Journal of Sport Rehabilitation, 2007, 16, 295-306

Effect of Fatigue on Neuromuscular Function at the Ankle

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Context: Lateral ankle sprains occur more frequently than any other orthopedic injury. Athletes often report sustaining more injuries late in competition when fatigue is present. ***Objective:*** To evaluate neuromuscular function of the ankle musculature after fatigue. ***Design:*** Experimental, pretest-posttest. ***Setting:*** Research laboratory. ***Participants:*** Ten female and 9 male college-aged subjects. ***Intervention:*** Fatigue was induced via continuous concentric and eccentric muscle actions of the ankle: inversion (INV), eversion (EV), plantar flexion (PF), and dorsiflexion (DF). ***Main Outcome Measures:*** Peak torque (PT), peak EMG, and median frequency (MF) were calculated prefatigue and postfatigue in the tibialis anterior (TA), peroneus longus (PER), and lateral gastrocnemius (GAS) muscles. ***Results:*** Main effects were noted for test ($P < 0.0125$) in all statistical tests performed indicating changes in PT, peak EMG, and MF after fatigue. ***Conclusions:*** A significant decrease in MF of the PER muscle after PF fatigue and corresponding with a decreased firing rate, may be of importance, especially with regard to the role in countering the violent moment seen with inversion ankle sprains. ***Key Words:*** EMG, eccentric, median frequency, ankle sprain, isokinetic.

Ankle injuries result in a significant amount of time loss from work and sport activity. The ankle is the most commonly injured joint in the body and 85% of those ankle injuries are inversion sprains.[1,2] The mechanism of a lateral ankle sprain is typically a violent inversion/hypersupination of the ankle complex. Unfortunately, these injuries often result in residual disability. Long-term studies have reported 44% to 74% of those who suffered an inversion ankle injury reported persisting symptoms.[3-6] Repetitive ankle sprains have been linked to osteoarthritis and articular degeneration of the ankle joint.[7] Due to the importance of the ankle joint as the main shock absorber in locomotion, it is imperative to reduce the debilitating effects of chronic ankle instability. Consequently, a more complete understanding of neuromuscular function surrounding the ankle joint is vital, especially in elucidating the etiology of ankle injuries in an attempt to decrease their incidence.

Some would suggest that fatigue, either central or peripheral, may play a role in contributing to the occurrence of lateral ankle sprains. Research on elite level soccer players has shown that injury risk is highest in the last 15 minutes of the contest,[8]

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when fatigue has set in. Some studies have reported that muscular fatigue delays reaction time.[9,10] Furthermore, a positive correlation has been observed between increased reaction time of the gastrocnemius and tibialis anterior muscles and the incidence of inversion ankle sprains.[11] Several studies have examined neuromuscular activation of the hamstrings and quadriceps in relation to knee injury, revealing that ACL-deficient individuals have altered EMG patterns.[12-19] No similar studies have been done at the ankle involving injured or uninjured subjects.

It is known that torque production normalized to lean body mass is very similar in both males and females.[20,21] Consequently, it could be inferred that neuromuscular function would change similarly in both males and females in response to isokinetic fatigue. Therefore, the purpose of this study was to investigate the effect of isokinetic fatigue on neuromuscular function at the ankle in male and female healthy subjects, specifically, measuring torque and muscle activation of the lateral head of the gastrocnemius (GAS), peroneus longus (PER), and tibialis anterior (TA) muscles.

Methods

Design

We used a two group (male vs. female) mixed model design looking for within-subject differences prefatigue and postfatigue and between-group differences in the dependent measures. Aside from gender and test (prefatigue and postfatigue), the other independent variables included contraction velocity (30°/s and 120°/s) and muscle action (concentric and eccentric).

Subjects

A total of 9 male (age: 20.1 ± 1.5 years; height: 1.81 ± 0.09 m; mass: 84.4 ± 14.2 kg) and 10 female (age: 20.5 ± 2.0 years; height: 1.66 ± 0.05 m; mass: 62.9 ± 3.7 kg) subjects were recruited from the university community. All subjects completed an ankle inclusion questionnaire to determine ankle health status. Subjects had to be free from lower extremity injury to participate in the study. Prior to participation, all subjects provided written informed consent approved by the Human Subjects Review Board (HS 05-224).

