surface electrode pairs (Blue Sensor SE, Ambu Inc, Denmark) interfaced with

a notebook computer. The raw EMG signal was amplified with an input impedance of $10\text{ M}\Omega$, with the gain set at $1000\times$ and a common-mode rejection ratio $>115\text{ dB}$. Surface EMG electrodes were placed over the most prominent part of the muscle belly of the PL, PB, and TA with a 2-cm interelectrode distance. Electrode placement sites were shaved, abraded, and cleaned according to standard EMG procedures. The electrode placement was similar to that used previously,^{20,21} and proper placement was verified by manual muscle testing and observation of the EMG signal on the computer for any potential crosstalk between adjacent muscles. To ensure measurement of activity from the PB, the electrodes for this muscle were placed over the largest portion of the muscle belly, which is located one-fourth of the distance from the lateral malleolus and the fibular head, and just anterior to the PL tendon.^{20,21}

A metal landing surface was developed, and the signal from the landing surface was synchronized with the EMG processor. Metal was also attached to the fulcrum and to the lateral border of the outer sole. When the fulcrum made contact with the landing area, a spike was produced in one of the EMG channels, indicating ground contact and closely coinciding with the beginning of the inversion moment. When the lateral border of the outer sole made contact with the landing area a second spike was produced in a different EMG channel, indicating that the participant had completed the task and 25° of inversion.¹⁸

Procedures

The participants were randomly assigned to order of testing (dominant or nondominant leg first). Nine participants

had their nondominant leg tested first, and 6 participants had their dominant leg tested first. To be consistent with previous research, the dominant leg was defined as the leg the participants would use to kick a soccer ball.^{16,18,22} The participants stood on a 27-cm-high box on the non-testing leg and moved the foot of the testing leg behind them by flexing the knee and extending the hip; this position prevented participants from seeing which outer sole was affixed to the sole of the shoe. Next, either the outer sole with fulcrum or flat outer sole was secured to the participant's shoe with Velcro, in random order. The purpose of the flat outer sole was to prevent anticipation of the inversion perturbation, as both outer soles were of similar mass. After the outer sole was secured, participants were instructed to swing the testing leg forward and allow the foot to hang down in front of them in a natural position. After confirming there was no excessive preactivity (above baseline) or spikes in muscle activity in the PL, PB, and TA, the participants were instructed (they were given the signal "go") to step down off the box onto the testing leg. When instructed to step down, the participants leaned forward and stepped down onto the testing foot (Figure 1). Participants were not allowed to use flexion of the contralateral knee to lower themselves down. They were instructed to land flat-footed to help keep the initiation of the inversion moment as consistent as possible, and all trials were visually inspected to ensure that this instruction was followed. In addition, the metal only covered the back third of the fulcrum, so any trials that resulted in a toe-landing were not recorded and subsequently discarded. After landing and completing the 25° of inversion (Figure 2), the outer sole was removed and placed behind the participant. The same procedure was followed until 10 trials had been performed with the outer

