Journal of Athletic Training 2016;51(6):491–497
doi: 10.4085/1062-6050-51.9.02

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original research

Localized Ankle Fatigue Development and Fatigue Perception in Adults With or Without Chronic Ankle Instability

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Context: Fatigue could contribute to ankle-sprain injuries during sport, particularly for individuals with chronic ankle instability (CAI).

Objective: To examine whether adults with or without CAI develop fatigue at similar rates when performing ankle exercises at the same relative effort level and whether these groups differ in their subjective perceptions of fatigue.

Design: Controlled laboratory study.

Setting: Biomechanics research laboratory.

Patients or Other Participants: A total of 11 volunteers with CAI (1 man, 10 women; age = 23.5 ± 3.0 years, height = 168.0 ± 11.2 cm, mass = 64.3 ± 13.5 kg) were recruited for the unstable-ankle group, and 11 volunteers matched for age, height, mass, and sex (1 man, 10 women; age = 24.1 ± 2.1 years, height = 169.5 ± 9.7 cm, mass = 62.3 ± 9.7 kg) were recruited as control participants.

Intervention(s): Localized muscle fatigue (LMF) was induced in the ankle of the dominant limb using a custom fatigue protocol. Plantar-flexion and dorsiflexion exertions were completed at a rate of 12 cycles per minute at isotonic loads equal to 70% and 30%, respectively, of individual maximal voluntary isometric strength. Intermittent measures of maximal voluntary isometric strength and ratings of perceived exertion (RPEs) were obtained.

Main Outcome Measure(s): We compared isometric-strength measures and RPE scores at each observation time (prefatigue and at 4, 8, 12, and 16 minutes into the fatigue protocol) and the group correlations between changes in strength and changes in RPE scores.

Results: Based on ankle-strength measures, the 2 test groups developed LMF at similar rates when exercising at equivalent levels of relative effort. The 2 groups also reported similar levels of discomfort as fatigue progressed.

Conclusions: The rate of LMF development at the ankle and the associated perception of fatigue did not differ between adults with or without CAI.

Key Words: ankle injuries, ankle torque, muscle strength, physical exertion, joint instability

Key Points

- Localized muscle-fatigue development did not differ between adults with and those without chronic ankle instability after exercising the ankle in plantar flexion and dorsiflexion at equivalent levels of relative effort.
- The increase in subjective perceptions of fatigue with fatigue development was similar for adults with and those without chronic ankle instability.

Injuries to the ankle account for the greatest percentage (approximately 11%) of self-reported musculoskeletal injuries in the United States.[1] Ankle sprains in particular remain a common injury, with incidence rates estimated at 2.15 per 1000 person-years in the United States[2] (approximately 685 000 sprains annually) or 11.55 sprains per 1000 exposures, based on rates pooled from international publications.[3] Roughly half of all ankle-sprain injuries result from participation in athletic activities,[2] with the highest incidences reported for soccer[2]; football[2,4]; and indoor/court sports, such as basketball and volleyball.[3,4] These injuries are painful, and in a longitudinal study, researchers[5] reported that three-quarters of individuals sustaining sport-related sprains continued to experience symptoms, such as pain, instability, weakness, or swelling, for a year or more after the injury. Some individuals will develop chronic ankle instability (CAI), which was identified by Freeman[6] and is characterized by frequent recurrent sprains.[5,6] This instability may be due to a functional or mechanical deficit or a combination of these deficits caused by the initial injury, including decreased proprioception, neuromuscular control, or postural control; changes in strength or joint kinematics; joint degeneration; or increased tissue inflammation or laxity.[6–8]

Resisting a sprain during ground contact requires detection of ankle position and orientation, as well as preparatory, reflexive, and voluntary control.[9,10] Sprains often result from excessive plantar flexion, inversion, or internal rotation at ground contact.[8,10] Whereas some researchers have reported sensorimotor and joint position sense deficits in adults with CAI,[11,12] others have refuted these claims,[13] resulting in some uncertainty regarding the roles of these factors in recurrent sprains. Preparatory muscle contraction and reflexive muscle-force development are critical to controlling ankle displacement during early ground contact,[9,10] and the voluntary cocontraction of muscles is important to joint stabilization during dynamic activity.[14,15] Deficits in reflexive or voluntary muscle control may also lead to sprain injury.

