

A Novel Dynamic Ankle-Supinating Device

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Lateral ankle sprains (LAS) are among the most common joint injuries, and although most are resolved with conservative treatment, others develop chronic ankle instability (AI). Considerable attention has been directed toward understanding the underlying causes of this pathology; however, little is known concerning the neuromuscular mechanisms behind AI. A biomechanical analysis of the landing phase of a drop jump onto a device that simulates the mechanism of a LAS may give insight into the dynamic restraint mechanisms of the ankle by individuals with AI. Furthermore, work evaluating subjects who have a history of at least one lateral ankle sprain, yet did not develop AI, may help elucidate compensatory mechanisms following a LAS event. Identifying proper neuromuscular control strategies is crucial in reducing the incidence of AI.

Keywords: ankle, instability, sprain, reflex, preactivation

Ankle instability (AI) is a complex neuromuscular disorder that affects a large percentage of individuals who suffer a lateral ankle sprain (LAS). The neuromuscular mechanism behind the pathology of AI remains unknown. Several theories exist and have been explored, yet there is no consensus in the literature. However, it is likely that a combination of factors leads to the development of AI. What is known is that episodes of the ankle “giving way” occur most often in dynamic conditions. Therefore, evaluating muscle activation and kinematics during dynamic activities, such as landings, may elucidate the mechanism of disorder. There is evidence to suggest that preprogrammed motor plans may be altered in individuals with AI, thus predisposing them to ankle inversion moments (Caulfield et al., 2004; Caulfield & Garrett, 2002; Delahunt et al., 2006). Furthermore, the effect of these altered open-loop control strategies should be evaluated when dealing with perturbations to the joint, as a perturbation of some magnitude is typically present during an episode of “giving way.” No work to date has evaluated preactivation of the ankle musculature or three-dimensional kinematics during landings on a supinating surface.

Evaluating dynamic stability (including both preparatory and reactive muscle activity, along with kinematics) in individuals with AI may help elucidate the pathology behind AI. Identifying the pathology behind AI, and perhaps a successful compensatory strategy for dealing with a LAS, may lead to the development of more appro-

priate treatment and rehabilitation measures for individuals who suffer a LAS, in an attempt to prevent them from developing AI. Therefore, an experimental design utilizing a device capable of recreating the mechanism of a LAS in a safe environment may help reveal optimal open- and closed-loop control strategies in individuals with ankle instability. As of yet, no published work exists evaluating peroneal muscle responses to sudden ankle inversion/supination during landing in subjects with AI. This may be due in part to safety concerns for individuals with unstable ankles who may injure themselves by landing on a device that does not return the foot to a neutral position after inversion. Recently published work from our laboratory (Jackson et al., 2009) evaluating the stretch reflex of the ankle musculature used a custom-made ankle inversion device developed by Beckman and Buchanan (Beckman & Buchanan, 1995) that creates a sudden ankle-supinating perturbation to 30° of inversion at 400–600°/s and returns to baseline position of the ankle (0° of inversion) within 100 ms of movement onset. Since this device returned to a neutral (level) position following perturbation, it serves as an instrument to evaluate perturbations during dynamic landing tasks in a safer manner than the traditional “trap-door” platforms. Consequently, the device was modified to evaluate preparatory and reactive muscle activations and kinematics during landings on supinating and nonsupinating surfaces in a safe and controlled environment.

Most of the work aimed at understanding the neuromuscular control paradigms in AI have evaluated only healthy (uninjured) ankles and those with AI. However, no work to date has evaluated neuromuscular control in individuals who have suffered a LAS, but did not develop AI. Evaluating these individuals may help elucidate some compensatory mechanisms or more appropriate neuromuscular control strategies following a LAS event. Based

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on these potential findings, future intervention studies can be performed to reduce the incidence and severity of acute and chronic lateral ankle injury. Furthermore, in other work evaluating landings on an inverting surface in healthy individuals, the task was not a goal-oriented movement other than properly performing the landing technique (Gruneberg et al., 2003), which is not a highly functional situation. In sports participation, injuries tend to occur while an individual is performing a goal-oriented movement, such as cutting maneuvers or landings followed by a subsequent jump, cut, or run. During these actions, individuals are often focused on the movement that follows the landing—as opposed to focusing on proper landing technique—and this places them in a vulnerable position for injury. Therefore, to properly evaluate muscle activation during a landing technique in a functional manner, subjects must be given a goal to attain following the landing so that they would not be focused on the landing specifically, as they would be in a real-life situation.

