

Ankle Mechanical Impedance Under Muscle Fatigue

by

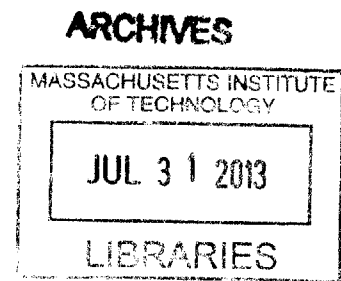
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ABSTRACT

This study reports the effects of ankle muscle fatigue on ankle mechanical impedance. It suggests that decreasing ankle impedance with muscle fatigue may contribute to an increased probability of ankle injury. If confirmed, this observation may have important athletic, military and clinical implications. The experiment was designed to induce fatigue in the tibialis anterior and triceps surae muscle groups by instructing subjects to perform isometric contractions against a constant ankle torque generated by a backdrivable robot, Anklebot, which interacts with the ankle in two degrees of freedom. Median frequencies of surface electromyographic (EMG) signals collected from tibialis and triceps surae muscle groups were evaluated to assess muscle fatigue. Using a standard multi-input and multi-output stochastic impedance identification method, multivariable ankle mechanical impedance was measured in two degrees of freedom under muscle fatigue. Results indicate that ankle mechanical impedance decreases in both the dorsi-plantarflexion and inversion-eversion directions under tibialis muscle fatigue. However, the effect of triceps surae on ankle mechanical impedance is uncertain since the current experimental protocol could not effectively induce fatigue in triceps surae.

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1. INTRODUCTION

Ankle dynamic behavior has been studied widely because of its impact on lower extremity function. Ankle mechanical impedance changes with varying force production and may also be expected to decrease with fatigue. Muscle fatigue reduces the maximal force muscle can produce [1]. Investigating ankle mechanical impedance under muscle fatigue will facilitate the design of ankle joint support systems and exoskeletons to compensate for fatigue, leading to potential applications in rehabilitation and the protection of the ankle in military and athletic scenarios.

Multi-variable static and dynamic ankle mechanical impedance in two coupled degrees of freedom (DOF) have been previously studied [8,10,15]. Ankle impedance in the dorsiflexion-plantarflexion (DP) direction coupled with the inversion-eversion (IE) direction are characterized, and ankle impedance has been shown to be weakest in the IE direction [8, 10]. In addition, muscle activation levels are linearly related to ankle mechanical impedance in the DP and IE directions [11]. However, no previous studies on the effects of muscle fatigue on multi-variable ankle mechanical impedance have been reported.

Muscle fiber conduction velocity is known to decrease as a result of fatigue during sustained muscle contractions, with multiple factors contributing to this phenomenon [2-4,13]. A direct consequence is a decrease in the frequency content of the measured surface electromyographic (EMG) signal. Thus, the median frequency of an EMG signal can be used to quantify the extent of fatigue [13]. Median frequency, defined as the frequency which divides the area under the power density spectrum in half, decreases over time. It typically exhibits a curvilinear behavior and is fit to an exponential curve [2, 13].

Many experiments have investigated muscle fatigue using isometric voluntary contractions [4,6,7]. These experiments report similar results about the changes of conduction velocity and median frequency; the rate of change of median frequency is greater than of conduction velocity [2].

In this study, we induced muscle fatigue over a short period of time using voluntary isometric muscle contractions against a constant torque applied to the tibialis anterior (TA) and triceps surae (TS) muscle groups in separate trials, where TS includes Soleus (SOL), and Gastrocnemius (GA). We analyzed the median frequency shift of the EMG signals during these sustained contractions to measure fatigue. This study contributes a new understanding of the relationship between multi-variable ankle mechanical impedance and muscle fatigue.

2. METHODS

2.1 Subjects

Twelve young subjects, with no history of neuromuscular disorders involving the ankle (5 females, 7 males; age 22-34; height 162-181cm; weight 49.3-73.0 kg) were recruited for this study. Informed consent was obtained as approved by MIT's Committee on the Use of Human as Experimental Subjects.

