DORSIFLEXOR AND PLANTARFLEXOR TORQUE-ANGLE AND TORQUE-VELOCITY RELATIONSHIPS OF CLASSICAL BALLET DANCERS AND VOLLEYBALL PLAYERS

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Resumo: O objetivo desse estudo foi comparar as relações torque-ângulo e torque-velocidade e a ativação dos músculos flexores plantares e dorsiflexores entre bailarinas clássicas (n=14) e atletas de voleibol (n=22). O pico de torque dos flexores plantares e dorsiflexores foi avaliado durante contrações voluntárias máximas isométricas nos ângulos de -10°, 0°, 10°, 20°, 30°, 40° e 50°, e durante contrações concêntricas nas velocidades angulares de 0°/s, 60°/s, 120°/s, 180°/s, 240°/s, 300°/s, 360°/s e 420°/s. Sinais eletromiográficos (EMG) de superfície foram obtidos dos músculos gastrocnêmio medial, sóleo e tibial anterior. A amplitude de movimento de dorsiflexão foi semelhante entre os grupos, enquanto bailarinas apresentaram maior amplitude de flexão plantar do que atletas de voleibol. Enquanto nos músculos flexores plantares a relação torque-ângulo das bailarinas deslocou-se para a esquerda quando comparada à das atletas de voleibol, nos flexores dorsais ela se deslocou para a direita nos menores comprimentos musculares. Os torques normalizados em todas as velocidades de flexão plantar e dorsiflexão foram mais elevados nas bailarinas do que nas atletas de voleibol. Os sinais EMG do gastrocnêmio medial e do sóleo permaneceram aproximadamente constantes entre os diferentes ângulos articulares nas bailarinas, mas diminuíram com a redução no comprimento muscular no caso das atletas de voleibol. Os sinais EMG do tibial anterior aumentaram com a redução dos ângulos do tornozelo em ambos os grupos. Os sinais EMG dos dorsiflexores nas diferentes velocidades angulares foram semelhantes nos grupos, enquanto os sinais EMG do sóleo e do gastrocnêmio foram mais elevados nas bailarinas comparados aos das atletas de voleibol. As adaptações dos flexores plantares podem ser explicadas por alterações musculares intrínsecas e alterações na ativação voluntária máxima, enquanto para os músculos dorsiflexores somente mudanças nas propriedades intrínsecas parecem explicar os resultados observados. Os torques relativos mais elevados das bailarinas comparados aos das atletas de voleibol são provavelmente resultantes da ativação aumentada dos flexores plantares e de um maior comprimento de fibra dos dorsiflexores.

Palavras-chave: propriedades mecânicas musculares, eletromiografia, ballet clássico, voleibol.

Abstract: The purpose of this study was to compare the torque-angle and torque-velocity relationships, and the electromyographic (EMG) activity of the plantar- and dorsiflexor muscle groups of classical ballet dancers (n=14) and volleyball players (n=22). Peak torques of the ankle plantar- and dorsiflexor muscles were evaluated for maximal voluntary isometric contractions performed at seven different ankle angles (-10°, 0°, 10°, 20°, 30°, 40°, 50°) and for maximal effort, concentric, voluntary contractions performed at angular velocities of 0°/s, 60°/s, 120°/s, 180°/s, 240°/s, 300°/s, 360°/s and 420°/s. Bipolar surface EMG signals were obtained from gastrocnemius medialis, soleus and tibialis anterior muscles, and ankle range of motion was measured with a goniometer. The range of motion for dorsiflexion was the same for both groups, while ballet dancers had a greater range for plantarflexion than volleyball players. For the plantarflexor muscles, the torque-angle relationship was shifted to the left for the ballet dancers compared to the volleyball players, while for the dorsiflexor muscles it was shifted to the right for short dorsiflexor lengths. The normalized torques at all speeds of plantar- and dorsiflexion were greater for the ballet dancers than the volleyball players. The gastrocnemius medialis and soleus EMGs remained nearly constant across all angles for the ballet dancers, but decreased with decreasing muscle length in the volleyball players. The tibialis anterior EMGs increased with decreasing ankle angles in both groups. The normalized dorsiflexor EMGs were the same for both groups across all speeds, while the EMGs for soleus and gastrocnemius were significantly greater for the ballet dancers than the volleyball players. These results support the idea that systematic physical activity changes the in vivo torque-angle and torque-velocity relationships in accordance with functional demands. The greater relative torques for the ballet dancers than volleyball players are likely caused by the increased activation of the plantarflexors and an increased fiber length for the dorsiflexors.