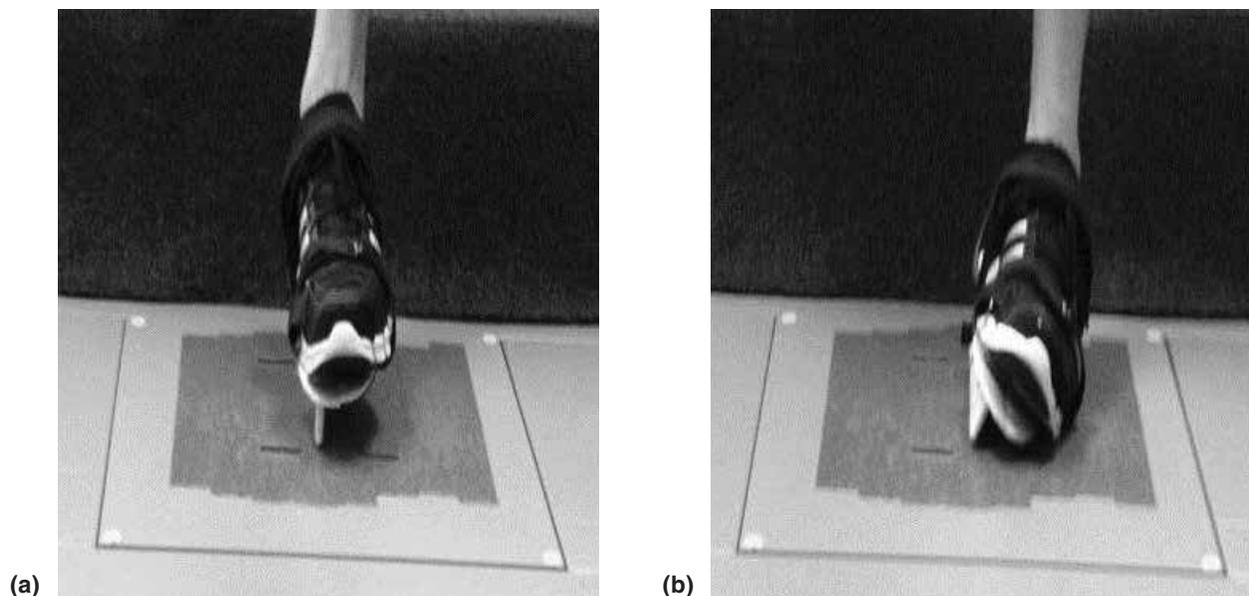


Figure 1 —Participant (a) landing on outer sole with fulcrum and initiating the inversion motion and (b) completing the 25° of inversion.



Figure 2 — Placement of EMG electrodes over the tibialis anterior, peroneus longus, and peroneus brevis.

sole and fulcrum, and then the other leg was tested. A flat outer sole was randomly interchanged during testing to prevent anticipation of the fulcrum outer sole and measure the response during a normal, flat landing. A total of 134 flat-outer-sole trials were included in the analysis across all 15 participants. The ratio of evertor to invertor activity was measured for each of the 10 trials of the outer sole with fulcrum for both the dominant and nondominant legs, and for the flat-outer-sole trials, as well.

Data Reduction

Both the EMG signal and the signal from the landing surface were band-pass filtered (sixth-order Butterworth, with cutoff frequencies of 8 and 535 Hz) and full-wave rectified. The dependent variable was the ratio of evertor activity (average activity of PL and PB) to invertor activity (TA). This ratio was calculated for the 200 milliseconds before contact of the fulcrum or flat outer sole with the landing area (prelanding ratio) and for the 200 milliseconds after contact of the fulcrum or flat outer sole with the landing area (postlanding ratio). EMG activity was normalized to the maximum amplitude in each trial type (fulcrum outer sole dominant leg, fulcrum outer sole nondominant leg, flat outer sole dominant leg, flat outer sole nondominant leg). The maximum was found for all prelanding and postlanding amplitudes in the previously mentioned trial types. After the data were normalized, the

ratio of evertor to invertor activity was calculated using the following formula: the average of the normalized EMG amplitude of the PL and PB over the 200 milliseconds divided by the average normalized amplitude of the TA. A ratio of 1.0 indicates equal activity in both the evertors and invertors of the subtalar joint; a ratio greater than 1.0 indicates greater evertor activity, while a ratio less than 1.0 indicates greater invertor activity. All data were exported into Microsoft Office Excel 2007 (Microsoft Corp, Redmond, WA) for calculation of the activity ratios.

Data Analysis

To examine the effects of the testing leg and outer-sole condition on the ratio of PL and PB activity to TA activity, the data were analyzed with 2 separate 2 (testing leg) \times 2 (outer sole) repeated-measures analyses of variance, 1 for the prelanding ratio and 1 for the postlanding ratios. An alpha level of .05 was established a priori as the criterion for statistical significance. All statistical analyses were conducted with the Statistical Package for Social Sciences v 14.0 (SPSS) for Windows. In the case of significant differences, Tukey tests of honestly significant difference were used post hoc.

Results

For the prelanding ratios, there was not a significant interaction between the testing leg and outer-sole condition ($F_{1,14} = 1.23, P > .05, \eta^2 = .081$), no significant difference between testing legs ($F_{1,14} = 1.67, P > .05, \eta^2 = .107$), and no significant difference between the outer soles ($F_{1,14} = 3.40, P > .05, \eta^2 = .024$). For the postlanding ratios, there was not a significant interaction between the testing leg and outer-sole condition ($F_{1,14} = 1.28, P > .05, \eta^2 = .098$), but there was a significant difference between testing legs ($F_{1,14} = 7.31, P < .017, \eta^2 = .343$) and a significant difference between the outer soles ($F_{1,14} = 16.19, P < .001, \eta^2 = .712$). The means and standard deviations can be seen in Table 1. The normalized EMG amplitudes for the fulcrum and flat outer soles can be seen in Table 2. For the postlanding ratios, the nondominant leg had a greater ratio of evertor to invertor activity than the dominant leg, and the fulcrum outer sole also had a greater ratio of activity than the flat outer sole.