2.2 Experimental Setup

A wearable robot, Anklebot, and EMG sensors were attached to the subject's dominant leg to measure ankle impedance and muscle activities (Figure 1). Leg dominance was determined by using the subject's soccer-playing leg. The Anklebot (Interactive Motion Technologies, Watertown, MA, USA) applied random torque perturbations to the ankle in the DP and IE directions. To measure muscle activation levels, EMG surface electrodes (Delsys, Boston,

MA, USA) were attached to four primary muscles related to ankle dynamics: TA, Peroneus Longus (PL), SOL, and GA. The EMG signals were sampled at 1000 Hz, and their magnitudes were estimated by a root-mean-square method described in [17]. A visual feedback system presenting muscle activation levels was provided to help subjects to identify muscle activation levels. The specific Anklebot setup instructions were described in previously published studies from the author's group [8, 14].



Figure 1. The Anklebot and knee brace were attached on a subject in a standing position with the dominant foot clear of the ground.

2.3 Experimental Protocol

The experimental protocol contained two parts: ankle mechanical impedance measurement and muscle fatigue measurement. Ankle impedance was measured in the standing position; it was investigated under TA and TS fatigue. In order to obtain references for active muscle studies, the maximal voluntary contraction (MVC) level of each muscle, TA, PL, SOL, and GA was measured using the method recommended in [12].

In order to induce fatigue in both TA and TS in a short period of time, subjects were asked to perform isometric muscle contractions against a constant torque generated by the Anklebot. The targeted active muscles were TA and TS, since the TA acts to dorsiflex the ankle, and the TS acts to plantarflex the ankle. While seated, all of the subjects were asked to activate TA and TS to 50% of MVC for three repetitions, and each repetition lasted for two minutes continuously, following the method introduced in [2, 13]. If subjects could not maintain the constant 50% of MVC level for the entire two minutes period, we asked subjects to reach the maximal level they could maintain.

The subjects' ankle mechanical impedance were measured at three distinct times during the experiment: before muscle fatigue, immediately after fatigue, and once more after 15 minutes of recovery from fatigue. At each of these times, the impedance was measured under three conditions: active TA (20% of MVC), active TS (20% of MVC), and fully relaxed muscle conditions, respectively. Measurements were repeated twice in each case.

The Anklebot stiffness applied to TA activations was 1000 N/m, while to TS activations was 2000N/m. Positive Anklebot stiffness was applied to retain the ankle at a nominal neutral position. A larger value was set for the TS study since larger restoring torque was needed to oppose plantarflexion torque, which was typically greater than for the TA study.

2.4 Data Analysis Method

Median frequencies of EMG signals collected from TA and TS isometric contractions were evaluated and compared based on the power spectral density (PSD) using MATLAB PSD function [5], which transfers EMG signals in time domain to frequency domain. Median frequency, f_{median} , is the frequency at which half of the area under the PSD lies at lower frequencies and half at higher frequencies.

Welch's periodogram approach (MATLAB's pwelch function) was used to calculate auto-power spectral density. The number of points for the Fast Fourier Transform was set to 1024. A periodic Hamming window was used to provide 50% overlap of the window size, 0.5 s. EMG signals were analyzed in three sessions based on time: 1– 40s, 41 – 80s and 81– 120s. The median frequency of each session was calculated as

$$\int_0^{f_{median}} S(f) df = \frac{1}{2} \int_0^{f_s} S(f) df \quad (1)$$

where PSD is denoted as $S(f)$.

Ankle mechanical impedance was estimated by a standard non-parametric multi-input multi-output (MIMO) stochastic identification method [9]. Mild random white noise inputs (bandwidth 100 Hz) were applied to each actuator of the Anklebot for a duration of 40 seconds. Correlation based spectral analysis was applied to the time history of torques and corresponding angular displacements at the ankle joint to identify ankle impedance in two major directions: DP and IE. Torque and angular displacement signals were sampled at 1000 Hz. Details of ankle impedance identification methods were described in [8].

Jarque-Bera tests (MATLAB, jbtest function) were applied to find normality of data, and one-way ANOVA was used to calculate the differences of muscle activation level and impedance change between pre-fatigue, post-fatigue 1, and post-fatigue 2. Moreover, we used Tukey's honestly significant different (HSD) test for pairwise comparisons. Inter subject statistical tests were used to test relaxed and TA active studies for all of the subjects; intra subject statistical test was used to test TS active studies, since the impedance results under TS fatigue were different from each subject.