Keywords: muscle mechanical properties, electromyography, classical ballet, volleyball.

INTRODUCTION

It is widely known that skeletal muscles adapt to their mechanical environment. Increased muscle use is shown to cause muscle hypertrophy, whereas reduced muscle use leads to muscle loss or atrophy. However, the chronic changes in the mechanical properties of muscles as a result of chronic training are not completely understood.

It has been suggested that torque-angle relationships may differ substantially in subjects who use muscle groups differently according to specific chronic training [e.g. Kitai and Sale 1989; Herzog et al. 1991]. Assuming that the moment arm geometry does not change with chronic training, and there is no systematic difference across groups of athletes, differences in the torque-angle relationships must be associated with changes in the intrinsic force-length relationships of the synergistic muscles, and/or changes in maximal voluntary activation as a function of joint angle.

The torque-velocity relationship is also affected by training [Moffroid and Whipple, 1970; Lesmes et al., 1978]. For example, sprinters and athletes in high power events show higher torques at increasing speeds of contraction compared to long distance runners or endurance athletes [Johansson et al., 1987; Taylor et al., 1991].

The purpose of this study was to compare the plantarflexor and dorsiflexor torque-angle and torque-velocity relationships for two special populations: classical ballet dancers and volleyball players. Classical ballet dancers use the plantarflexors mostly in a shortened and the dorsiflexors in a lengthened position when maintaining whole body weight on the tip of their toes, while volleyball players use the same muscles mostly in a dorsiflexed position. In addition, ballet dancers show increased ankle plantarflexor flexibility compared to normal subjects [Hamilton et al. 1992; Wiesler et al. 1996], while the active range of ankle motion of volleyball players is similar to that of the normal population [Richards et al., 2002]. These different functional demands change the mechanical environment of muscle groups, and may change the mechanical properties of these muscles within each training or athlete group.

METHODS

Thirty-six female subjects (ballet dancers = 14; volleyball players = 22) gave written informed consent to participate in this study. The Ethics Committee of the University approved all experimental procedures. Classical ballet dancers had at least eight years of training (with a minimum of two daily hours of practice, five times a week), and volleyball players had an average of five years of experience (with a minimum of four daily hours of practice, three times a week).

Range of Motion

The active range of plantar- and dorsiflexor motion was evaluated with a goniometer. The 0° reference angle was defined with the foot perpendicular to the shank axis. Plantarflexion was defined positive.

Torque

Peak torque of the plantar- and dorsiflexor muscles was evaluated for maximal voluntary isometric contractions obtained at seven different ankle angles (-10°, 0°, 10°, 20°, 30°, 40°, 50°) and for maximal voluntary isokinetic contractions at eight nominal angular velocities (0°/s, 60°/s, 120°/s, 180°/s, 240°/s, 300°/s, 360°/s, 420°/s) using a Cybex Norm (Lumex & Co., Ronkonkoma, New York, USA) isokinetic dynamometer. All subjects performed a series of submaximal contractions at different ankle angles and angular velocities for warming up and familiarization with the dynamometer prior to the tests.