The primary purpose of this work is to describe a novel ankle-supinating device designed to evaluate dynamic conditions, such as jump landings. Furthermore, we aim to demonstrate the ability of the device to not only test individuals with no history of LAS, but also to test those who have suffered a LAS, but did not develop AI, as well as those who have developed AI. Finally, this work serves as a pilot study investigating preparatory (open-loop) and reactive (closed-loop) muscle activity and kinematics in these three groups of subjects.

Methods

The pneumatic ankle-rotating device was originally designed such that subjects stood within foot “wells” in order for the device’s axis of rotation to be located

as close as possible to the inversion/eversion axis of ankle rotation (Beckman & Buchanan, 1995). Although this configuration was ideal for producing ankle inversions during static testing, it left little room for dynamic activities, such as landings. Therefore, the device was modified and is depicted in Figure 1. The modified ankle-supinating device is driven by the Pneu-Turn pneumatic rotary actuator (PT-247090-A1 QE; Bimba Manufacturing Company, Monee, IL), which propels the rotation of a 0.5-inch-thick aluminum plate via a linkage system. The plate can be made to rotate within a 160° arc; however, it is set to rotate from a neutral position (level) to 25° . When assembled, the plate is centered on a 4- × 8-foot carpeted landing platform. A 1-inch stainless steel rod is placed through the linkage mounting bracket and held in place by the surrounding platform. The rod is located one half inch below the bottom of the plate (approximately 1 inch below the surface of the plate) and serves as the axis of rotation. While the device was originally designed to rotate the ankle through the inversion/eversion axis, this new configuration with the axis of rotation located under the foot, aimed to produce an ankle supination that included plantar flexion and adduction of the foot, along with inversion, during the perturbation. This was intended to simulate a more functional perturbation, as opposed to simply mimicking inversion and stretching the peroneals to induce a reflex response. The supinating device was placed over a force plate whose output was connected to the gating input of a function generator, such that when the subjects landed on the platform, a trigger signal was sent to the device to rotate during the supinating trials. A switch was used to isolate the platform during the nonsupinating trials, thus preventing the platform from rotating. The force plate was also used to determine the instant of touchdown. Touchdown was defined as the initiation of the vertical ground reaction force from the force plate under the device.

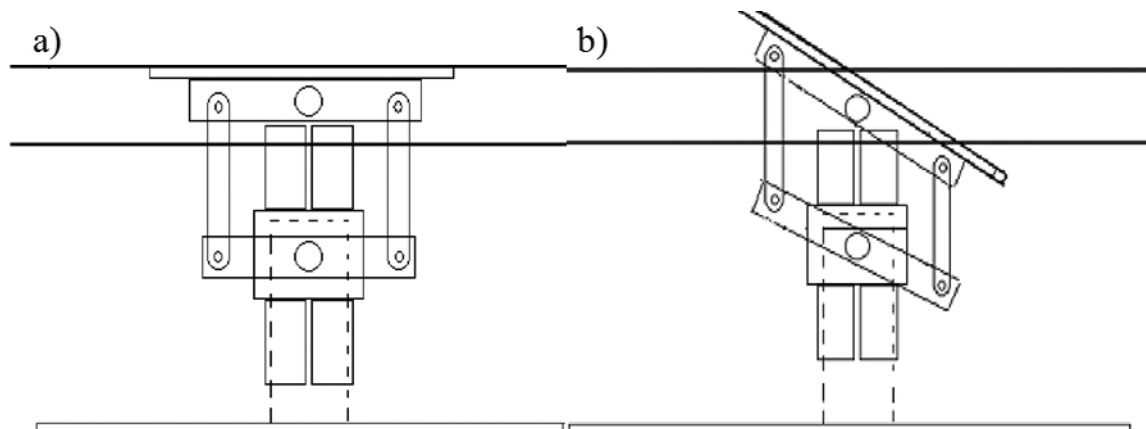


Figure 1 — A schematic of a custom-designed ankle-supinating device in the (a) neutral and (b) supinated position. A linkage system was used to translate the axis of rotation of the rotary actuator to a location just under the supinating plate. The device is placed over a force plate, which is used to trigger the device via the use of a function generator. The rotary actuators can rotate at speeds up to $700^\circ/\text{s}$ from a neutral (level) position to a preset angle.