Instrumentation

Electromyographic activity was recorded in the TA, PER, and GAS muscles using bipolar surface electrodes (Ag-AgCl, 6 mm contact diameter, 2 cm spacing). The raw EMG data were collected and amplified (input impedance 10 MΩ, gain 1000-1500x, common mode rejection ratio > 115 dB) using a Bortec AMT-8® EMG system (Bortec Biomedical Ltd., Calgary, Alberta, Canada). A Kinetic Communicator (Kin Com) 125-AP isokinetic dynamometer (Chattecx Corp., Chattanooga, TN) was used for strength testing and to induce fatigue. The dynamometer was operated in isokinetic mode, and thus quantified resistive force generated by the subject, concentrically and eccentrically, at a preset angular velocity (30°/s and 120°/s) for each ankle movement. Subject positioning on the dynamometer is demonstrated in Figures 1 and 2. The EMG signals and isokinetic torque data were collected using a laptop computer with a 12-bit analog-to-digital converter (6024-E, National Instruments Corp., Austin, TX) at a sampling rate of 1000 Hz, using custom LabVIEW software (version 7.1, National Instruments Corp., Austin, TX) to synchronize and save the data for future analysis.

Figure 1 — Subject positioned for INV/EV testing.

Figure 2 — Subject positioned for PF/DF testing.

A Bod Pod® (Life Measurement, Inc., Concord, CA) Body Composition Tracking System was used to determine lean body mass via air plethysmography methods. The subjects were weighed in minimal clothing or a bathing suit. An acrylic swim cap was worn for lean body mass recording in order to obtain the most accurate measurements from the Bod Pod ®,[22] using methods detailed by Dempster and Aitkens.[23] Lean body mass was used to normalize isokinetic PT measurements.

Procedure

Subject Preparation. The subjects' dominant legs were tested in two testing sessions, either PF/DF or INV/EV, scheduled at least 72 hours apart to reduce any "carry-over" effect of the fatigue protocol. The dominant leg was determined by asking the subjects which leg they would use to kick a ball. The first testing session was initiated by using coin flips to randomly determine the order of motions and angular velocities at which the subjects were tested. Age, height, and mass measurements were recorded, followed by body composition testing. The Bod Pod® testing involved two trials, administered consecutively to ensure that subject movement or other discrepancies did not provide inaccurate measurements. If the two trials were inconsistent, a third trial was administered; otherwise just the first two trials were averaged. Each trial lasted approximately 40 seconds. Subjects then performed a 5-minute warm-up on a stationary bike followed by static stretching of the lower extremity musculature.

Electrode placement was determined using finger and handbreadths as detailed by Perotto.[24] The electrodes for the GAS were placed on the belly of the muscle, one handbreadth below the popliteal crease on the lateral side of the calf, at an angle consistent with the direction of the muscle fibers. The electrodes for the TA were placed four fingerbreadths below the tibial tuberosity and one fingerbreadth lateral to the tibial crest. The electrodes for the PER were adhered three fingerbreadths below the fibular head in the direction of the lateral side of the fibula. Prior to strength testing, maximal voluntary isometric contractions (MVIC) with the ankle in a neutral position were performed to normalize all EMG data.

Prefatigue Testing. Based on the random assignment of the ankle motion to be tested (PF/DF or INV/EV), a separate coin flip was then used to determine the order of testing within that agonist/antagonist pair. For example, if PF/DF was assigned, we then performed a separate coin flip to determine which of those motions was to be tested first during that session. Whatever motion was tested first, 3-5 submaximal warm-up repetitions were performed, followed by 3 maximal concentric and 3 maximal eccentric muscle actions to determine baseline strength. Baseline isokinetic strength measurements were performed at angular velocities 30°/s and 120°/s, for each ankle motion, in a predetermined random order.

Fatigue Protocol. Subsequently, subjects performed continuous concentric and eccentric movements at 120°/s until fatigued. Fatigue was determined by a 50% decrease in PT (as determined from the baseline testing) for three consecutive eccentric muscle actions.[25,26] Torque deficits involving the eccentric portion of the ankle motion were chosen because eccentric force production is generally much higher than concentric force, therefore assuring fatigue in both muscle actions.

Furthermore, eccentric muscle actions are more representative of dynamic ankle stabilization mechanisms.