Discussion

The purpose of this study was to determine the ratio of evertor to invertor activity during a simulated lateral ankle-sprain mechanism and to see if this response differed between the dominant and nondominant legs. The results revealed no significant differences in the prelanding ratios (200 ms before ground contact) between the dominant and nondominant legs and the fulcrum and flat outer soles, supporting the findings of Niu et al.¹¹ This is to be expected because this muscle activity before landing

Table 1 Mean (\pm SD) Evertor:Invertor Prelanding and Postlanding Ratios, Mean (SD)

Condition	Prelanding Ratios			Postlanding Ratios		
	Dominant leg	Nondominant leg	Total	Dominant leg	Nondominant leg	Total
Flat outer sole	1.59 (1.62)	1.68 (1.05)	1.63 (1.34)	0.99 (0.50)	1.25 (1.00)	1.12 (0.79)#
Fulcrum outer sole	1.39 (0.56)	2.11 (1.50)	1.75 (1.17)	1.74 (1.00)	2.58 (1.09)	2.16 (1.11)
Total	1.49 (1.20)	1.89 (1.30)		1.37 (0.89)*	1.97 (1.23)	

*Statistically significant difference between leg conditions for the postlanding ratios ($P < .05$).

#Statistically significant difference between outer sole conditions for the postlanding ratios ($P < .05$).

Table 2 Normalized EMG Amplitudes (%) for the Fulcrum and Flat Outer Soles, Mean (SD)

Condition	Electrode	Prelanding Amplitude		Postlanding Amplitude	
		Dominant leg	Nondominant leg	Dominant leg	Nondominant leg
Fulcrum outer sole	Peroneus longus and brevis	26.81 (13.25)	24.45 (14.89)	127.25 (50.54)	148.75 (70.56)
	Tibialis anterior	25.05 (17.56)	20.39 (13.45)	103.24 (52.79)	93.23 (64.45)
Flat outer Sole	Peroneus longus and brevis	22.52 (21.98)	27.45 (22.66)	45.01 (15.01)	63.03 (44.59)
	Tibialis anterior	34.24 (32.97)	22.93 (18.88)	58.65 (36.92)	61.59 (37.44)

is generated in a feed-forward manner, and the participants did not know if they were being exposed to the fulcrum or flat outer sole. For the postlanding ratios (200 ms after ground contact), the ratio of evertor to invertor activity was greater for the fulcrum outer sole. There was a significantly greater ratio of evertor to invertor activity for the nondominant leg compared with the dominant leg. This finding supports the concept postulated by Niu et al¹¹ and Sadeghi et al,¹² suggesting that the nondominant leg functions more efficiently in a posture-stabilizing task than the dominant leg, which functions more efficiently in a mobilizing task. Furthermore, the findings of the current study and the previous findings^{11,12} suggest that a more protective mechanism may be present in the ankle musculature of the nondominant leg than the dominant leg when exposed to a postural-stabilizing task.

In the current study, the ratio of evertor to invertor activity was significantly greater for the nondominant leg (1.97 ± 1.23 evertor:invertor activity) compared with the dominant leg (1.37 ± 0.89 evertor:invertor activity) across both outer-sole conditions for the postlanding ratios. This difference may be explained by the dominant and nondominant limbs' using different activation strategies to achieve the same motor goal. A recent study¹¹ found that during an unperturbed bilateral drop landing, there was greater activity in the TA than the lateral gastrocnemius of the nondominant limb compared with the dominant limb. The authors concluded that this increase in activity of the TA would better protect the ankle of the nondominant limb during a drop landing by constraining excessive motion at the ankle.¹¹ These findings are similar to the current study, in that the activity of the PL and PB of the

nondominant leg increased more than the activity of those 2 muscles of the dominant leg. This would potentially constrain the motion of the ankle of the nondominant leg when it is forced into inversion. This finding may also help explain why some researchers have found that the ankle of the dominant limb is sprained more frequently than the ankle of the nondominant limb.^{16,17} In the current study, the nondominant limb was tested first in 9 of the 15 participants, and habituation could have led to a smaller response in the dominant limb.²² However, of the 6 participants who had their dominant limb tested first, the nondominant limb still showed a greater ratio than the dominant limb in 5 of the participants (83%), indicating that habituation of the response likely did not occur between the dominant and nondominant limbs.