Three-dimensional kinematic and EMG analyses of landings on supinating and nonsupinating surfaces were performed on both legs of six individuals (two per group) with bilaterally equivalent ankle status (AI = unstable ankles; NO = individuals with a history of LAS, but no instability; CO = uninjured controls). Before participation, all subjects provided written informed consent approved by the Human Subjects Review Board (HS 07–288). Participant demographics are presented in Table 1.

Table 1 Participant demographics

Subject	Gender	Age (years)	Height (m)	Mass (kg)
AI1	M	33	1.73	100.0
AI2	F	22	1.72	63.6
NO1	M	25	1.72	90.0
NO2	M	25	1.78	75.0
CO1	M	22	1.80	81.8
CO2	F	23	1.65	72.7

For the jump landing testing, subjects were asked to drop off a 30-cm-high platform and perform a two-legged landing with the test leg on the supinating device approximately 30 cm away in an anterior direction (Figure 2). They were asked to land on both feet simultaneously and to spot their landing on the device, and then perform a maximal vertical leap following landing. They were instructed to jump “as high and as fast as possible.” The resultant vertical jump height was measured using a Vertec (Sports Imports, Columbus, OH) jump trainer. To help familiarize the subjects with the protocol, they were asked to perform the maneuver twice with the knowledge of the condition; once *without* the platform supinating and once *with* the platform supinating (Figure 3). This was done to allow the subjects to experience the perturbation while anticipating it, which assured the subject that the risk of injury was minimal. Once the subject was familiar with the device and experimental setup, 10 consecutive trials were performed, with 3 being supinating trials and 7 nonsupinating trials, using an order selected at random and unknown to the subject to reduce anticipation.

Electromyography was used to investigate the neuromuscular activity in the lower limb during landings in an effort to determine neuromuscular control strategies