Postfatigue Testing. Immediately after the fatiguing event, posttest isokinetic strength measurements were recorded using the same procedures as baseline measurements. Following the posttest, the antagonist muscle was then tested and fatigued in the identical manner. Upon conclusion of all testing, the subject completed static stretching of the lower extremities.

Second Session. The second testing session was administered no less than 72 hours after the first to allow sufficient recovery time from the initial session. The ankle motions that the subject did not perform in the first testing session were assessed in the second. MVIC trials, strength testing, and fatiguing were performed in an identical fashion to the first session.

Data Analysis

Isokinetic strength for each of the four ankle motions was determined by averaging the PT from each of the three concentric (CON) and eccentric (ECC) trials. The raw EMG signals were band pass filtered (2nd order, zero-lag, Butterworth filter, with cutoff frequencies of 10 Hz and 500 Hz), full-wave rectified, and smoothed (2nd order, zero-lag, low-pass Butterworth filter with a cutoff frequency of 7 Hz). Peak EMG values were extracted and normalized based on peak EMG from the MVIC trials for each muscle tested (TA, PER, & GAS). A power spectrum analysis was performed on the EMG data and median frequency (MF) was obtained for each muscle. MF is defined as the frequency at which the EMG signal can be divided into two parts of equal power and is known to increase with increasing contraction intensity and decrease with fatigue.[27] Therefore, MF can be used as an indicator of contraction intensity and fatigue.

Statistical Analysis

Four separate 2 × 2 × 2 × 2 (Type × Gender × Velocity × Test) mixed MANOVAs, with repeated measures on the last factor were performed, one per ankle motion. The seven dependent variables were PT normalized for lean body mass (Nm/kg); Peak EMG for the TA, PER, and GAS (%); and MF for the TA, PER, and GAS (Hz). The independent variables were Type (CON vs. ECC muscle actions), Gender (male vs. female), Velocity (30°/s and 120°/s), and Test (prefatigue vs. postfatigue). A Bonferroni correction for multiple statistical tests was performed to decrease the risk of Type I error. The α-level was set at 0.0125, a priori. Overall significance of MANOVA was followed by univariate tests. All statistical tests were performed using SPSS software (version 13, SPSS Inc., Chicago, IL).

Results

Inversion

For the inversion motion, there were between subjects main effects for Gender, $F_{7,50} = 4.323$, Wilks $\lambda = 0.623$, $P = 0.001$ and for Type, $F_{7,50} = 9.611$, Wilks $\lambda = 0.426$,

$P < 0.001$. Males had a greater PT than did females ($P = 0.012$), while females had a greater peak GAS activation ($P < 0.001$). Furthermore, ECC muscle actions had a greater PT than CON muscle actions ($P < 0.001$). A within subjects interaction was detected for Test × Gender, $F_{7,50} = 3.114$, Wilks $\lambda = 0.696$, $P = 0.008$, for peak activation of the PER muscles ($P = 0.012$). The females (-7.0%) decreased more than the males did (-4.5%), although the peak activations were low for both. A within subjects main effect for Test, $F_{7,50} = 22.515$, Wilks $\lambda = 0.241$, $P < 0.001$, was also noted. The PT, peak TA, PER, and GAS activation, and the MF of the TA all decreased after inversion fatigue ($P < 0.001$). Inversion pretest and posttest data are presented in Table 1.

Eversion

For the eversion motion, a between subjects main effect for Type, $F_{7,54} = 5.718$, Wilks $\lambda = 0.574$, $P < 0.001$, was detected in that ECC muscle actions had a greater PT than CON actions ($P < 0.001$). A within subjects main effect for Test, $F_{7,54} = 12.036$, Wilks $\lambda = 0.391$, $P < 0.001$, was also noted. The PT ($P = 0.005$), peak TA ($P = 0.002$), PER ($P < 0.001$), and GAS ($P < 0.001$) activations all decreased with eversion fatigue. Eversion pretest and posttest data are presented in Table 2.