3. RESULTS

Ankle mechanical impedance was investigated under TA and TS muscle fatigue. Muscle activities and ankle mechanical impedance of all subjects were evaluated and compared, and the results showed that ankle mechanical impedance decreased under TA muscle fatigue in both IE and DP directions. However, the effects of TS muscle fatigue on ankle mechanical impedance were unclear.

3.1 Muscle Fatigue

Over the two-minute muscle fatigue experiment, we noticed that subjects could only maintain the target muscle activation levels, 50% of MVC for both TA and TS, for at most 90s. Thus, subjects activated their target muscles to the maximal levels they could maintain for the remaining 30s. One of these twelve subjects could only activate TS to 30% of MVC; therefore, TS muscle fatigue was evaluated at 30% of MVC for that subject.

The evaluation of median frequencies for EMG signals, collected from 1- 40s (Initial), 41-80s (Mid), and 81-120s (Final) of muscle isometric contraction, showed that median frequencies decreased over time, suggesting that muscles were fatigued in a short period of time. From Initial to Final, eleven (out of twelve) subjects showed median frequency decrease in EMG signals collected from TA muscles, while only seven (out of twelve) subjects showed median frequency decrease in TS muscle group. Therefore, median frequency results were averaged for eleven subjects for TA active study and seven subjects for TS active study. For each of the three trials that induced TA and TS muscle fatigue, Final median frequencies were lower ($p < 0.05$) than Initial median frequencies for both TA and TS (Figure 2).