Another contributing factor to sprain recurrence may be muscle fatigue. By definition, muscle fatigue reduces maximal voluntary force generation. In adults with healthy, stable ankles, fatigue has, in addition, been shown to reduce passive and active joint position sense.[16,17] Thus, even among adults with stable ankles, fatigue is likely to increase the risk of sprain injury. However, the risk to adults with CAI may be substantially higher. As mentioned, adults with CAI may exhibit deficits in joint position sense,[11] and when fatigued, they have less postural stability when standing on the affected ankle than do control participants.[18] In patients with unilateral CAI, Gribble et al[19] observed decreased postural stability for the affected (history of sprain) ankle compared with the unaffected (no history of sprain) ankle and reported that stability differences were amplified by both localized muscle fatigue (LMF) and generalized lower extremity fatigue. Lastly, conflicting reports about possible deficits in concentric invertor and evertor strength[13,14,20] have indicated that fatigue could impose motor-control impairments in adults with CAI that are similar to, if not greater than, those in adults without CAI.

The effects of fatigue on stability, strength, and physical performance measures are often evaluated by comparing groups that have been fatigued to similar levels. Yet the time required to reach this equivalent fatigue level or the progression of fatigue development over time is not considered. Therefore, the purpose of our study was to determine whether adults with CAI developed fatigue in the muscles controlling the ankle at a rate similar to control-group adults. In our estimation, a faster rate of fatigue development in those with CAI would imply an earlier onset of detrimental fatigue effects when exercising at a similar effort level. In addition, we aimed to determine whether adults with CAI and control participants experienced similar perceptions of fatigue as it developed. Adults with and those without CAI completed a fatigue protocol requiring all participants to work at equivalent levels of relative effort. Intermittent maximal voluntary isometric contractions (MVICs) and ratings of perceived exertion (RPEs) were measured to monitor changes in strength and perceptions of fatigue, respectively, during the protocol. Rates of changes in these outcomes were compared between groups, and the null hypothesis was that these rates would be similar between groups. We examined the rates of change in strength and in RPE scores provided throughout the protocol. Rates of change in strength and RPE scores, as well as the correlation between them, were compared between groups to determine if adults with CAI (1) developed ankle fatigue at a faster rate than healthy controls and (2) exhibited a poorer perception of fatigue development.

METHODS

Participants

Participants were 11 adults with unstable ankles (1 man, 10 women; age = 23.5 ± 3.0 years, height = 168.0 ± 11.2 cm, mass = 64.3 ± 13.5 kg) and 11 adults serving as control participants (1 man, 10 women; age = 24.1 ± 2.1 years, height = 169.5 ± 9.7 cm, mass = 62.3 ± 9.7 kg) and matched individually for age, height, mass (mean differences between groups: age = 2.2 years, height = 5.3 cm, mass = 6.3 kg, respectively), and sex. Ankle instability was determined using the Cumberland Ankle Instability Tool (CAIT) questionnaire[21] and self-reported medical history. The unstable-ankle group (CAI group) had a CAIT score equal to or less than 24 (mean = 19.1 ± 2.8), had a history of 2 or more inversion sprains to the same ankle, and provided anecdotal reports of their ankle "rolling" or "giving way" during activity.[4,20] Participants in the control group had no history of ankle sprains and had CAIT scores of 28 or greater (mean = 29.7 ± 0.6). Exclusion criteria for both groups were chronic joint pain, previous joint surgery or neuropathy of the lower extremities, muscle weakness, or vestibular or balance disorder. Volunteers experiencing joint pain, participating in physical rehabilitation programs, or regularly using ankle tape or braces at the time of the study were also excluded.

The *dominant limb* was identified as the limb preferred for kicking a ball. Among participants in the CAI group, the ankle with the lowest CAIT score was tested. Members of the control group were tested using the ankle with the same limb dominance or nondominance as their CAI group counterparts. Both groups wore the same model of sex-specific athletic shoe (women: Danskin Now; DJM International LLC, Dayton, NJ; men: Starter Inc, New Haven, CT) fitted to the nearest whole size during testing. All participants provided written informed consent, and the study was approved by the Institutional Review Board of Virginia Polytechnic Institute and State University.