Subjects were placed in a prone position on the dynamometer chair. The right foot was fixed onto a footplate by Velcro straps. The ankle joint axis, defined by a line connecting the lateral and medial malleolus, was aligned with the machine's axis of rotation. Subjects performed a maximal voluntary isometric contraction with the ankle joint positioned at seven different angles: -10°, 0°, 10°, 20°, 30°, 40°, and 50°. Three maximal voluntary contractions were performed at each of the eight test velocities. Subjects were instructed to reach their maximal force in approximately one second, and to hold the maximal effort for at least one more second before relaxing. If subjects felt that the contraction was not maximal, or if the contraction was not maintained for at least one second, the test was repeated. The order of the joint angles and of the angular velocities was randomly assigned for each subject, and two-minute intervals were observed between contractions to avoid fatigue. At the end of the entire protocol, the first trial was repeated to assess the possible effects of fatigue.

Electromyographic Signals

Bipolar surface electromyographic (EMG) signals (AMT-8, Bortec Biomedical, Canada) were obtained from the gastrocnemius medialis, soleus and tibialis anterior muscles. The skin underneath the recording electrodes was prepared using standard procedures [e.g. Basmajian and De Luca, 1985]. Electrodes were placed on the distal third of the muscles, along the approximate direction of the muscle fibers. A ground electrode was placed on the skin over the tibia. EMG signals were recorded at a frequency of 2000 Hz using Windaq data collection (16-bit resolution, $\pm$10 Volts) and playback software (Dataq Instruments, Akron, OH, USA), and stored on a Pentium (200MHz) personal computer.

Data Analysis

EMG data were extracted for segments of one second from the plateau (middle) region of the isometric torque signals for each of the seven joint angles. From the three maximal isokinetic voluntary contractions, the contraction with the highest torque was selected for data analysis. EMG data were extracted for the entire concentric contractions. EMG signals were band-pass filtered using cut-off frequencies of 3Hz and 800 Hz, and root mean square (RMS) values were calculated.

Means and standard errors of the torques and of the RMS values at each joint angle and speed were calculated for the ballet dancers and volleyball players.

After determining the joint angle at which peak torque was achieved for each group, torque and RMS values were normalized for each subject relative to the torque and RMS values obtained at that angle. For the dorsiflexor torque-angle relationship, which showed an ascending and descending part, the ankle angle of maximal torque was determined by fitting Gaussian curves to the torque values above 75% of maximum and differentiating the torque-angle curve with respect to the angle and identifying the unique angle of zero slope [Jones et al. 1997; Talbot and Morgan 1988; Whitehead et al. 2003].

Torques and RMS values were also normalized with respect to the maximal isometric contraction for the concentric contractions.

In order to compare the torque and RMS values of the plantar- and dorsiflexors between the two groups across all ankle angles and all angular velocities, a two-way (group, angle/velocity) analysis of variance for repeated measures (angle/velocity) was performed. When a significant interaction was observed, post-hoc analyses were performed with Newman-Keul's test. One-way analysis of variance for repeated measures was used to determine statistical differences between the first and last trials to test for fatigue effects. One-way analysis of variance was used to determine differences in the joint range of motion between the two groups. A 0.05 level of significance was adopted for all tests.

RESULTS

Ballet dancers showed a greater plantarflexor range of motion than the volleyball players (p<0.001, Figure 1). The dorsiflexor range was similar for both groups. The total range of motion for the ballet dancers was greater than that for the volleyball players (p<0.001).
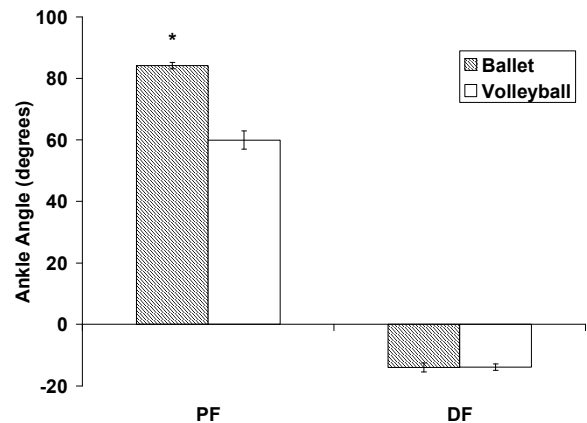

Figure 1. Plantarflexor and dorsiflexor ankle joint range of motion of classical ballet dancers and volleyball players (PF = plantarflexion; DF = dorsiflexion; *=p<0.05). Mean values and standard errors correspond to both right and left ankle joint range of motion for each group.