Dorsiflexion

For the dorsiflexion motion, there were between subjects main effects for Gender, $F_{7,46} = 3.698$, Wilks $\lambda = 0.640$, $P = 0.003$, and for Type, $F_{7,46} = 15.531$, Wilks $\lambda = 0.297$, $P < 0.001$. Males had a greater peak TA activation than did females ($P < 0.001$), while females had a greater peak PER activation ($P < 0.001$). Furthermore, ECC muscle actions had a greater PT than CON actions ($P < 0.001$). A within subjects main effect for Test, $F_{7,46} = 18.680$, Wilks $\lambda = 0.260$, $P < 0.001$, was noted. The PT ($P < 0.001$), peak TA ($P < 0.001$) and PER ($P < 0.001$) activations, and the MF of the TA ($P = 0.002$) all decreased after dorsiflexion fatigue. Dorsiflexion pretest and posttest data are presented in Table 3.

Table 1 Prefatigue and Postfatigue Measures for the Inversion Motion, Collapsed Across Velocity, Gender, and Contraction Type

	Pre	Post	P-Value
PT (Nm/kg)*	0.40 ± 0.13	0.34 ± .12	0.000
Peak EMG – TA (% max)*	45.64 ± 19.56	32.46 ± 16.26	0.000
Peak EMG – PER (% max)*	29.89 ± 13.22	24.42 ± 12.50	0.000
Peak EMG – GAS (% max)*	53.96 ± 26.22	39.09 ± 14.29	0.000
MF – TA (Hz)*	161.48 ± 22. 85	151.52 ± 21.94	0.000
MF – PER (Hz)	145.14 ± 24.89	142.74 ± 23.59	0.385
MF – GAS (Hz)	147.18 ± 34.10	151.85 ± 28.22	0.505

*denotes $\alpha < 0.0125$. Mean ± SD.

Table 2 Prefatigue and Postfatigue Measures for the Eversion Motion, Collapsed Across Velocity, Gender, and Contraction Type

	Pre	Post	P-Value
PT (Nm/kg)*	0.59 ± 0.28	0.52 ± 0.29	0.005
Peak EMG – TA (% max)*	31.09 ± 13.98	25.61 ± 16.12	0.002
Peak EMG – PER (% max)*	83.91 ± 23.13	68.84 ± 27.60	0.000
Peak EMG – GAS (% max) *	43.38 ± 16.23	39.65 ± 20.72	0.000
MF – TA (Hz)	156.83 ± 24. 03	156.78 ± 20.34	0.504
MF – PER (Hz)	181.58 ± 32.25	175.22 ± 27.88	0.902
MF – GAS (Hz)	157.33 ± 33.44	154.11 ± 29.26	0.349

*denotes $\alpha < 0.0125$. Mean ± SD.

Table 3 Prefatigue and Postfatigue Measures for the Dorsiflexion Motion, Collapsed Across Velocity, Gender, and Contraction Type

	Pre	Post	P-Value
PT (Nm/kg)*	1.02 ± 0.27	0.82 ± 0.25	0.000
Peak EMG – TA (% max)*	69.95 ± 19.49	51.56 ± 23.99	0.000
Peak EMG – PER (% max)*	57.19 ± 37.52	46.93 ± 31.64	0.000
Peak EMG – GAS (% max)	33.08 ± 22.39	33.71 ± 23.94	0.352
MF – TA (Hz)*	153.29 ± 29.56	148.07 ± 22.43	0.002
MF – PER (Hz)	123.15 ± 28.27	124.80 ± 27.72	0.793
MF – GAS (Hz)	112.98 ± 30.40	114.84 ± 30.33	0.205

*denotes $\alpha < 0.0125$. Mean ± SD.

Plantar Flexion

For the plantar flexion motion, there were between subjects main effects for Gender, $F_{7,61} = 4.570$, Wilks $\lambda = 0.656$, $P < 0.001$, and for Type, $F_{7,61} = 20.997$, Wilks $\lambda = 0.293$, $P < 0.001$. Males had a significantly higher MF for the PER muscle ($P < 0.001$), while ECC muscle actions had a greater PT than CON actions ($P < 0.001$). A within subjects interaction was detected for Test × Gender, $F_{7,61} = 4.624$, Wilks $\lambda = 0.653$, $P < 0.001$, for the MF of the PER muscles ($P = 0.012$); the males (-21.8 Hz) decreased more than the females did (-2.7 Hz). A Test × Type interaction was noted for PT, $F_{7,61} = 6.692$, Wilks $\lambda = 0.566$, $P < 0.001$. ECC muscle actions (-0.87 Nm) demonstrated a greater decrease in PT than CON actions (-0.25 Nm). A main effect was also detected for Test: $F_{7,61} = 17.154$, Wilks $\lambda = 0.337$, $P < 0.001$. The PT ($P < 0.001$), peak TA ($P < 0.001$) and PER ($P < 0.001$) activation, MF of the PER ($P < 0.001$) and GAS ($P = 0.005$) muscles all decreased with plantar flexor fatigue. Additionally, peak GAS activation tended to decrease ($P = 0.016$). Plantar flexion pretest and posttest data are presented in Table 4.