The ratio of evertor to invertor activity was less for the flat outer sole than for the fulcrum outer sole. This ratio of activity increased for the fulcrum outer sole after touchdown/initiation of the inversion perturbation, and this ratio decreased for the flat outer sole after touchdown. Previous research has found nearly equal activity in the TA and soleus muscles during unperturbed single-leg drop landings.²³ Previous research has also found nearly equal activity in the TA and PL muscles during unperturbed landings among healthy participants.³ The current study found similar results, as there was greater activity in the evertor muscles before landing (1.63 ratio of evertor:invertor activity) and a nearly equal ratio after landing (1.12 ratio of evertor:invertor activity). This nearly equal cocontraction would serve to help stiffen the ankle during a flat landing to help limit unwanted motion in either direction. However, the ratio of activity increased

during the fulcrum-outer-sole trials (1.75 prelanding to 2.16 postlanding). This increase in evertor activity would possibly limit the amount of inversion and protect against a possible lateral ankle sprain.

The TA is a primary invertor of the foot/ankle complex, and it is also a dorsiflexor.³ While it would be beneficial to have a decrease in invertor activity or a greater increase in evertor activity compared with invertor activity when the ankle is rapidly forced into inversion, it has been proposed⁸ that the primary mechanism of a lateral ankle sprain is a combination of inversion and plantar flexion. This means the TA would help counteract the plantar-flexion moment that would contribute to a lateral ankle sprain,³ while the peroneals would help counteract the inversion moment that contributes to a lateral ankle sprain.⁵ However, a study that examined an accidental lateral ankle sprain recorded in a laboratory setting²⁴ and a recent study²⁵ that examined 2 actual ankle sprains during the 2008 Summer Olympics reported lateral ankle sprains that occurred during a combination of inversion and dorsiflexion.^{24,25} In this scenario, increased activity in the TA compared with the activity of the peroneals after the initiation of the inversion moment would increase the amount of both inversion and dorsiflexion, which would not be beneficial in protecting against a lateral ankle sprain if plantar flexion is not a component of the mechanism of injury. In the current study, there was a much larger increase in evertor activity than invertor activity after initiation of the inversion perturbation for the fulcrum outer sole. The increase in activity was also significantly greater for the nondominant leg. The design of the fulcrum outer sole used in the current study limited the amount of plantar flexion at the ankle after landing. In this specific case, an increase in the activity of the PL and PB after landing compared with the TA would help limit the amount of inversion caused by the fulcrum and may be beneficial in preventing or attenuating the severity of a lateral ankle sprain.

There were several limitations to the current study. The kinematics of the task were not measured. Therefore, it is not possible to determine the exact position of the foot/ankle during landing. Metal was only placed on the back third of the fulcrum, so any landing that occurred where the forefoot made contact with the landing area was not recorded and was discarded. All 3 muscles are multijoint muscles, so it is not possible to determine their exact contribution to each joint action in both the sagittal and frontal planes. In addition, only uninjured subjects were tested, so it is not possible to make any conclusions about the effects of a previous lateral ankle sprain on this response.

Conclusions

The results of this study indicate that the ankle musculature of the dominant leg responds differently than the ankle musculature of the nondominant leg when exposed to an inversion perturbation. The ratio of evertor to invertor activity was significantly greater for the nondominant

ankle than for the dominant ankle. This increase in the ratio for the nondominant leg lends support for the theory that the nondominant leg functions more efficiently than the dominant leg during posture-stabilizing tasks,^{11,12} and it may potentially protect the nondominant ankle against lateral ankle sprains better than the dominant leg. Due to the design of the fulcrum outer sole used in the current study, which limited the amount of plantar flexion that occurred on landing, the ratios reported in this study are specific to this type of methodology and may be different across different mechanisms of inversion perturbation. Future research should investigate if this increased ratio for the nondominant leg does offer greater protection against lateral ankle sprains and if training protocols can be developed to increase the protective response of the ankle evertors.

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