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Differences in Force Gradation between Tug-of-War Athletes and Non-Athletes during Rhythmic Force Tracking at High Exertion Levels

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Abstract

There is little knowledge regarding the force production capacities of tug-of-war athletes, who undergo years of high-load strength training on handgrip muscles. The purpose of this investigation was to determine the force-grading strategies of tug-of-war athletes by examining force fluctuation properties at high exertion levels. Sixteen tug-of-war athletes and sixteen sedentary non-athletes performed sinusoidal handgrip grip at 50%-100% of maximal effort at 0.5 Hz under visual guidance. Force outputs of the designate task were recorded with a strain gauge. Force fluctuations were separated from the rhythmic output of the target rate in the handgrip force. In addition to a comparable normalized tracking error, the tug-of-war athletes exhibited a greater mean force output (Fmean) and a higher ratio of mean force output (Fmean) to body mass than the non-athletes. The athletes also had lower approximate entropy (ApEn) and a lower mean frequency of force fluctuations than the non-athletes, despite a similar relative size of force fluctuations for the two groups. The scaling of the fundamental element (force pulses) of force fluctuations was also group-dependent, with a greater pulse gain (duration-amplitude regression slope) than the non-athletes. The tug-of-war athletes exhibited superior force-generating capacity and more economic force-grading as compared with the non-athletes, without additional costs to task accuracy and force steadiness, during a highly-demanding rhythmic force task.

Key Words: force variability, isometric contraction, regularity

Introduction

In tug-of-war, athletes of two opposing teams pull on a rope until a mark on the rope crosses a central line. Powerful handgrip is one of the key elements for success in a tug-of-war contest (34). Therefore, the athletes are trained to increase their grip strength with high-intensity resistive exercises. In spite of potential strength gain (4), intriguingly, force-tuning capacity of the tug-of-war athletes is rarely investigated. Evidence from healthy and aged adults suggests an increase in force steadiness at low-force levels following resistance training for a short period (4 weeks) (16, 33), or with light loads (14). However, benefits of the training may not be replicable for tug-of-war athletes who receive long-term strength training using high-volume endurance. Alternatively, the athletes are suspected to exhibit coarser force grading than non-athletes due to training-specific remodeling of motor units (28), such as hypertrophy of a higher percentage

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of type II muscle fibers (9, 36). Especially at higher exertion levels, strength-trained individuals can exert a greater force at the cost of task precision, pertinent to exaggerated motor unit synchronization (8, 19, 20) and preferential recruitment of fast twitch motor units with more variable discharge rates (5, 27).

Inherent with numerous force pulses (21), a force profile can never be completely smooth. Owing to intermittent use of afferent information by the brain to counter feedback delays (21, 29), low-frequency force fluctuations below 3 Hz are functionally important to gain insight into force regulation of visually-guided force tasks (21, 29), as they are linked to processing capacity of visual information (31) and error-correction strategies to remedy trajectory deviations (2, 23). There are two important dimensions of force fluctuations: the size and the regularity. Typically indexed with standard deviation (SD), or coefficient of variation, the size of force fluctuations is a negative aspect of force precision control. The regularity of force fluctuations is indexed with entropy measures (11, 18, 32), pertaining to engagement of the use of sensory cues during tracking (15, 29). Task difficulty (2) and availability of visual information (12) are known to affect characteristics of low-frequency force fluctuations. Dynamic force-tracking that entails meticulous scaling of force outputs across various force levels exhibited larger force fluctuations with more complex on a low time scale than static force-tracking of a comparable exertion level (2). This observation revealed that dynamic force task is more demanding than static force task, involving a vast amount of intricate trajectory adjustments to satisfy the task needs. As compared to non-visual force-tracking, tracking with visual feedback adds to the complexity of force variability, underlying enhanced perceptual-motor information transmission (29).