Instrumentation

Pairs of surface electromyography (EMG) electrodes (model A10012-5S; Vermed, Inc, Bellows Falls, VT) were applied to the skin over the tibialis anterior (TA), peroneus longus (PL), and lateral gastrocnemius (GS) muscles of the test limb.[22] These 3.4- × 5.7-cm rectangular foam Ag/AgCl wet-gel electrodes had an interelectrode distance of 3.4 cm. The EMG signals were preamplified near the electrode sites and amplified with a gain of 2 K using a hardware system (Measurement Systems, Inc, Ann Arbor, MI). Signals were filtered digitally using a fourth-order, zero-lag bandpass filter at a frequency of 20 to 450 Hz and notch filtered at a frequency of 60 Hz during subsequent signal processing in software. This notch filter was employed to remove observable 60-Hz noise from the power source used for data collection. All exercises were conducted using a commercial dynamometer (System 3; Biodex Medical Systems, Inc, Shirley, NY) in the plantar-flexion–dorsiflexion (PF-DF) configuration. The PF-DF configuration allowed for fatigue of the muscles controlling the ankle, and pilot work suggested it was better tolerated than fatiguing in the inversion-eversion directions. Prefatigue MVICs were performed to determine ankle strength in both PF and DF. Seated body position in the dynamometer was standardized, with 20° of back-rest recline, 50° of knee flexion, and the ankle in neutral position. A lap belt and thigh support were used to minimize extraneous leg and body movements, and padded straps secured the foot to the dynamometer footplate. A minimum of three 3-second MVICs were recorded for both the PF and DF directions,

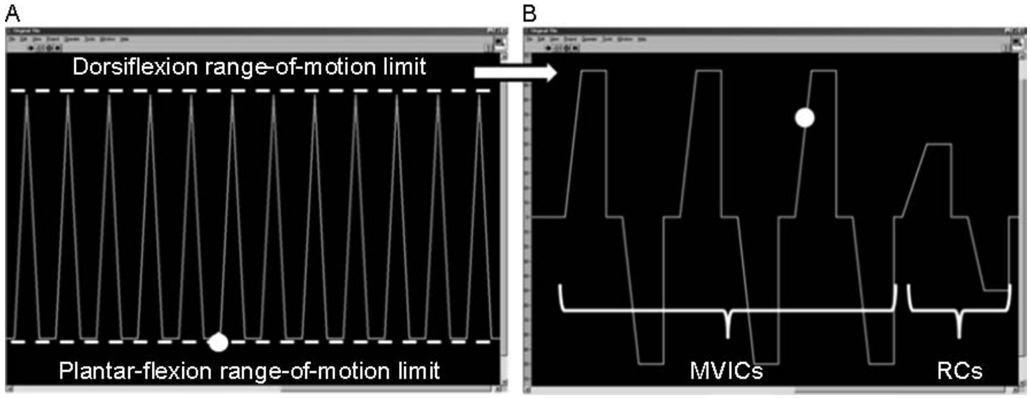

Figure 1. Visual feedback provided to guide participants through the fatigue protocol. A, A solid line displays cyclic motion between range-of-motion limits. Participants were required to trace this line with the white indicator dot (enlarged for image). B, A solid line displays target ankle-torque values during maximal voluntary isometric contractions (MVICs) and reference contractions (RCs). Displays were scaled so that plantar-flexion exertions (below midline) and dorsiflexion exertions (above midline) were equivalent in size. Target values displayed represent either 100% or 50% of prefatigue MVICs for intermittent MVIC and RC measures, respectively.

with at least a 1-minute rest between MVICs. Ankle torque and EMG were recorded at 2048 Hz via a custom LabVIEW program (version 10.0; National Instruments Corporation, Austin, TX). If MVICs were inconsistent or increased, they were repeated until peak values plateaued. Oral encouragement was given for all attempts. Participants also completed a series of 4 reference contractions (RCs) in both the PF and DF exertions. During these RCs, participants were instructed to maintain an ankle-torque level equivalent to 50% of their MVICs in each direction (PF or DF). Visual feedback of ankle torque was provided through a computer monitor. These prefatigue RC measures were used to assess fatigue-induced changes in EMG signal content.