Torque and Angle Relationship

The plantarflexor torque-angle relationship was different between the two groups (p<0.001; Figure 2A). Maximal torque increased continuously with decreasing plantarflexion (or increasing muscle length) for the volleyball players, while ballet dancers reached a plateau between 0° to -10°. Ballet dancers had consistently higher relative torque values compared to the volleyball players for all ankle angles studied, except of course, at an ankle angle of -10° which was defined as 1.0 for both groups.

The torque-angle curve for the dorsiflexor muscles had a similar shape for the two groups of athletes. However, volleyball players were able to produce relatively higher torques at short dorsiflexor muscle lengths (i.e. ankle angles between -10° and 10°) compared to ballet dancers (p<0.05; Figure 2B). There was no shift of peak torque occurrence in the dorsiflexor torque-angle relationships between the two groups.

Torque-Velocity Relationship

The normalized torque for plantarflexors and dorsiflexors as a function of ankle angular velocity is shown in Figure 3. Plantarflexor torque was the same for the two groups at all angular velocities (Figure 3A). Dorsiflexor torque was greater in ballet dancers than in volleyball players at angular velocities of 120°/s and greater (Figure 3B).
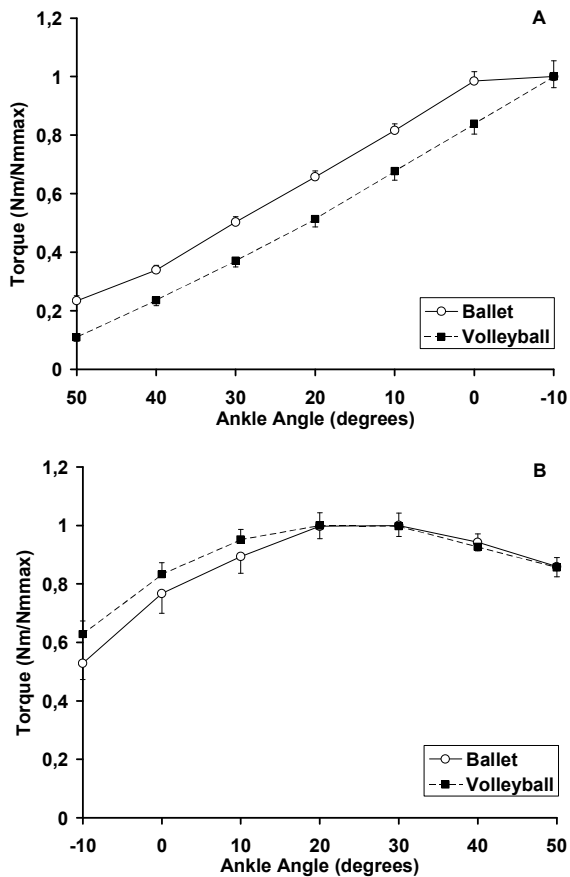
Figure 2. Plantarflexor (A) and dorsiflexor (B) torque-angle relationship of classical ballet dancers and volleyball players. Torque values were normalized relative to the peak torque value of each group (mean ± S.E.).

Muscle Activation

EMG activity of the gastrocnemius medialis decreased with decreasing plantarflexor angles in the ballet dancers, and it increased in the volleyball players (Figure 4A). The normalized RMS values of soleus remained about constant across ankle angles for ballet dancers, and increased with decreasing plantarflexor ankle angles (decreasing muscle length) for the volleyball players (Figure 4B).

There was an increase in the normalized RMS values of the tibialis anterior muscle with decreasing muscle length for both groups (Figure 5).

Root mean square values of the gastrocnemius and soleus EMGs for the ballet dancers were greater than for the volleyball players (Figures 6A and 6B, respectively), while the values for tibialis anterior were the same (Figure 7).