On the account of the adaptive changes in muscular structure that implies coarser force grading of the tug-of-war athletes, it is of theoretical interest to reinvestigate the force fluctuation properties of the tug-of-war athletes, especially when they are vigorously challenged with dynamic force tasks at relatively high exertion levels. The purpose of this study was to compare the force-generation capacities of tug-of-war athletes and non-athletes, with a specific focus on the low-frequency force fluctuations associated with a rhythmic isometric handgrip (0.5 Hz sinusoidal wave) at high exertion levels (50%-100% maximal effort) with relatively rigorous time and target constraints. It was hypothesized that the basic force characteristics (mean force and tracking error) of the tug-of-war athletes were greater than those of the non-athletes, and that the force fluctuation properties (size, complexity, and spectral components) for the athlete group was greater than those of the non-athlete group. Our observations on group-dependent differences in low-frequency force fluctuations extend previous works to gain a better insight into adaptive changes in force-tuning capacity following long-term high-intensity strength training. Analysis of the restructures in force fluctuation dynamics in tug-of-war athletes can extend our understanding of the strengthening effects on force control properties.

Materials and Methods

Sixteen tug-of-war athletes (all males, age: 21.5 ± 0.6 years; weight: 82.1 ± 5.7 kg; height: 177.3 ± 4.1 cm) were recruited from two university teams to participate in this study. They had been involved in the sport of tug-of-war and had practiced daily for 1 to 7 years (5.6 ± 1.2 years). The tug-of-war athletes were from an elite team that had ever won the champions of 2014 Citizen Games in Taiwan and the 2014 Asia Games. Their counterparts were sixteen healthy male adults (age: 21.3 ± 0.6 years; weight: 64.4 ± 7.7 kg; height: 174.1 ± 3.3 cm) without regular exercise habits (< 1 h per week) from a local community and a university campus. All of the participants were self-reported as being right-handed, and none had symptoms or signs of neuromuscular diseases. The research project was approved by the Chung Shan Medical University Hospital Institutional Review Board, and all participants signed informed consents before the experiments conforming to the Declaration of Helsinki.

All participants completed a unilateral force-tracking protocol of isometric handgrip for three trials of 20 seconds, with 3-min inter-trial periods of rest. The participants reported no feeling of fatigue before each contraction trial to minimize fatigue effect. The subject sat on a chair with the left arm hanging naturally by the trunk and remained still while gripping a hand dynamometer (sensitivity: 0.01 N, bandwidth: DC–1 kHz, Model 9810P, Aikoh, Japan) connected to an analog amplifier (Model: PS-30A-1, Entran, UK). At the beginning of the experiment, all participants first performed 3 maximal voluntary contractions (MVC) of 3 seconds, separated by 3-min pauses. The maximal force for the 3 MVCs of handgrip was defined as the peak grip force. During the load-varying force-tracking, the participants were requested to couple grip force to the target signal (0.5 Hz sinusoidal wave in range of 50%-100% MVC) as precisely as possible without moving the wrist. A 22-inch computer monitor with a pixel resolution of 1680 × 1050 was used, and visual gain for the tracking task was the same for the athlete and non-athlete groups (10.5 pixels for 1% MVC). Visual feedback was provided to guide the force-tracking maneuver in the form of the force output of the hand-grip and the target curve displayed on the computer monitor. The target signal