Fatigue Protocol and Test Procedures

The fatigue protocol consisted of four 4-minute "rounds," each requiring 3 minutes of cyclic, isotonic PF and DF exertions and 1 minute of MVIC and RC measures. A counterweight was added to the dynamometer arm to offset the moment created by the weight of the participant's foot and the footplate. Visual feedback of ankle orientation or ankle torque was provided to guide participants through the protocol (Figure 1), and initial practice was allowed to acquaint them with the timing and feedback response. Isotonic PF and DF exertions were performed at a rate of 12 cycles per minute over a specified range of motion (ROM), with limits of 30° of PF and 15° of DF measured from the neutral ankle position. Isotonic loads were set to 70% and 30% of an individual's MVIC in the PF and DF directions, respectively, to ensure all participants were working at an equivalent level of relative effort. A pilot study suggested that these levels were sufficient to produce substantial fatigue ($\geq$20% decrease in MVIC) while still permitting movement through the entire ROM.

After 3 minutes of isotonic exertions, participants used the Borg CR-10 RPE scale[23] to rate their perceived level of fatigue in the front (dorsiflexors [RPE_{DF}]) and back (plantar flexors [RPE_{PF}]) of the lower leg. The Borg CR-10 scale presents values of 0 to 10, with 0 representing *no sensation of fatigue or exertion* and 10 representing *absolute maximal fatigue or exertion*. At every fourth minute of the protocol (observation time), the ankle was returned to the neutral position and held in place by the dynamometer. Three MVICs and a 50% RC were alternated in the PF and DF directions. Participants were instructed to increase their ankle torque to their current maximum and maintain that effort for 3 seconds. For RCs, participants increased to 50% of their prefatigue MVIC and maintained that level for 3 seconds. These intermittent MVIC and RC data were obtained at minutes 4, 8, 12, and 16 of the fatigue protocol.

Dependent Measures

Dependent measures were ankle MVICs and RPE scores collected at each observation time (4, 8, 12, and 16 minutes). Additional measures were EMG median frequency (MF) for each muscle during the RCs. Given that the PL and GS muscles are primary plantar flexors, the MFs of these muscles were calculated during PF RC efforts. Similarly, given that the TA muscle is a primary dorsiflexor, its MF was calculated during DF RC efforts. The EMG signals were filtered using a fourth-order, zero-lag bandpass filter with a frequency of 20 to 450 Hz and a notch filter with a frequency of 60 Hz. The MF was calculated using a fast Fourier transform and the method of Welch[24] with a 100-millisecond window.

Statistical Analysis

Paired-samples *t* tests were used to compare prefatigue ankle strength (PF and DF MVICs) between the control and CAI groups. We found no order effects ($P > .17$) on consecutive MVICs at any observation time in either exertion direction. Postfatigue measures at each observation time (4, 8, 12, and 16 minutes) were converted to change scores relative to prefatigue MVIC levels (ie, post–pre). For each of the MVIC, RPE, and MF measures, we constructed a linear mixed model, with group and time as fixed effects and participant as a random effect. Main and interaction effects of group and time were assessed by performing a χ^2 test comparing the goodness of fit of models constructed with and without the factor of interest. When we observed main or interaction effects, we used the Tukey honestly significant difference test to compare factor levels. For interaction effects, contrasts were specified to compare the means between groups at each observation time and to

Table. Prefatigue Measures of Ankle Strength, Rating of Perceived Exertion, and Electromyography Median Frequencies (Mean ± SD)