The initial and final torque and EMG values (of plantar- and dorsiflexors) were similar for all subjects of both groups, indicating that fatigue did not affect the results.
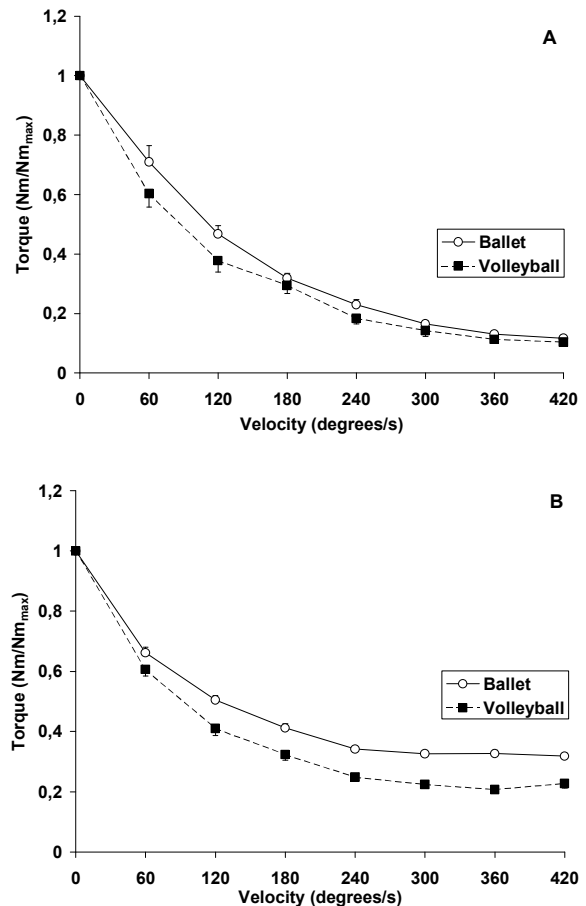

Figure 3. Plantarflexor (A) and dorsiflexor (B) torque-velocity relationships of classical ballet dancers and volleyball players. Torque values (mean ± S.E.) were normalized relative to the peak torque value of each group.

DISCUSSION

Torque-Angle Relationship

A primary purpose of this study was to compare the torque-angle relationship of two distinct groups of athletes (classical ballet dancers and volleyball players) with different demands for the ankle joint muscles. Female ballet dancers often work with the ankle in a hyper-extended position, while volleyball players use the ankle joint for jumping within a "normal" range of motion. The results obtained in this study support the hypothesis that chronic training changes the torque-angle relationship.
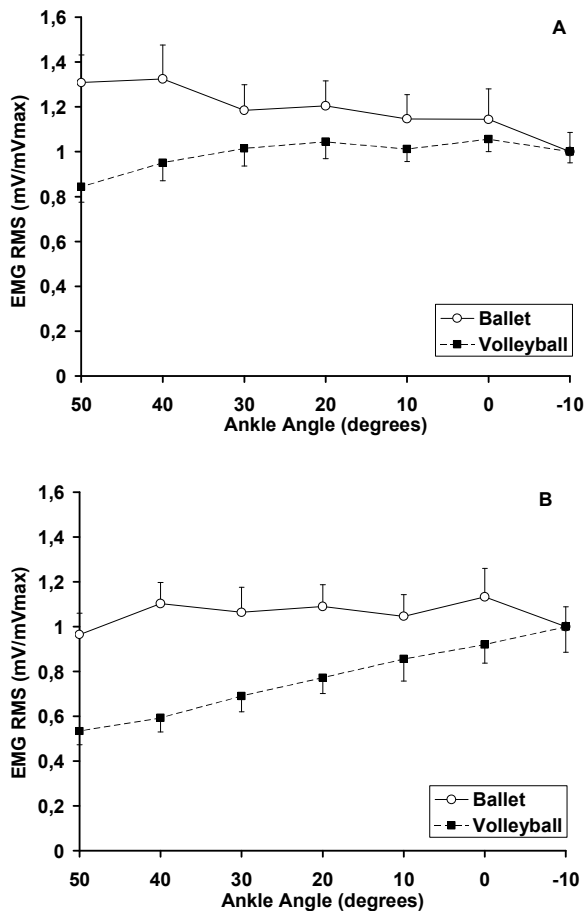
Figure 4. RMS values (mean ± S.E.) of the EMG signal of gastrocnemius medialis (A) and soleus (B) muscles at the seven different ankle joint angles. RMS values were normalized relative to the RMS value obtained at the contraction of highest torque for each subject.