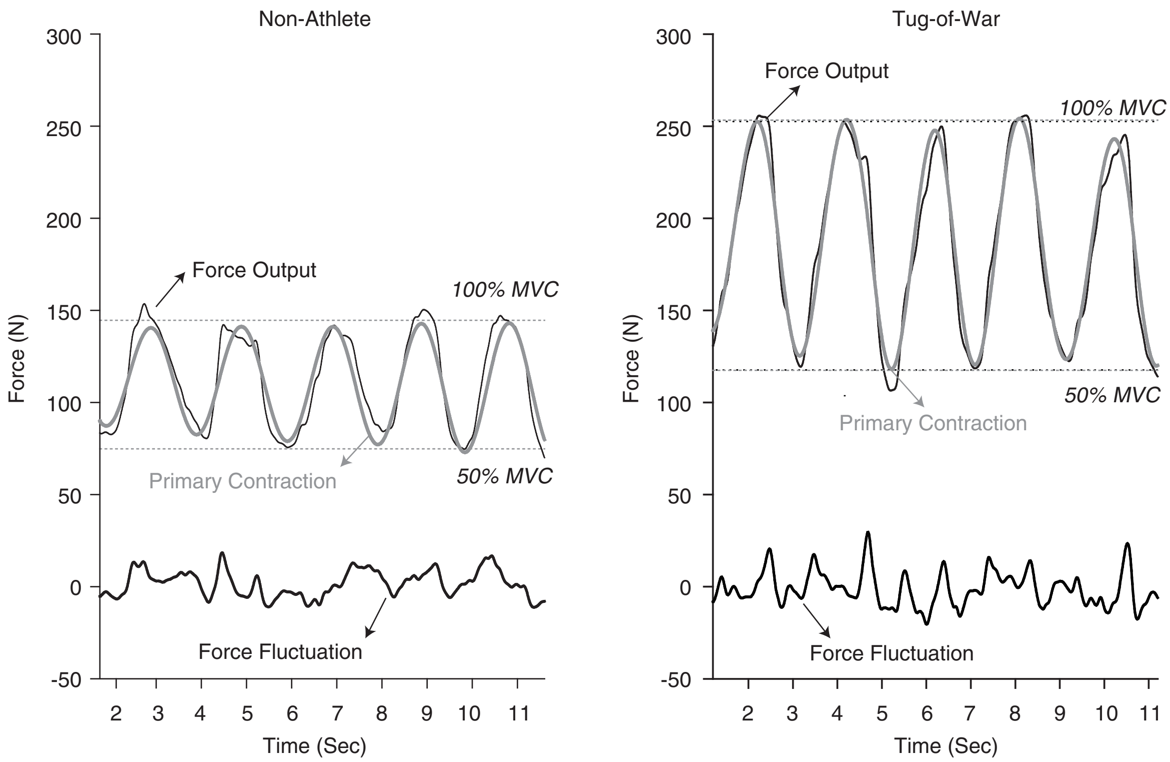

Fig. 1. Illustrative examples of force fluctuation profile and primary contraction from typical tug-of-war athlete and non-athlete groups. Force fluctuation profile (bold black line) was the force output (thin black line) subtracted from the sinusoidal primary contraction (grey line). Linear trend of force fluctuation profile (zero mean) was removed for further temporal and spectral analyses.

was used to challenge the slow and dynamic force-generating capacities across a spectrum of grip forces at high exertion levels. All signals were sampled at 1 kHz by an analog-to-digital converter with 16-bit resolution (DAQCard-6024E; National Instruments Inc., Austin, TX, USA), controlled by a custom program on a Labview platform (Labview v.8.5, National Instruments Inc., Austin, TX, USA).

To extract low-frequency force fluctuations, handgrip force output was first conditioned with a low-pass filter (cut-off frequency: 6 Hz) (2, 23). Hence, conditioned force output did not contain involuntary force tremors in the range of 8-12 Hz. The rationale was that only low-frequency force fluctuations reflect force gradation with the use of visual feedback loops to remedy tracking deviations. Three basic force characteristics, mean force output (F_{mean}), ratio of mean force output to body mass (F_{mean}/BM) and normalized tracking error were obtained from conditioned grip force. The F_{mean} was the mean level of grip force in an experimental trial. The F_{mean}/BM, F_{mean} divided by the body mass, was used to offset the potential influence of body weight on handgrip strength between athlete and non-athlete groups (34). The grip force output and the sinusoidal target signal were represented in terms of percentage of maximal effort (% MVC) of handgrip; normalized tracking error was defined as the root mean square (RMS) value of the mismatches between the normalized force output and the target signal. The normalization procedure of the error signals allowed for a comparison of force error between the two groups, even though maximal grip force could be a group difference.