Table 4 Prefatigue and Postfatigue Measures for the Plantar Flexion Motion, Collapsed Across Velocity, Gender, and Contraction Type

	Pre	Post	P-Value
PT (Nm/kg)*	2.97 ± 1.40	2.41 ± 1.16	0.000
Peak EMG – TA (% max)*	16.38 ± 8.05	13.67 ± 7.67	0.000
Peak EMG – PER (% max)*	92.96 ± 66.97	64.01 ± 41.74	0.000
Peak EMG – GAS (% max)	100.18 ± 51.14	88.89 ± 68.65	0.016
MF – TA (Hz)	152.39 ± 25.41	148.13 ± 25.12	0.106
MF – PER (Hz)*	175.94 ± 42.01	164.22 ± 33.33	0.000
MF – GAS (Hz)*	131.52 ± 33.01	125.80 ± 29.89	0.005

* denotes $\alpha < 0.0125$. Mean ± SD.

Discussion

The purpose of this study was to determine the effects of isokinetic fatigue on torque and EMG activity produced by muscles contributing to ankle joint stability. Many studies have measured the effects of fatigue on variables affecting function of the lower extremity. Few studies have directly measured the effects of fatigue on force production, peak activation, and median frequency of muscles surrounding the ankle joint. As expected from previous results,[26,28-31] and lending support to the effectiveness of our own fatigue protocol, force production decreased significantly ($P < 0.005$) after fatigue.

One of the factors evaluated in this study was the effect of gender on ankle function after fatigue. It has been found that there are no significant strength differences between the genders when lean body mass is used for normalization.[20,21] Once corrected for lean body mass, gender differences in torque production were only significantly different in one case— for the inversion motion, males had a greater normalized torque than females had. A possible explanation for this difference arises when inspecting the activation levels of the PER muscles in the males and females during the inversion testing. Although not statistically significant, females activated the PER muscle more than males did (33.3% vs. 21.4%). Because the evertors are antagonists to the inversion movement, this provides evidence that the females may have been cocontracting when attempting to produce maximal inversion torque, which would decrease force production in the agonist direction. With regard to plantar flexion, dorsiflexion, and eversion movements, our findings support the previous results that once corrected for lean body mass, no significant strength differences exist between males and females.

For all four motions, eccentric muscle actions produced greater normalized PT than concentric muscle actions, as can be expected based on the traditional force-velocity relationship. Pasquet et al[29] completed a similar study examining the effects of fatigue on concentric and eccentric muscle actions in the ankle dorsiflexors measuring torque and EMG activity. As in this study, they found that eccentric muscle actions produced more torque than concentric muscle actions. Pasquet and colleagues[29] did not find any differences in activation after fatigue; however, in this study the peak activation of the prime mover for each motion decreased after fatigue. A more interesting finding was that muscle activation decreased even for muscles that are not the primary movers for a given motion. For example, PER and GAS activation decreased with inversion fatigue. Intuitively, one could argue that our subjects were centrally (or generally) fatigued after the isokinetic protocol was completed. This in turn would cause all muscle activations to decrease. Another plausible explanation for this decrease in activation in the surrounding musculature is that our subjects may have been cocontracting the muscles around the ankle joint. Cocontraction is generally present to stabilize the joint, which may have been necessary to compensate for the subjects' inexperience with testing on an isokinetic dynamometer. As they became more comfortable on the device throughout the fatigue event, they may have felt less of a need to activate the surrounding musculature for stabilization, therefore displaying significant decreases in peak activation levels of these muscles.