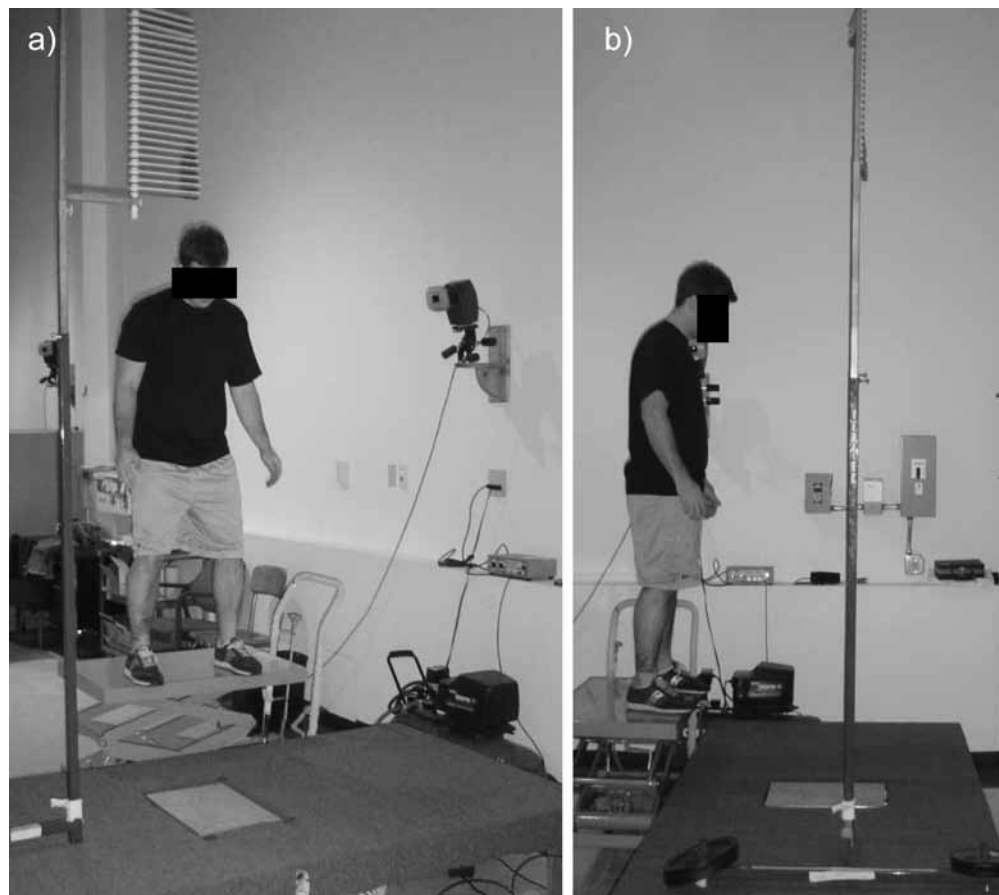


Figure 2 — Representation of a participant in experimental set-up (before jump landing) from (a) anterior and (b) lateral views

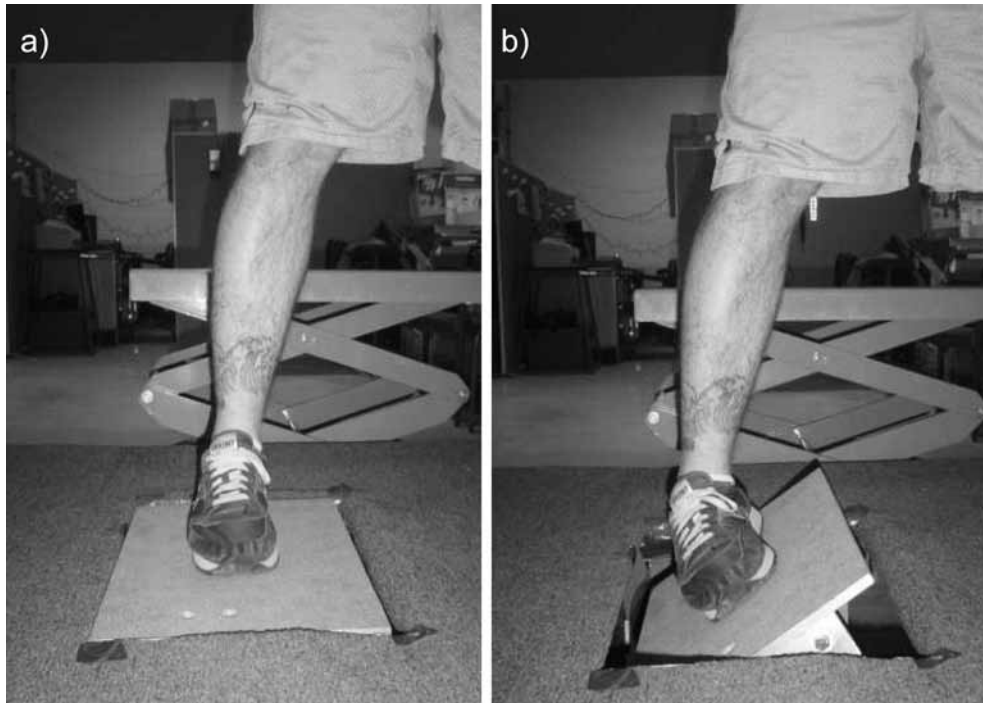


Figure 3 — Device in (a) nonsupinating and (b) supinating conditions.