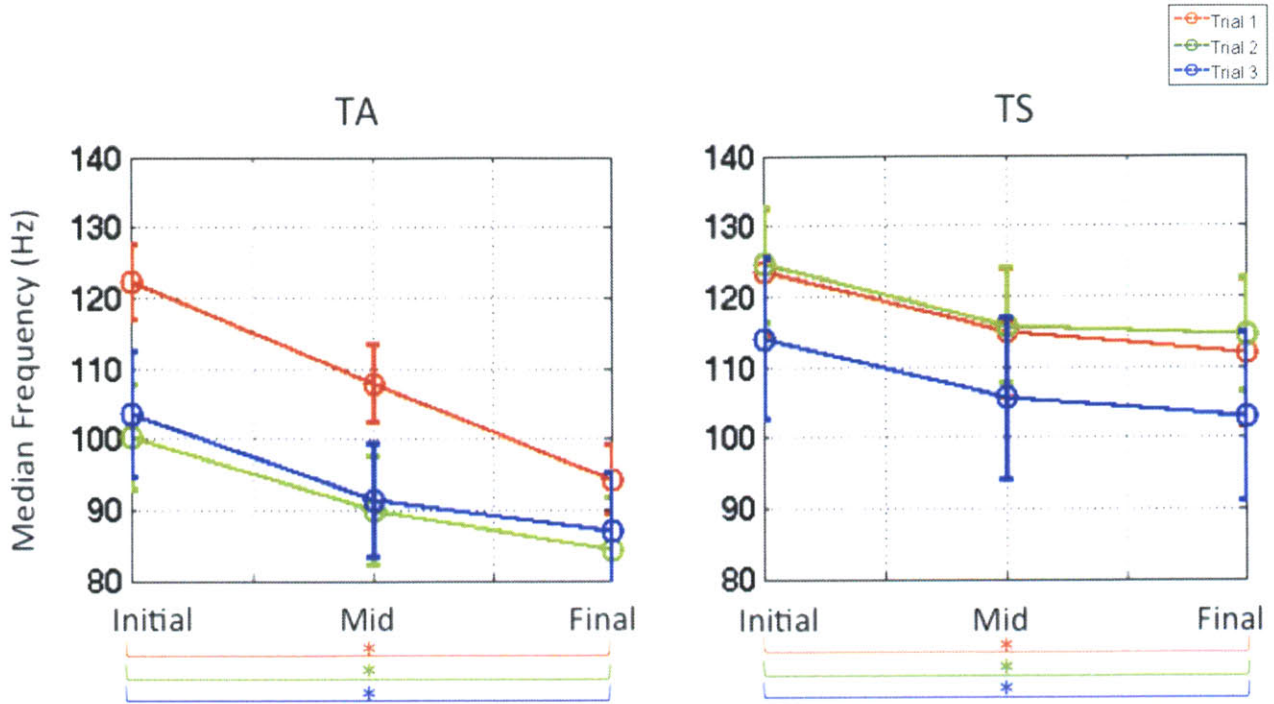


Figure 2. This figure represents the average median frequencies of eleven subjects who showed TA muscle fatigue and seven subjects who showed TS muscle fatigue. The three dots represent the average median frequency of EMG signals collected from the fatigue protocol, 1- 40s, 41 – 80s, and 81- 120s (Initial, Med, Final), respectively. The Final median frequencies (81-120s) are statistically ($p < 0.05$) different from the Initial median frequencies (1-40s), indicating the decreases of median frequency with time, suggesting TA and TS (GA and SOL) muscle fatigue.

3.2 Muscle Activity Consistency

To measure ankle mechanical impedance, we commanded a muscle activation level at 20% of MVC in all muscle active measurements. Activation levels were consistent before and after the muscle fatigue protocol for both target active muscles (TA or TS) and total measured muscles (TA, PL, SOL, and GA). Since activation of target muscles evokes activities in related muscles, it is necessary to show muscle activation consistency of the target active muscles as well as total measured muscles. To show this consistency, we calculated the ratios of post-fatigue (Post1 and Post2) to pre-fatigue (Pre) muscle activation levels. For all of the twelve subjects, the ratios were not statistically different from 1 ($p < 0.05$) for both targeting muscles (TA, Mean: 1.02 ± 0.04 ; TS, Mean: 1.02 ± 0.06) and total muscles (TA, Mean: 0.96 ± 0.07 ; TS, Mean: $0.95 \pm$

0.08), as shown in Table 2. Post1 represents the ankle impedance measurement right after muscle fatigue; Post2 represents the ankle impedance measurement 15 minutes after muscle fatigue.

Table 2. Ratio of post-fatigue to pre-fatigue muscle activation levels of Target muscles (TA, TS) and Total muscles (TA, PL, SOL, GA)

EMG 20% MVC	TA				TS			
	Target		Total		Target		Total	
	Post1/ Pre	Post2/ Pre	Post1/ Pre	Post2/ Pre	Post1/ Pre	Post2/ Pre	Post1/ Pre	Post2/ Pre
1	1.03	0.96	1.05	1.02	0.94	1.01	1.37	1.46
2	1.03	0.96	1.05	1.02	1.02	1.10	0.85	1.13
3	1.00	0.99	0.91	0.93	0.99	1.01	1.01	0.97
4	1.01	1.02	0.95	0.97	0.98	1.00	1.08	1.19
5	1.05	1.03	1.01	0.99	1.07	1.02	1.09	1.11
6	1.03	1.02	1.01	1.00	0.99	1.02	1.19	1.15
7	1.04	0.97	0.94	0.84	0.93	0.94	1.49	1.53
8	1.11	1.06	1.00	0.94	1.13	1.10	1.07	0.99
9	1.00	1.00	0.81	0.76	1.04	1.06	1.56	0.73
10	1.01	1.02	0.95	0.97	0.98	1.00	1.08	1.19
11	1.02	1.05	0.88	1.05	1.06	1.04	0.80	0.76
12	0.94	0.96	0.92	0.92	1.10	0.92	0.98	0.94
Mean	1.02	1.00	0.96	0.95	1.02	1.02	1.13*	1.10
SD	0.04	0.04	0.07	0.08	0.06	0.05	0.23	0.24

Ratios of muscle activation levels between post-fatigue (Post1 and Post2) to pre-fatigue (Pre) impedance measurements were evaluated in TA and TS active studies for both Target and Total muscles (all monitored muscles including TA, SOL, GA, and PL). The ratios are not statistically different from 1 ($p < 0.05$), indicating the consistency of muscle activation levels for TA active studies pre and post the fatigue protocol. However, the total muscle activity of TS Post1/Pre is statistically different from 1 ($p < 0.05$). * denotes statistically significantly different from 1.

3.3 Ankle Impedance

This study focused on static component of ankle mechanical impedance, so ankle mechanical impedance was quantified by averaging the impedance magnitude in low frequency region, from 0.5 to 5 Hz, where no impedance magnitude shifts have occurred. Impedance decreased ($p < 0.05$) under TA muscle fatigue; however, there are no significant impedance changes in relaxed and TS active studies ($p < 0.05$), as shown in Figure 3.