Measure	Group		*P* Value
	Control	Chronic Ankle Instability	
Maximal voluntary isometric contraction, Nm			
Plantar flexion	40.9 ± 14.1	39.0 ± 11.0	.74
Dorsiflexion	24.5 ± 8.9	23.1 ± 5.2	.66
Rating of perceived exertion[a]			
Plantar flexion	0.5 ± 0.4	0.1 ± 0.2	.04[b]
Dorsiflexion	0.6 ± 0.6	0.1 ± 0.2	.01[b]
Electromyography median frequency, Hz			
Tibialis anterior	130.1 ± 12.1	137.4 ± 15.6	.23
Peroneus longus	130.2 ± 25.3	126.5 ± 18.4	.70
Gastrocnemius	156.7 ± 21.8	147.2 ± 19.3	.29

[a] Range = 0–10, with 0 = *no sensation of fatigue or exertion* and 10 = *absolute maximal fatigue or exertion.*
[b] Indicates effect ($P < .05$).

compare the means at each pair of observation times within a group. We calculated rates of change in MVIC and RPE measures between consecutive observation times for each participant. For each group, bivariate correlations were fit between the rates of change in MVIC measures and the rates of change in RPE measures for the corresponding motion (PF, DF). We used paired-samples *t* tests to compare correlation coefficients between groups. We set the α level at .05 for all analyses. Statistical analysis was completed using open-source R software (version 3.1.2; The R Foundation for Statistical Computing, Vienna, Austria).

RESULTS

Prefatigue strength did not differ between groups for either the PF ($t_{20} = 0.34$, $P = .74$) or DF ($t_{20} = 0.45$, $P = .66$) exertions (Table). At each observation time, both PF and DF ankle strengths were less than prefatigue levels ($P < .001$), and final mean strength reductions across participants were 21.6% and 35.7%, respectively (Figure 2). No group differences in strength losses were found at any observation time.

The RPE_{PF} (N = 22; $\chi^2_4 = 125.03$, $P < .001$) and RPE_{DF} (N = 22; $\chi^2_4 = 153.40$, $P < .001$) scores increased during the fatigue protocol. For both exertion directions, the RPE scores at each observation time were greater than prefatigue levels ($P < .001$), and the RPE scores were greater at 12 and 16 minutes than at 4 minutes ($P < .01$ for all). The mean ± SD values for RPE_{PF} and RPE_{DF} scores were 4.7 ± 2.0 and 6.5 ± 1.7, respectively, and we did not observe group differences in RPE changes at any observation time. Time and interaction effects for MF were observed only for the TA muscle (N = 22; $\chi^2_4 = 47.05$, $P < .001$; Figure 3). In