between groups. The peroneus longus (PL) and tibialis anterior (TA) were selected for EMG recording because of their role in controlling frontal plane movement (inversion and eversion), as well as their close proximity to the skin surface so as to allow for surface EMG data collection. Ag-AgCl surface electrodes (Philips, interelectrode distance = 22 mm; electrode diameter = 33 mm), integrated with a differential preamplifier circuit were placed on the skin over each muscle belly, such that the contact surfaces were aligned in parallel with the muscle fibers and in locations detailed by Perotto (Perotto, 1994). To reduce impedance at the skin–electrode interface, the skin of each electrode site was shaved, abraded, and cleaned with isopropyl alcohol. A single reference electrode was placed on the skin over the patella. A T42–8T eight-channel telemetered EMG transmitter (Konigsberg Instruments Inc., Pasadena, CA) was used for collection, and all EMG data were sampled at 1200 Hz. All EMG data were bandpass filtered (2nd-order, zero-lag, Butterworth filter, with cutoff frequencies of 20 Hz and 300 Hz), rectified, and smoothed with a low-pass filter (2nd-order, zero-lag, Butterworth filter, with a cutoff frequency of 7 Hz). The EMG data were normalized to the maximal voluntary isometric contraction during manual muscle tests.

Eight high-speed cameras operating at 120 Hz (Eagle; Motion Analysis Corporation, Santa Rosa, CA) were used for data collection. Retro-reflective markers were placed bilaterally according to a modified Helen

Hayes marker set on the ASIS, sacrum, thigh, medial and lateral knee joint lines, shank, medial and lateral malleoli, second metatarsal head, and an offset marker on the right posterior shank, to establish anatomical coordinate systems for the pelvis, thighs, shanks, and feet. The medial markers were removed during dynamic trials. The standard Helen Hayes marker set was modified to include both a proximal and distal calcaneal marker (Figure 4) to better monitor foot motion, specifically in the frontal plane. The heel counters of several pairs of shoes were removed so that rearfoot calcaneal markers could be fastened directly to the skin and allow for unobstructed motion of the markers on the heel. All data were collected with EvaRT software (Version 5.1; Motion Analysis Corporation) and imported into Visual3D software (C-Motion, Inc., Rockville, MD) for data reduction and analysis. Ankle and knee joint angles were calculated, as well as preparatory and reactive EMG activity (defined as the area under the linear envelope) for the two muscles. The preparatory phase was defined as 200 ms before touchdown, and the reactive phase was defined as 200 ms after touchdown. Due to the small sample size and low statistical power, only descriptive statistics were calculated.

Results

Ipsilateral ankle angles are presented in Figure 5. No substantial kinematic differences were apparent between groups; however, the effects of the inversion platform



Figure 4 — Posterior view of the shoes with heel counter removed and the custom heel markers

are observable. Specifically, the inversion platform creates increased ankle plantar flexion, adduction, and inversion, similar to that of the LAS mechanism in the period 50–200 ms post-touchdown during the supinating trials. Furthermore, although not presented, increased knee flexion and internal rotation were evident as well. Preparatory and reactive EMG activity for both muscles in each group are presented in Figures 6 and 7, respectively. The only obvious disparity between groups is an increased peroneal activation in the NO group in both the preparatory and reactive phases, albeit with relatively high standard deviations.

Discussion

The primary aim of this preliminary work was to evaluate the efficacy of a novel ankle-supinating platform in simulating the mechanism of a LAS in a safe, controlled environment. Observation of the kinematic patterns (Figure 5) indicates that the platform creates a perturbation to the lower limb that causes increased ankle plantar flexion ($\sim 8^\circ$), adduction ($\sim 9^\circ$), and inversion ($\sim 13^\circ$). These patterns are similar to the mechanism of injury during a LAS event (hypersupination at the ankle), indicating that the platform does create a perturbation that simulates the mechanism of a LAS event, within a safe range of motion. The kinematic data suggest that the perturbation begins to take effect 30–50 ms post-touchdown, which is during the loading phase of landing when ankle injuries typically occur. Subjective feedback from the participants indicated that after the familiarization period, they felt safe, although abnormal, while landing on the device during supinating trials. Coupled with the fact that no

injuries or falls occurred during the testing, including in individuals with unstable ankles, it can be concluded that the device does in fact simulate the mechanism of a LAS event in a safe, controlled environment.