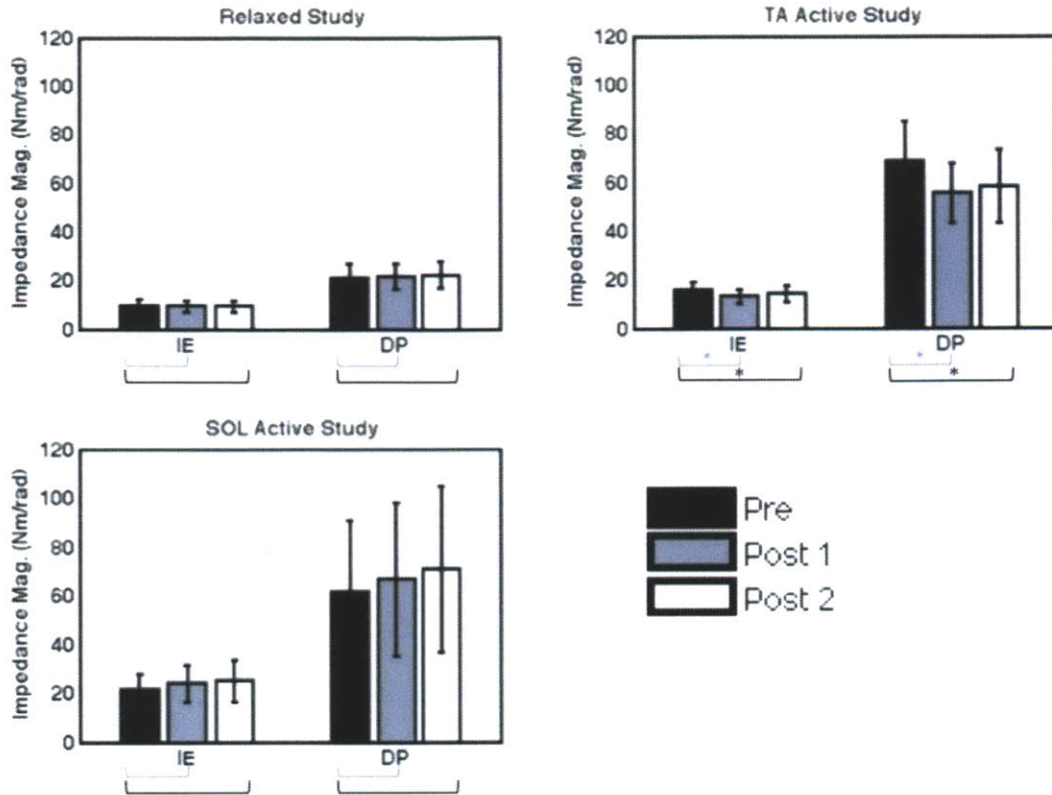


Figure 3. The figure represents ankle mechanical impedance of in pre-fatigue (Pre), post-fatigue1 (Post1), and post-fatigue2 (Post2), relaxed, TA, and TS studies respectively. For relaxed and TA studies, the impedance was calculated by averaging eleven subjects' impedance, who showed evident TA muscle fatigue; while for TS studies, the impedance was averaged for seven subjects who showed evident TS muscle fatigue.

Measured under the same muscle activation levels, it was clear that ankle mechanical impedance decreased under TA muscle fatigue; however, the change of ankle mechanical impedance was unclear under TS muscle fatigue. The ratios of ankle impedance measured from the post-fatigue protocol (Post1 and Post2) to the pre-fatigue protocol (Pre) were estimated in 2 DOF for both TA and TS. For ankle impedance under TA fatigue, the ratios were significantly ($p < 0.05$) less than 1 (DP, Mean: 0.82 ± 0.12 ; IE, Mean: 0.85 ± 0.13) for eleven out of twelve subjects, demonstrating that ankle mechanical impedance decreased under fatigue in both DP and IE directions (Table 3). Subject 4, whose TA muscle was not successfully fatigued, did not show ankle impedance decrease.