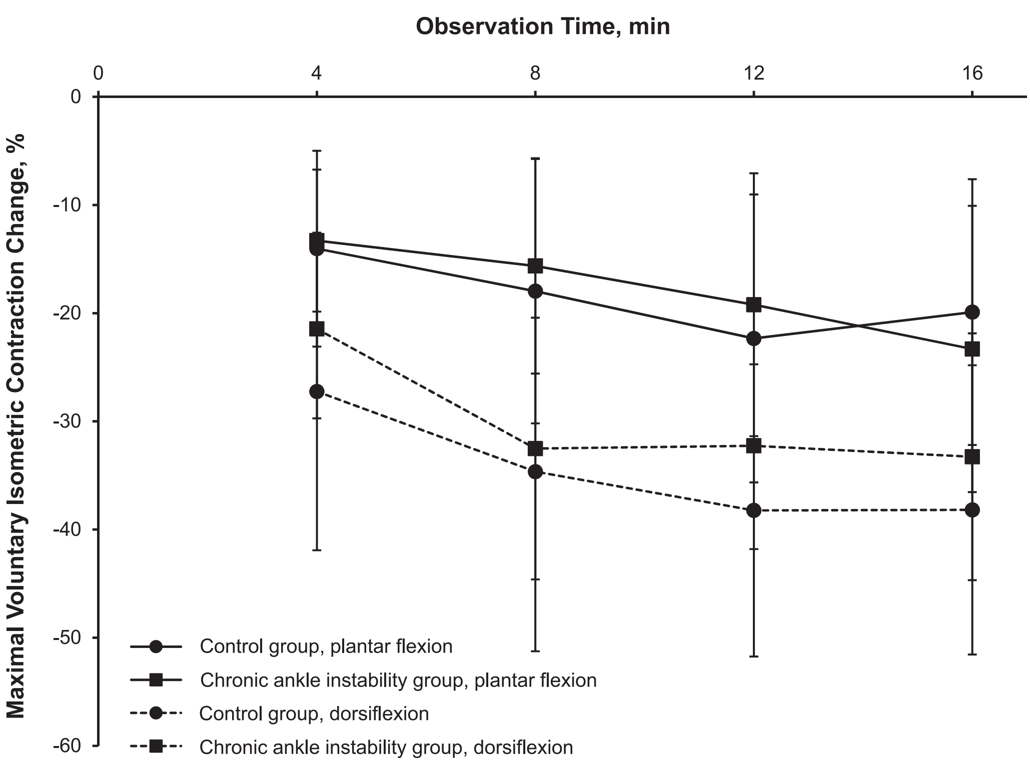

Figure 2. Change scores (mean ± SD) for plantar-flexion and dorsiflexion strength at each observation time during the fatigue protocol.

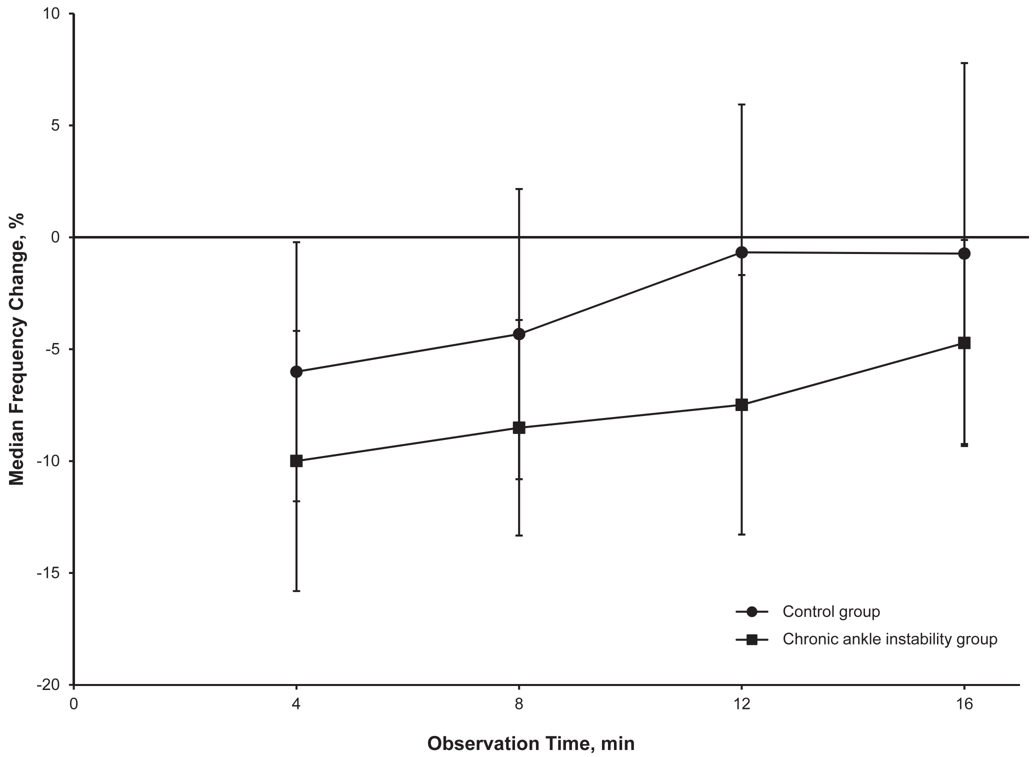

Figure 3. Change scores (mean ± SD) for median frequency of the tibialis anterior muscle at each observation time during the fatigue protocol.

both groups, TA MF was less at 4 minutes than at prefatigue ($P < .01$). It then increased at each subsequent observation time, and at 16 minutes, it was no longer different from the prefatigue level. Change scores at each observation time were not different between groups. We found no effects for MF of either the PF or GS muscles.

No group differences were found in the correlation coefficients between rates of change in the strength and RPE scores (PF: $t_{20} = -0.30$, $P = .76$; DF: $t_{20} = -0.96$, $P = .35$). Across both groups, the mean ± SD correlation coefficients between PF and DF strength changes and RPE changes were 0.43 ± 0.28 and 0.53 ± 0.34, respectively.