Despite its promise in simulating the ankle sprain mechanism, the device does have several potential areas for improvement. First and foremost, a kinetic analysis, including joint torques and moments, would be instrumental in truly understanding the biomechanics of the ankle supination. Unfortunately, it is not possible at this time to instrument the device with a force plate. Plantar pressure assessments can be used in conjunction with this type of perturbation; however, these are currently limited to one dimension and would not provide the complete kinetic picture, to fully understand what is happening. Furthermore, upon inspection of kinematic graphs, it is apparent that a slight amount of dorsiflexion precedes touchdown (~ 20 ms before touchdown), which may indicate that our definition of touchdown is not completely accurate. Our determination of touchdown is centered on the vGRF from the force plate placed under the device that is tied to the surrounding landing platform by a 1-inch steel rod. This indicates to us that initial impulse is shifted to the surrounding floor space via the landing platform, until the subject applies enough force to the device for the steel rod to flex and allow the device and subject to push onto the plate. In this light, differing subject sizes and landing strategies may affect how fast or slow the perturbation is presented. This should be accommodated for in any future research involving similar configurations. Unfortunately, there is not an actuator available that is small enough to fit in the space yet strong enough to support the impulse of a subject

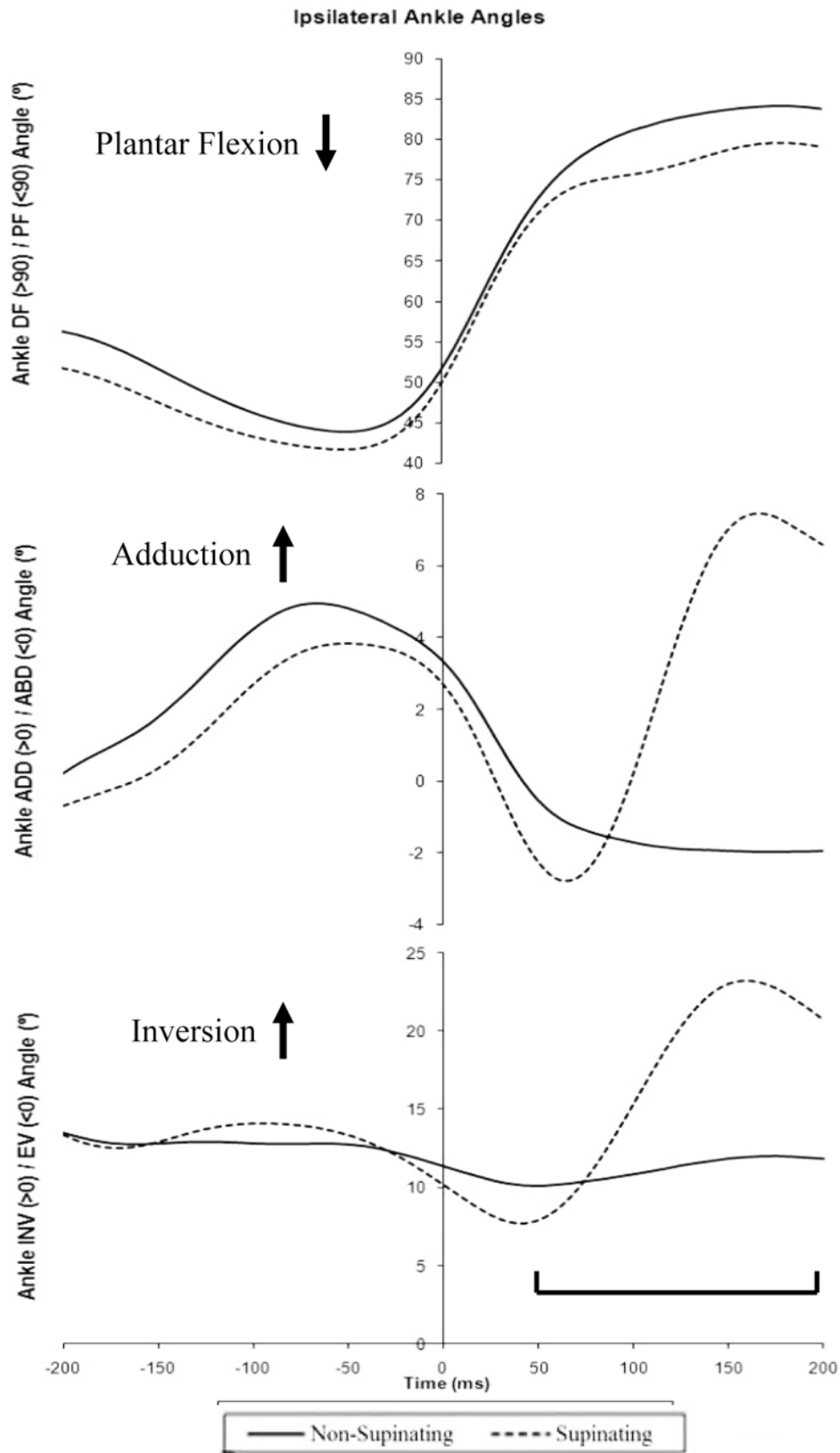