Moreover, ankle mechanical impedance measured after fifteen minutes of rest was lower than the pre-fatigue condition. Ratios of post-fatigue measurements 2 (Post 2) and post-fatigue measurements 1 (Post 1) to pre-fatigue measurement (pre) were similar, suggesting that muscles did not recover after fifteen minutes of rest (Table 3). No preferential change of impedance was found in the DP or IE directions.

Table 3. Ratio of post-fatigue ankle impedance under TA fatigue

Impedance	DP		IE	
	Post1/ Pre	Post2/ Pre	Post1/ Pre	Post2/ Pre
1	0.72	0.76	0.69	0.85
2	0.91	0.92	0.99	1.08
3	0.67	0.76	0.78	0.84
4	0.96	1.07	0.98	1.06
5	0.90	0.98	1.01	1.07
6	0.76	0.83	0.69	0.83
7	0.89	0.76	0.96	0.82
8	0.79	0.77	0.84	0.89
9	0.94	0.93	0.88	0.90
10	0.96	1.07	0.98	1.06
11	0.74	0.87	0.76	0.93
12	0.63	0.68	0.66	0.76
Mean	0.82*	0.87*	0.85*	0.92
SD	0.12	0.13	0.13	0.11

The ratios of ankle mechanical impedance at post fatigue measurement 1 (Post1) and 2 (Post2) to pre-fatigue (Pre) measurement for all subjects were averaged. The ratios are statistically less than 1 ($p < 0.05$) in both DP (Post1: 0.82 ± 0.12 , Post2: 0.87 ± 0.13) and IE (Post1: 0.85 ± 0.13 , Post2: 0.92 ± 0.11) directions, showing a clear ankle impedance decrease in two DOF under TA muscle fatigue. Subject 4 showed an increase in ankle mechanical impedance. * denotes statistically significantly different from 1.

For TS active studies, ankle mechanical impedances were calculated for those seven subjects who showed clear TS muscle fatigue evidence. Subject 3 showed ankle mechanical impedance decrease; the ratios (DP: 0.83 IE: 1.03) are significantly less than 1 ($p < 0.05$) in both DP and IE directions. Ankle mechanical impedance for the remaining six subjects did not decrease in both DP and IE directions; the ratios of post-fatigue impedance to pre-fatigue impedance were statistically no different from 1 ($p < 0.05$), as shown in Table 4.

However, the muscle activities for TS study were not consistent between post-fatigue and pre-fatigue protocols. Intra subject statistical tests indicated that all of the seven subjects showed some inconsistencies for both target and total muscle activities. The ratios were statistically different from 1 ($p < 0.05$). These inconsistencies may account for the change of ankle impedance change under TS muscle fatigue (Table 4).

Table 4. Ratio of post-fatigue ankle impedance under TS fatigue

Subject	Impedance				Muscle Activity			
	DP		IE		Target		Total	
	Post1/ Pre	Post2/ Pre	Post1/ Pre	Post2/ Pre	Post1/ Pre	Post2/ Pre	Post1/ Pre	Post2/ Pre
1	1.22*	1.14*	1.35*	1.00	0.94**	1.01	1.37*	1.46*
3	0.97	1.00	1.02*	1.10*	0.99	1.01	1.01	0.97**
6	0.83**	1.03*	0.95**	1.06*	0.99	1.02*	1.19*	1.15*
7	1.40*	1.53*	1.39*	1.46*	0.93**	0.94**	1.49*	1.53*
8	1.12*	1.14*	1.03*	1.19*	1.13*	1.10*	1.07*	0.99
10	1.01	1.10*	1.07*	1.19*	0.98	1.00	1.08*	1.19*
12	1.01	1.06*	0.99	1.02	1.10*	0.92**	0.98	0.94**
Mean	1.08	1.14	1.11	1.14	0.99	1.01	1.00	1.23
SD	0.18	0.18	0.19	0.16	0.01	0.01	0.02	0.33

The ratios of ankle mechanical impedance under TS muscle fatigue of post fatigue measurement 1 and 2 to pre-fatigue measurement for seven subjects and averaged. For six subjects, the ratios are close to or larger than 1 ($p < 0.05$) in DP and IE directions. Also, muscle activities are inconsistent for these seven subjects. ** denotes statistically lower than 1, and * denotes indifferent or statistically greater than 1.