The conditioned force output was dichotomized into two different force components, force fluctuations and primary contraction (Fig. 1) (2, 18). The force fluctuation profile was obtained by conditioning the force output with a zero-phasing notch filter that passes all frequencies except for a target rate at 0.5 Hz. The transfer function of the notch filter (H(z)) was $H(z) = b_0(1-e^{j\omega_0}z^{-1})(1-e^{j\omega_0}z^{-1})/(1-re^{j\omega_0}z^{-1})(1-re^{j\omega_0}z^{-1})$, r = .9975, $\omega_0 = \pi/360$. After that, the primary contraction was obtained by subtracting the handgrip force output from the force fluctuation profile. The force fluctuation profile was a relatively irregular component of gripping force, whereas the primary contraction was a regular component of target rate (0.5 Hz) that approximated the force profile of load-varying gripping in amplitude. For further analysis, the linear trend of the force fluctuation profile was removed such that the force fluctuation profile was zero-mean. Physically, the force fluctuations included all the force components of the grip force except for the target rate. The force fluctuation profile consisted of a number of individual

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force pulses, which are the major sources of force variability.

The standard deviation of the force fluctuation profile (STD_{FF}) was calculated to determine the absolute size of force fluctuations. The ratio of force fluctuations to the mean level of grip force ($R_{FF/Fmean}$) was denoted as the relative size of force fluctuations. The regularity of the force fluctuation profile was quantified with approximate entropy (ApEn) (11, 15, 17, 25). The force fluctuation profile was first normalized with the SD of the time series before calculation of ApEn. The general mathematical expression for ApEn is as follows:

$$-ApEn = \varphi_m + 1(\gamma) - \varphi_m(\gamma)$$

where φ_m is the average value of a natural logarithm for the regularity function of a given window length m = 2, and r is the tolerance level ($0.15 \times STD\_{FF}$) (24, 25). ApEn measures the logarithmic likelihood that runs of patterns that are close to each other for m observations (within tolerance r) will remain close on the next incremental comparisons. ApEn ranges from 0 to 2. An ApEn close to 0 represents greater periodicity (or regularity), while a value near 2 represents higher complexity of data. Mean frequency and spectral dispersion (spectral range between the 10th and 90th percentiles of the power spectra) were determined from the smoothed spectral profile of the force fluctuations following the Welch method and a fast Fourier transform (spectral resolution: 0.01 Hz).

The scaling of pulse-like elements in a force fluctuation profile was characterized with mean pulse amplitude, mean pulse duration and pulse gain. A local peak in the force fluctuation profile was defined as a force pulse, and individual force pulses were identified in a force fluctuation profile (Fig. 2A). The amplitude of each force pulse was the difference between a local maximum and the average value of the two nearest minima (2, 23). The pulse duration was the time between two successive local minima in the force fluctuation profile. The pulse amplitude and duration of each pulse were determined, and then the pulse amplitudes and pulse durations of all force pulses in a force fluctuation profile were averaged. Linear regression between the pulse duration and pulse amplitude in a force fluctuation profile provided a duration-amplitude regression slope (Fig. 2B) (23). The regression slope, referred to as pulse gain in the remainder of the article, represented the internal function of force pulse genesis that caused force fluctuations. Pulse gain of the three experimental trials was averaged across the participants for the two populations.

All force variables of the three trials were averaged for each subject of the two populations. Hotelling's T^2 statistics were used to compare variable