Plantarflexion

The ballet dancers had a greater plantarflexor range of motion than the volleyball players. The dancers were also stronger at short plantarflexor lengths, and had greater levels of activation at short plantarflexor lengths. The ballet dancers reached the plateau of the torque-angle relationship at the longest muscle lengths tested. These results might be explained in different ways, but it is tempting to speculate that ballet dancers may have a smaller number of sarcomeres arranged in series in their plantarflexor fibers. If this was indeed the case, each individual sarcomere would be longer for a given muscle length.

The results obtained in this study are conceptually the same as those obtained by Herzog et al. [1991] for the force-length relationship of the rectus femoris in high performance runners and cyclists. Because of the flexed hip angle in cycling, cyclists use the rectus femoris at a chronically shortened length compared to the runners. In accordance with this

specific chronic use, cyclists' rectus femoris was strong at short and weak at long muscle lengths while the reverse result was found for runners.
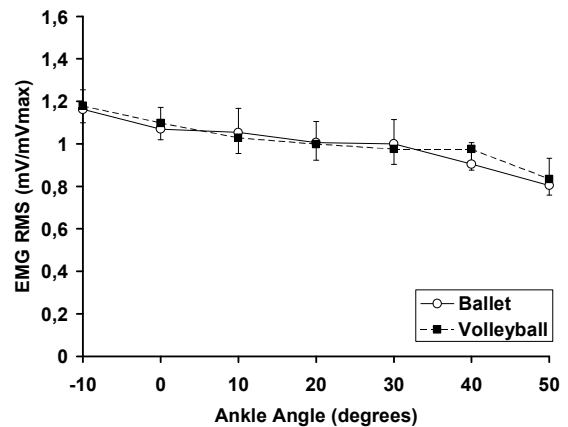

Figure 5. RMS values (mean ± S.E.) of the EMG signal of tibialis anterior muscle at the seven different ankle joint angles. RMS values were normalized relative to the RMS value obtained at the contraction of highest torque for each subject.

Dorsiflexion

The dorsiflexor range of motion and muscle activation values were similar between ballet dancers and volleyball players. However, compared to the ballet dancers, the volleyball players were relatively stronger at short dorsiflexor lengths (i.e. from -10° to 10°).

This increased torque production for the volleyball players cannot be explained by an increase in muscle activation, as the tibialis anterior EMG was similar between the two groups, suggesting that the increased torque in the volleyball players at short dorsiflexor lengths is associated with changes in muscle properties. One possible explanation is that although there is no shift in the ankle angle at which peak torque occurs, there is a significant shift of the torque-angle relationship at short muscle lengths (i.e., a shift of the ballet dancers' torque-angle relationship to the right).

Torque-Velocity Relationship

The relative torques of ballet dancers were greater than the torques of volleyball players at speeds of dorsiflexion of 120°/s and above, while EMGs in dorsiflexion were similar for the two groups of athletes. The torque-velocity relationships for plantarflexion were similar, although there was an increase in the relative EMG of the plantarflexors of the ballet dancers at all speeds.