It is generally accepted that median frequency of muscle firing decreases with fatigue[32] as a compensation for a decrease in twitch strength. In this study, we were able to demonstrate this phenomenon, and we report significant decreases ($P < 0.005$) in the MF of the TA for inversion and dorsiflexion and in the GAS for plantar flexion. Contrary to this accepted concept, the MF of the PER muscles during the eversion motion did not significantly decrease. Interestingly, Yeung et al[30] had similar findings in a study of the vastus medialis muscle in humans, where they did not find significant decreases in the MF ($P = 0.062$) following an isometric fatigue event involving the quadriceps musculature. They postulated that their fatigue protocol maintained central drive; hence the fatigue resided in the contractile properties of the muscle. The peroneals are generally smaller than the other muscle groups acting at the ankle joint; therefore it is possible that fatiguing a relatively small muscle group would not have decreased central drive.

Perhaps the most interesting finding of this study is that the MF of PER muscle decreased with plantar flexion fatigue. This is not a completely novel finding. Gefen[33] induced fatigue in 4 subjects by intense marching and found a decrease in MF of the peroneal muscles after fatigue. This is a reasonable finding in that the peroneal muscles are secondary plantar flexors, so it could be expected that as they fatigue along with the plantar flexors, they subsequently fire less frequently. Of further interest is that the peroneals provide important dynamic stabilization to the ankle joint, especially during periods of inversion stress, an action that may be compromised in a post-fatigued state. The plantar flexors are often used and fatigued in jumping/landing/cutting activities such as basketball, volleyball, football, etc. These activities are the same activities associated with a high risk of ankle sprains. A decreased firing rate in the lateral ankle stabilizers (peroneal muscles) during high-risk activities may help explain the anecdotal evidence that more ankle sprains happen later in competition, when fatigue has set in.

Inherent to most fatigue studies are limitations that need to be addressed. Generally speaking, subject performance in fatigue studies is the result of muscular fatigue *and* the effort of the subject.[25] Our data were analyzed under the assumption that each subject elicited maximal effort during prefatigue and postfatigue testing. Although data were normalized for lean body mass, individual efforts for each motion performed prior to fatigue determined the value at which each individual was declared "fatigued." Therefore, if prefatigue efforts were not maximal, fatigue as defined in our study would not have been reached. Furthermore, it is arguable whether the 50% deficit in force production criteria is an adequate standard of fatigue.[34]

Due to the type of protocol administered, declines in torque can only be attributed to local muscular fatigue as a result of the movements performed. In contrast to a functional fatigue protocol, the present study is unable to account for fatigue developed as a result of ongoing dynamic muscle stabilization of the ankle during activity.[35] During dynamic activities, especially those requiring running, jumping, and cutting, the ankle musculature is activated for both stabilization and movement purposes. Utilizing isolated, isokinetic movements as a means of inducing localized muscular fatigue enables researchers to control and quantify the level of fatigue; however, the applicability to what happens during dynamic sport activities is questionable. Because our fatigue protocols involved isolated movements and did not exhaust the muscle groups collectively, we cannot speculate as to whether or not fatigue-related strength imbalances would contribute to ankle injury. Other factors, such as dehydration and depletion of energy stores, may increase the risk of ankle injury due to their contribution to declines in absolute strength and general fatigue.[35] Neither of these factors were controlled for nor analyzed in our study. Without utilizing a functional fatigue protocol, it can only be concluded that the strength and EMG changes resulted from the isolated, isokinetic actions being performed.

This study aimed to provide torque and EMG measures of the ankle musculature and to evaluate the effect of fatigue on those measures. Our goal was to gain a better understanding of the muscles that stabilize the ankle joint in order to help elucidate the causes of lateral ankle sprain. The most interesting finding in this study was the decrease in the MF of the PER muscle after plantar flexor fatigue. The plantar flexors are often very active, and therefore fatigued, in the same activities that are known to be of risk for lateral ankle sprains. The peroneals, along with being secondary plantar flexors, are the primary lateral stabilizers responsible for countering violent inversion moments. If the peroneals do not fire fast enough, as indicated with a decreased in median firing frequency after fatigue, this would predispose an individual to lateral ankle sprain, especially late in competition when most sprains are said to occur. With this in mind, future research should aim to validate these conclusions concerning fatigue and ankle function. Although plenty of anecdotal accounts have suggested that most lateral ankle sprains occur late in practice and competition, further study is necessary to confirm this. Furthermore, examining neuromuscular function in a group of subjects who suffer from chronic ankle instability is needed in an attempt to further understand the differences between them and those with stable ankles.

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