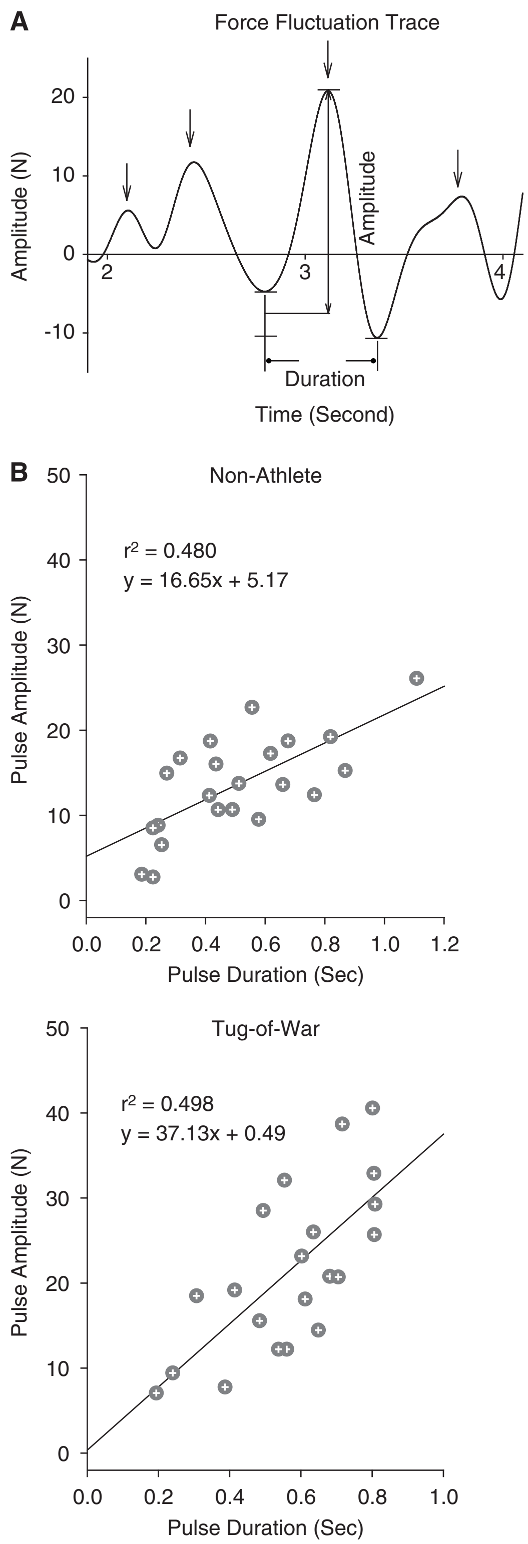

Fig. 2. Schematic illustration of force pulse variables (A) and representative scatter plots of pulse amplitude versus pulse duration in a single experimental trial for the athlete and non-athlete participants (B). The arrow signals in the force fluctuation profile indicate the local maxima of four individual force pulses in the time window. Pulse gain is defined as the regression slope of the amplitude-duration scatter plots.

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Table 1. The contrast of basic force characteristics, force fluctuation properties and force pulse variables between the tug-of-war athletes and non-athletes

		Non-athlete	Tug-of-war	Statistics
Force characteristics	F_{mean} (N)	117.8 ± 21.9	186. 5 ± 26.5†††	Λ = 0.231, P < 0.001
	F_{mean}/BM (N/Kg)	1.85 ± 0.35	2.31 ± 0.40†	
	Normalized tracking Error (%MVC)	16.49 ± 1.66	16.36 ± 1.74	
Force fluctuation	$STD_{\_FF}$ (N)	5.26 ± 1.11	7.86 ± 1.43†††	Λ = 0.319, P < 0.001
	$R_{FF/Fmean}$	0.046 ± 0.005	0.047 ± 0.007	
	ApEn	0.489 ± 0.016***	0.450 ± 0.025	
Force pulse variables	Mean amplitude (N)	9.20 ± 1.75	14.82 ± 2.41†††	Λ = 0.364, P < 0.001
	Mean duration (Sec)	0.462 ± 0.032	0.475 ± 0.034	
	Pulse gain (N/Sec)	23.84 ± 4.11	35.32 ± 6.17†††	

The data shown are mean ± S.E. F_{mean}, mean force output; F_{mean}/BM, ratio of mean force output to body mass; $STD_{\_FF}$, standard deviation of force fluctuations; $R_{FF/Fmean}$, ratio of the force fluctuations to mean force output; ApEn, approximate entropy; Pulse gain, amplitude-duration regression slope of force pulse. ***Non-athlete > Tug-of-war, $P \leq 0.001$; †Tug-of-war > Non-athlete, $P < 0.05$; †††Tug-of-war > Non-athlete, $P < 0.001$.

differences between the tug-of-war athletes and non-athletes in the following aspects: [1] force characteristics (F_{mean}, F_{mean}/BM, and normalized tracking error); [2]) force fluctuation properties ($STD_{\_FF}$, $R_{FF/Fmean}$, and ApEn); [3]) spectral parameters of force fluctuations (mean frequency and spectral dispersion); and [4]) force pulse variables (pulse amplitude, pulse duration, and pulse gain). The levels of significance for the Hotelling's T^2 statistics and *post-hoc* comparisons were 0.05 using Bonferroni correction. All statistical analyses were completed with the statistical package for Social Sciences (SPSS) for Windows v. 15.0 (SPSS Inc., USA). The graphing software was SigmaPlot 12 (Systat software Inc., USA).