4. DISCUSSION

Studying ankle mechanical impedance under rapid muscle fatigue has application to athletic, clinical, and military contexts. This study has investigated the effects of TA and TS muscle fatigue on ankle mechanical impedance in DP and IE directions. The results indicate that ankle mechanical impedance decreases under TA muscle fatigue; however, it is uncertain whether ankle mechanical impedance decreases under TS muscle fatigue, since the current experimental protocol could not reliably induce fatigue in the TS muscle group.

Our experiment effectively induced muscle fatigue in TA by isometric contractions. For all of the subjects, median frequencies of EMG signals collected from TA muscle activities during the fatigue protocol decreased over time, indicating that TA was fatigued successfully. This result agrees with the shift of median frequency under muscle fatigue calculated in EMG recordings [5]. Under TA muscle fatigue, ankle impedance decreased in all four principal directions, DP and IE.

Seven out of twelve subjects showed TS muscle fatigue. Among these seven subjects, only one subject showed a decrease of ankle mechanical impedance, with impedance ratios statistically less than 1; two subjects' ratios were no different from 1, while four subjects' ratios were greater than 1 at 95% significance level, showing an increase of ankle mechanical impedance. However, for some subjects, the muscle activation levels of post-fatigue 1 and post-fatigue 2 were higher than of pre-fatigue. The changes were significantly different from 1 ($p < 0.05$); it suggested that the TS impedance change may have resulted from increasing muscle activation levels. Therefore, from the current setup, since TS muscles were not fatigued very effectively, and muscle activations levels were not consistent between pre-fatigue and post-fatigue protocols, we can not draw any reliable conclusion about the effects of TS muscle fatigue on ankle impedance.

For future studies, new experimental protocols on inducing fatigue in TS muscle groups should be developed. Contracting TS to 50% of MVC may not be enough to induce fatigue. For Subjects 2, 5, and 11, the median frequencies of TS EMG even increased over time (Table 1). This increase may occur because the SOL needs time to warm up, since it has a larger proportion of aerobic muscle fibers compared to the TA [13]; this proportion suggests that it may be more challenging to induce fatigue in TS than in TA. Therefore, further investigation and a better

fatigue protocol need to be developed to induce fatigue in the TS muscle, such as increasing the isometric contraction level (from 50% to 70%) or increasing the activation time (from two minutes to three minutes).

As Table 1 shows, the study illustrated the consistency of muscle activation for both targeted muscles and all monitored muscles during ankle mechanical impedance measurement before and after the muscle fatigue protocol. Since activation of a single muscle normally involves activation of related muscles due to muscle synergy [16], estimation of total muscle activity is required to investigate the effect of muscle fatigue on the corresponding ankle mechanical impedance. Even when the target muscle activation levels were comparable across measurements, if the total muscle activations were significantly different, we may not conclude that impedance changes are due to muscle fatigue. The consistency of muscle activation levels before and after muscle fatigue eliminates the possibility that the observed impedance reduction was caused by changing muscle activation levels [11]. Indeed, this consistency confirms that muscle fatigue contributed to the decreases of ankle mechanical impedance.

From our data sets, we can see that subjects can maintain target muscle activation levels. However, with muscle fatigue, higher EMG amplitude is associated with the same force levels, and less force is associated with the same EMG amplitude. Therefore, the decrease of impedance may be due to the reduction of force at constant EMG levels. For future studies, we should design a complementary experiment in which we will ask subjects to maintain a constant force instead of constant muscle activation levels.

Fifteen minutes of rest was given to subjects to study the effects of muscle fatigue recovery on ankle mechanical impedance; however, the impedance of fatigued TA muscle was lower than it was in the pre-fatigued TA muscle (Table 2). This suggests that a longer period

may be needed for the muscle to recover from fatigue. Since the effect of TS muscle fatigue on ankle mechanical impedance was uncertain, we could not validate the recovery time of TS muscle. For future studies, we plan to explore the ankle mechanical impedance under muscle fatigue with various muscle recovery times.

This study showed ankle impedance decreases in both DP and IE directions under TA muscle fatigue. Decrease of ankle mechanical impedance may increase the probability of ankle injuries. Therefore, this finding may help to develop joint support systems to prevent ankle injuries caused by muscle fatigue.

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