Figure 5 — Ipsilateral mean ankle angles, including dorsi-/plantar flexion, add-/abduction, and inv-/eversion angles. Increased plantar flexion, adduction, and inversion are evident following touchdown in the supinating trials (solid line vs. dashed line), specifically 50–200 ms following touchdown.

landing from a jump. However, one way to examine this is to monitor the timing and speed of platform rotation via the use of a potentiometer, which would allow for the verification of perturbation times and intensities (speed). The timing and intensity of the perturbation would have a distinct effect on kinematics and muscle activity, so controlling this perturbation is crucial to understanding the effects across groups. The reality is that ankle injuries can occur at any point following touchdown, so for research purposes, consistency is the key, rather than “accuracy.”

Even though improvements to the device and protocol can be made, the device does simulate the mechanism

of ankle sprain and thus allows us to monitor preparatory and reactive neuromuscular control in several populations. The potential to monitor motor control strategies in unstable populations was the aim of altering this device. In this pilot work, we evaluated the EMG data of the PL and TA to evaluate the effect of a perturbation on neuromuscular control in three small groups—uninjured ankles (CO), injured and unstable ankles (AI), and injured, yet not unstable ankles (NO). The preliminary EMG data (Figures 6 and 7) suggest that the NO group presents with altered neuromuscular control patterns as compared with the other two groups. Specifically, NO

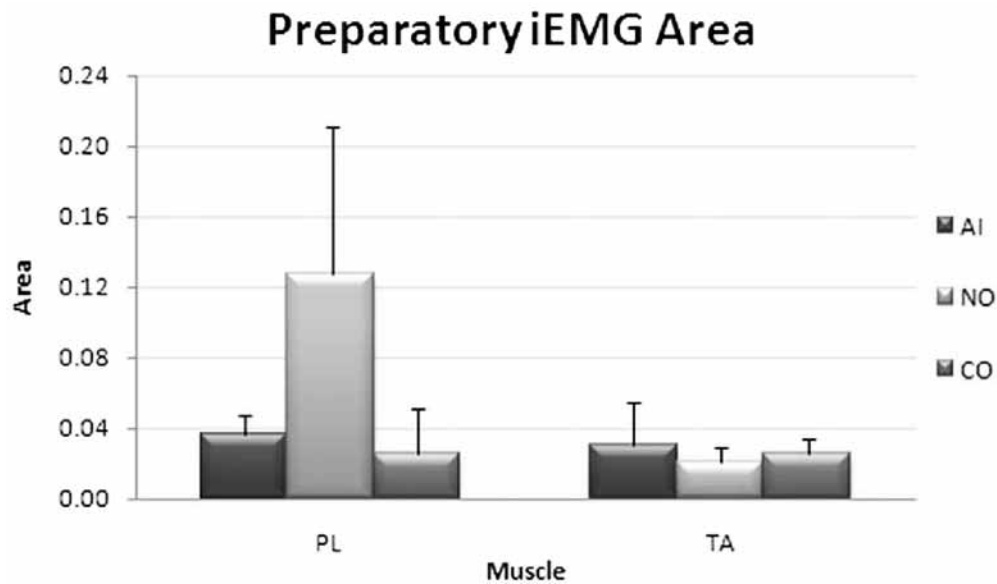


Figure 6 — Preparatory EMG activity for the peroneus longus (PL) and tibialis anterior (TA) muscles for all three groups. The NO group demonstrates significantly higher preparatory muscle activity in the PL muscle, albeit with a high standard deviation.