Results

The Hotelling's T^2 test suggested a significant difference in basic force characteristics between the tug-of-war athletes and their counterparts (Λ = 0.231, P < 0.001) (Table 1). The athletes had a greater mean force output (F_{mean}) (P < 0.001) and ratio of mean force output to body mass (F_{mean}/BM) (P = 0.008) than the non-athlete participants. It was clear that the grip force of the tug-of war athletes was superior to that of the non-athletes, irrespective of body weight normalization. However, normalized tracking error did not differ between the athlete and non-athlete groups (P = 0.747), which implied similar tracking accuracy under visual guidance for both groups.

The results of the Hotelling's T^2 test to contrast the standard deviation ($STD_{\_FF}$), relative size ($R_{FF/Fmean}$), and regularity (ApEn) of force fluctuations between the athletes and non-athlete groups are also shown in Table 1. There were significant differences in force fluctuation properties between the two groups (Λ = 0.319, P < 0.001). The athletes had a larger $STD_{\_FF}$ (P < 0.001) and lower ApEn (greater regularity of force fluctuations) (P = 0.001) than the non-athletes. However, $R_{FF/Fmean}$ did not differ between the two groups (P = 0.691). The pooled power spectra of force fluctuations of the athletes and non-athletes, which contained no target frequency 0.5 Hz, are shown in Fig. 3A. The results of the Hotelling's T^2 test suggested significant group differences in the spectral features of the force fluctuations (Λ = 0.488, P < 0.001). The athletes exhibited a smaller mean frequency (P = 0.001) but a greater spectral dispersion (P < 0.001) of force fluctuations than the non-athletes (Fig. 3B).

The results of Hotelling's T^2 test suggested group differences in the scaling parameters of force pulse (Λ = 0.364, P < 0.001) (Table 1). The tug-of-war athletes exhibited greater pulse amplitude (P < 0.001) and pulse gain (P < 0.001) than their counterparts, though pulse duration did not vary significantly with the group (P = 0.479).

Discussion

The present study is the first to show that force-generating capacity and force gradation are different for tug-of-war and non-athlete groups at high exertion levels. The tug-of-war athletes had greater mean force output and less complex force fluctuations that occurred predominantly at low-frequency components to achieve dynamic target goals than their counterparts who led sedentary lifestyles.

Grip strength in tug-of-war athletes has not been systematically investigated in the literature probably because it is often regarded as an auxiliary function