DISCUSSION

Fatigue has been implicated as an important factor in sport-related injuries, as most of these injuries occur during the latter half of a period of play or during the second half of a competition.[25,26] In a study of injuries among professional soccer players, Woods et al[26] reported that ankle sprains occurred with greater frequency during the last third of each half of play. Fatigue not only reduces maximal voluntary force generation but also reduces passive and active joint position sense,[11,12] both of which are essential to resisting ankle sprain.[9,10] Whereas fatigue may increase the risk of ankle injuries, adults with CAI tend to sustain ankle sprains more frequently than adults with stable ankles. The goal of our study was to assess whether a similar level of exertion might result in more rapid fatigue development for individuals with CAI or whether such individuals have decreased perceptions of fatigue development that may contribute to recurrent ankle sprains.

The 2 groups in our study had equivalent prefatigue ankle strength in both the PF and DF directions. Kaminski and Hartsell[14] also observed that ankle instability was not associated with decreased ankle PF or DF strength. We noted comparable decreases in ankle strength during our fatigue protocol, indicating that both groups developed LMF at similar rates in response to isotonic exercise at equivalent levels of relative effort. Furthermore, both groups exhibited similar correlations between changes in ankle strength and changes in RPE scores. These findings indicate that recurrent ankle sprains in adults with CAI are likely not substantially attributable to differences in fatigability of the muscles controlling ankle stability or a poorer perception of ankle fatigue.

Despite clear losses in ankle strength, EMG MF appeared to be relatively insensitive as a measure of fatigue during this protocol. Median frequency is expected to decline as fatigue develops,[27] and fatigue decreases EMG MF during both static and dynamic contractions.[28,29] In those studies, MF was calculated from EMG data collected periodically during continuous performance of either static or dynamic exertions. In our study, however, we calculated MF from EMG recorded during RCs for which the target ankle-torque value was 50% of the prefatigue MVIC. We made this decision to permit comparisons of MF independent of a participant's changing ankle-torque capacity during the fatigue protocol. Yet the reduction in MF during fatigue is due to longer, low-amplitude action potentials[30] and a shift to dependency on slow-twitch motor units. It seems possible that the 50% RC did not sufficiently tax motor-unit recruitment to demonstrate a consistent decrease in MF. Note that, even at the completion of the fatigue protocol, MVICs were reduced by only 20% to 35%. Participants might have been able to attain the RC target by selective recruitment of motor units, masking the anticipated changes in MF. In addition, participant adherence to the 50% RC was monitored during the experiment but was not included in the data analysis. The MF changes might also have been masked if ankle torque deviated from the 50% target value.

A potential limitation of our study was that the fatigue protocol induced LMF rather than whole-body fatigue, and the latter may have more external validity for sport-related injuries. The LMF protocol, however, provided a way to isolate fatigue of muscles that directly control the ankle and allowed us to control the level of exertion required of each participant. Exertions in the inversion-eversion directions may have had more relevance to ankle sprains, but pilot work suggested that these exertions were not well tolerated in the dynamometer configuration. In addition, fatiguing the ankle in PF-DF is likely more similar to the mode of fatigue development during sports because the plantar flexors and dorsiflexors are the primary movers for actions such as running and jumping. Mental fatigue and declining personal motivation during a fatigue protocol could have reduced physical performance.[31] However, positive oral encouragement was provided, and multiple MVICs were recorded at each observation time to minimize these effects. An a priori power analysis suggested that, to detect a between-groups strength difference of 5 Nm with 80% power given an SD of 10 Nm, the sample size in each group should be 9 or more. With 11 participants in each group, this study likely had sufficient statistical power, but including more participants could have helped to identify smaller effect sizes.

CONCLUSIONS

Exercising the ankle in PF-DF at equivalent levels of relative effort resulted in similar levels of fatigue development for adults with or without CAI. Furthermore, subjective perceptions of fatigue increased with fatigue development at comparable rates for both groups. We did not observe faster fatigue development or impaired perceptions of fatigue levels among adults with CAI.

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