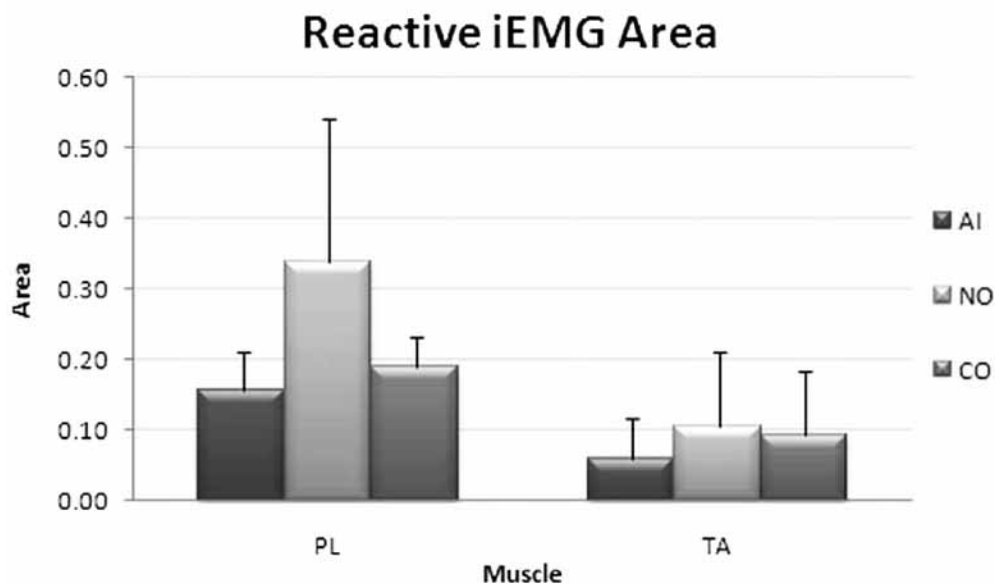


Figure 7 — Reactive EMG activity for the peroneus longus (PL) and tibialis anterior (TA) muscles for all three groups during the supinating trials only. The NO group demonstrates significantly higher reactive muscle activity in the PL muscle, albeit with a high standard deviation.

subjects demonstrated an increased activation of the PL before landing and in response to a perturbation. Obviously, with only two subjects per group, no definitive conclusions can be drawn. It is evident that one of the two NO subjects demonstrated a higher activation throughout the protocol, leading to the high standard deviations. However, if this pattern bears out in future analyses with larger sample sizes and more experimental power, it may indicate a neuromuscular control pattern in NO subjects that allows them to control dynamic ankle stability after damage to the lateral ankle ligaments. It has been demonstrated in the ACL injury literature that some individuals (termed *copers*) can return to activities of daily living, and even sports participation, with an ACL deficiency. Although discrepancies in the literature exist on the specific muscle activation patterns used by ACL-deficient copers, it is clear that they do present with different activation patterns than do non-copers to produce movement patterns similar to uninjured controls (Houck et al., 2007; Rudolph et al., 2001). Perhaps individuals who develop AI following a LAS event never alter their muscle activation strategies (i.e., they remain similar to uninjured patients) to compensate for damage to the lateral ankle stabilization structures.

In conclusion, the aim of this work was to evaluate the efficacy of a novel dynamic ankle-supinating device in mimicking the mechanism of an ankle sprain in a safe environment, such that individuals with unstable ankles could be evaluated for the preparatory and reactive dynamic neuromuscular control strategies. In this respect, the device was successful, in that it did produce ankle plantar flexion, adduction, and inversion, which constitute a supination of the ankle within a safe range of motion. Furthermore, individuals with no history of ankle injury; those with a history of ankle injury, but no instability; and those with a history of injury and instability were tested and all safely completed the protocol. Preliminary data suggest that the group of individuals who have suffered an ankle injury, but do not present with instability, may have altered neuromuscular control strategies, such that they can maintain dynamic joint stability following injury to the lateral ankle ligaments.

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