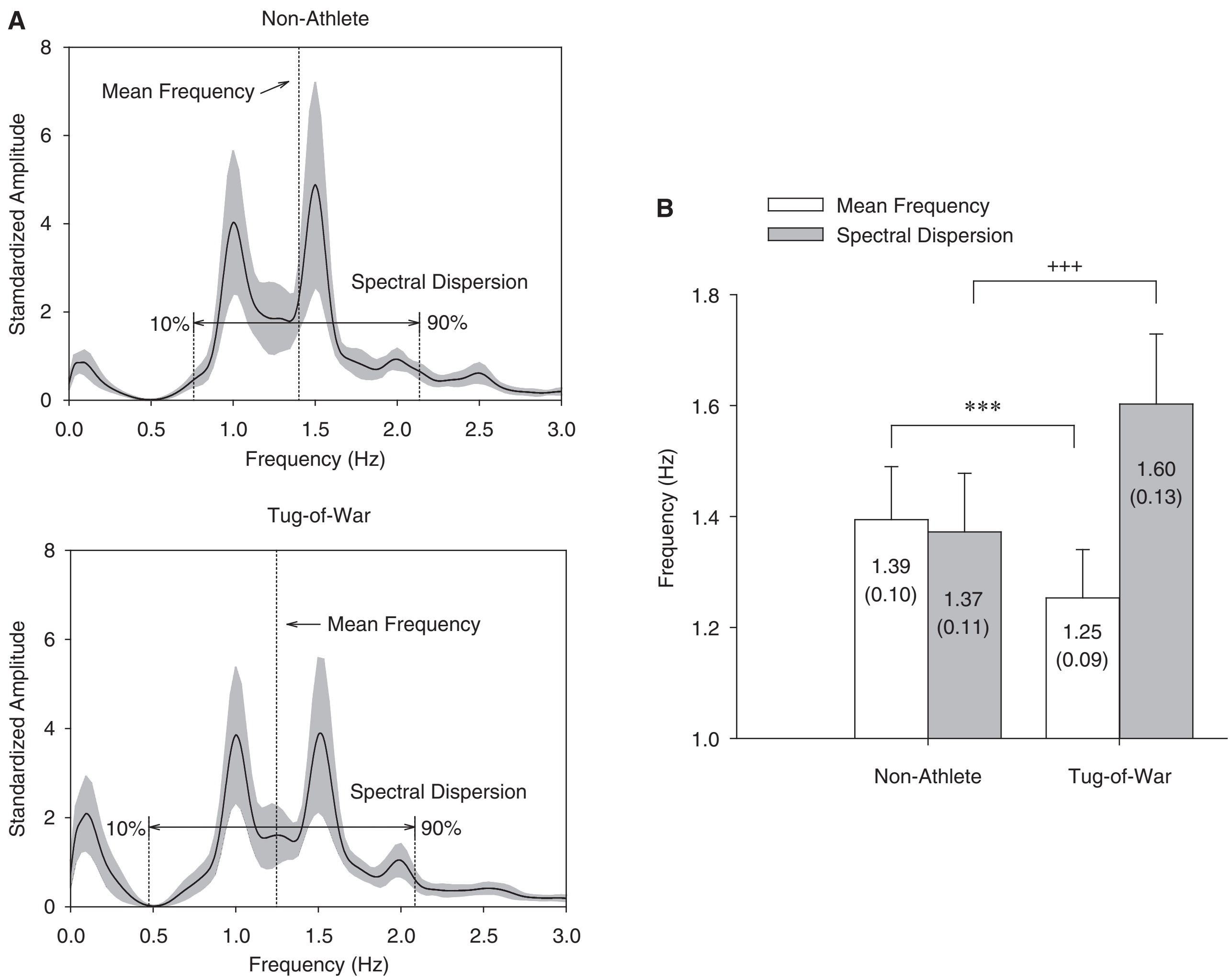

Fig. 3. Contrast of spectral features of force fluctuation profile between the athlete and non-athlete groups. (A) Pooled power spectra of force fluctuations. The shaded area of the spectral profiles represents a confidence interval of ± 1 SD. (B) The contrast of population means and SD of mean frequency and spectral dispersion of force fluctuations. (***Non-athlete > Tug-of-war, *P* ≤ .001; $^{+++}$Tug-of-war > Non-athlete, *P* < .001)

of the sport (34). Irrespective of mean force output (F_{mean}) and normalized grip strength (F_{mean}/BM), this study clearly revealed that the tug-of-war athletes had a greater force-generating capacity than the non-athletes (Table 1). Advantageous to overall tug-of-war performance, the greater grip force of the athletes was likely the result of routine resistance exercises, such as rope climbing without the use of the legs, to strengthen the rope grip. An athlete with greater grip strength resists better the pulling force of the opposing team by taking advantage of his or her body weight. Despite a marked strength gain in handgrip, there is a paucity of research concerning force gradation of tug-of-war athletes, who receive long-term strength protocols that may contribute to hypertrophy of type II fibers (9, 36). The amplitude-duration scaling of force pulse (Table 1) agrees with the trend of fiber-type transformation for the athlete group, as preliminary evidences have indicated that pulse amplitude and pulse gain multiply linearly with increases in the external force field during circular force-tracking (23). However, known neurophysiological evidences from motor unit research have implied that type II fiber transformation in athletes could be harmful to precise force gradation and force steadiness, such as enhanced motor unit synchronization (8, 20) and preferential recruitment of fast type motor units with a more variable discharge at relatively high force levels (5, 27). Contrary to expectations, our results suggested that normalized tracking error and $R_{FF}/_{Fmean}$, functionally connected to the magnitude of error correction relative to that of primary movement (Table 1), were not subject to group effects. Hence, force gradation and force steadiness may not be affected by long-term high-intensity resistance training in tug-of-war athletes. This observation is largely compatible with the study of Smits-Engelsman *et al.*