Plantarflexion: The similarity in the normalized plantarflexion torque values between the two groups was expected. This result is intuitively appealing as the range of motion in dorsiflexion, which determines the amount of stretch of the plantarflexor group, is similar

between the two groups, and therefore differences in fiber length should not be expected.
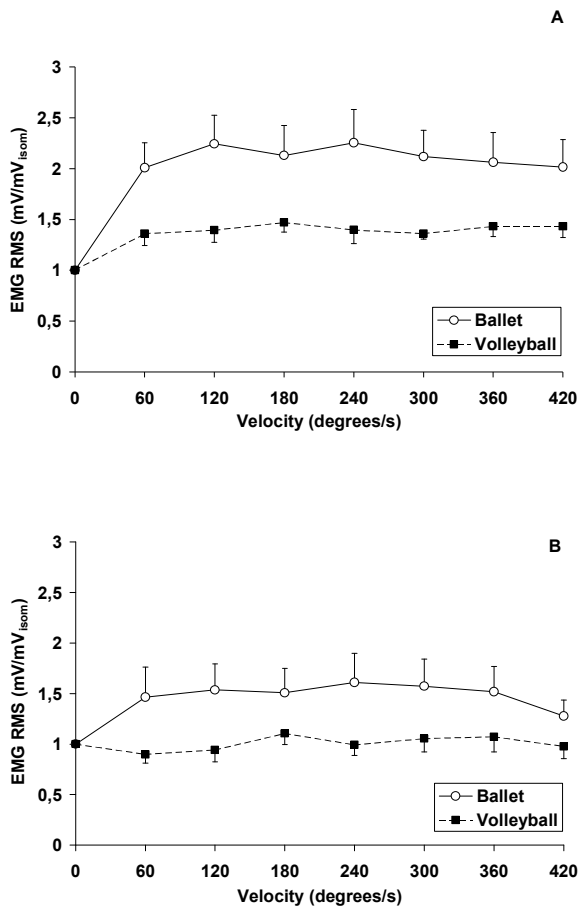

Figure 6. RMS values (mean ± SE) of the gastrocnemius medialis (A) and soleus (B) muscles at different angular velocities. RMS values were normalized relative to the RMS value obtained at the contraction of highest torque for each subject.

Figure 7. RMS values (mean ± SE) of the tibialis anterior muscle at different angular velocities. RMS values were normalized relative to the RMS value obtained at the contraction of highest torque for each subject.
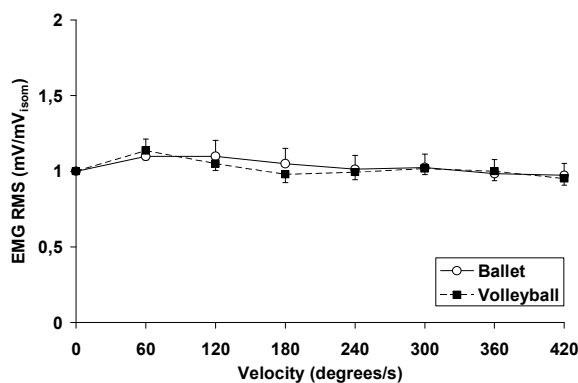
Why are ballet dancers able to activate their plantarflexors more effectively during shortening contractions than volleyball players? This study cannot provide a conclusive answer to this question, but ballet dancing, in contrast to volleyball playing, requires sustained and precisely controlled contractions of the plantarflexor group, and thus, activation might be much better trained in these athletes than the volleyball players.

Dorsiflexion: The increase in relative torques for the ballet dancers at all speeds of dorsiflexion cannot be explained by changes in muscle activation, as EMGs were the same between the two groups of athletes. Therefore, it appears that the differences in dorsiflexion torques are associated with intrinsic differences in the dorsiflexor muscles. Greater torques at the same angular speed of movement could be associated with a greater proportion of fast twitch fibers or an increase in fiber lengths in the ballet dancers compared to the volleyball players The ballet dancers have a greater range of plantarflexion (by 24°), and since excursion is known to be a potent stimulator for sarcomere addition [Koh & Herzog, 1998], fiber length may be longer in the ballet dancers, which could explain the observed results.

CONCLUSION

The results of this study suggest that human muscles adapt to functional demands associated with chronic training in athletes. Therefore, chronic training may not only increase the size, strength, and oxidative capacity of muscles as demonstrated in previous studies [Jones & Carter, 2000; Ahtiainen et al., 2003; Izquierdo et al., 2005], but might also affect the force-velocity and force-length relationships, which are typically assumed to be invariant.

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ACKNOWLEDGEMENTS

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