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(30), who reported an insignificant adaptive change in the relative size of force fluctuations (signal-to-noise ratio) for trained young men. However, it is worth noting that young men in the previous study received only low-intensity strength training with free-weight exercises, and force fluctuations were assessed with static isometric contraction at relatively low force levels (6-60% MVC). The tug-of-war athletes in the present study were heavily trained and assessed with a force task with a complex nature because a dynamic force task usually exhibits a more vigorous force-grading challenge than a static force task (2, 6). On the other hand, strength training in the tug-of war athletes did not contribute to greater force steadiness, as reported in aged adults following strengthening with light or heavy weights (16). Hence, it is prudent to conclude a strengthening effect on force steadiness, which depends interactively on the training paradigm, exercised muscles and population.

The tug-of-war athletes in the present study appeared to use a different force-tuning approach to achieve the targeted goal during the high-intensity rhythmic force task. The athletes exhibited force fluctuations of enhanced lower-spectral components (Fig. 3B) and lower ApEn (Table 1) than the non-athletes. Granting that low-frequency fluctuations for a visuomotor task are related to an additive accuracy control mechanism to remedy trajectory deviations with a visual feedback loop (17, 21), the athletes appeared to use less frequent and simpler trajectory adjustments than the non-athletes. There are several possible explanations for the force-grading simplification of the athletes with respect to the smaller amount of information in the error correction profile. The athlete might have relied less on the feedback process *via* visual or proprioceptive input, such that the number of error correction attempts was reduced during the rhythmic force-tracking task. The arguments gain empirical support from very similar dimensional changes in force fluctuations (a larger absolute size of force fluctuations with smaller complexity, as shown in Table 1) under the condition of force-tracking without sufficient visual spatial information (3, 15). Alternatively, strengthen training is known to increase neural drive (7, 10) or attenuate short-interval intracortical inhibition for voluntary movements (35), as evidence for enhanced neural economy. For the altered sensitivity of inhibitory control over the cortical and spinal neurons, it is possible to achieve a target force with fewer motoneurons for a trained muscle (1) as well as to reduce discharge rate variability for a rhythmic force-tracking task (6, 13). Therefore, coordination of fewer motor units with reduced discharge variability might contribute to complexity reduction in force fluctuations for the athletes. However, the present experimental design cannot confirm the exact neural mechanisms underlying expertise-related force gradation for tug-of-war athletes.

There is an important methodological issue in this study. Force characteristics was contrasted between the athlete and non-athlete groups, which exhibited a marked group difference in body weight. However, it is questionable to compare force characteristics between the athlete and non-athlete groups with equivalent body weight because the non-athletes without regular exercise habits must have more fat tissue but less muscle tissue than the tug-of-war athletes, if they had a similar body weight. The Body Mass Index (BMI)-related errors in obesity (22, 26) raise another critical issue for comparison of force generation capacity between the athlete and non-athlete inherent with body weight difference. A compromised approach was to normalize force output with body weight (30), despite this approach was not completely ideal. The best manner of normalization in this study remains to be elucidated.

In addition to the superior force-generating capacity, this study reveals the economic force gradation strategy of tug-of-war athletes, who undergo many years of high-intensity strength training. Tug-of-war athletes are able to use simpler force-tuning to meet task demands without sacrificing force accuracy and force steadiness for a high-intensity dynamic force task. However, the effect of strength training on force fluctuations in tug-of-war athletes differs from that previously reported in aged adults, who can reduce force fluctuations after strength training. It seems that the strengthening benefit on force variability reduction is only possible for weakened muscles.

Acknowledgments

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