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Effect of elbow joint angle on the magnitude of muscle damage to the elbow flexors

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ABSTRACT

NOSAKA, K., and K. SAKAMOTO. Effect of elbow joint angle on the magnitude of muscle damage to the elbow flexors. *Med. Sci. Sports Exerc.*, Vol. 33, No. 1, 2001, pp. 22–29. **Purpose:** It has been shown that eccentric actions at a long muscle length result in a larger decrease in force and more muscle tenderness compared with those at a short muscle length. To further investigate the effect of elbow joint angle on the development of muscle damage, this study compared two maximal eccentric exercise regimens in which the starting position of the action was different, but the range of movement was the same. **Methods:** One arm of 10 male students performed 24 maximal eccentric actions of the elbow flexors at the elbow joint angle from 0.87 to 2.27 rad (50–130°: *S* condition) and the other arm at the elbow joint angle from 1.74 to 3.14 rad (100-180°: *L* condition). Maximal isometric force, range of motion, muscle soreness, plasma creatine kinase activity, upper arm circumference, and B-mode ultrasound pictures of the elbow flexors (US) were measured before and for 5 d postexercise in both conditions. Magnetic resonance imaging (MRI) of the transverse scans of the upper arm was taken at 4 d after exercise. **Results:** All measures changed significantly ($P < 0.01$) after exercise for both conditions; however, significantly ($P < 0.01$) larger changes in the measures were found in the *L* condition compared with the *S* condition. MRI and US displayed that only the brachialis was damaged for the *S* condition but the biceps brachii was also damaged for the *L* condition. **Conclusion:** The greater development of muscle damage in the *L* condition compared with the *S* condition is likely to be associated with the elbow flexors muscles affected by the exercise. **Key Words:** ECCENTRIC EXERCISE, ISOMETRIC FORCE, PLASMA CREATINE KINASE ACTIVITY, MUSCLE SORENESS, MRI

Eccentric muscle actions induce muscle damage, when the muscles are unaccustomed to this type exercise (2,5,8,9,17,25,30). Morphological changes are direct evidence of muscle damage, and some indirect makers, such as a long-lasting decrease in force generation and range of motion (ROM), swelling, increases in muscle specific proteins (i.e., creatine kinase: CK, myoglobin) in the blood, development of muscle soreness, and abnormality in magnetic resonance or ultrasound images, are also used to demonstrate damage (5,24,25).

Underlying mechanisms of the eccentric exercise-induced muscle damage have been proposed (2), and a failure in the excitation-contraction coupling process is likely to be a primary site for the damage (10). This failure results in the decrement of force generating capacity via reduced Ca^{2+} release and sensitivity (3). It has been suggested that mechanical factors rather than metabolic factors seem to play the dominant role in the initiation of the muscle damage (30). Several mechanical factors such as initial and/or final fiber length (8,12,23,27), strain (4,27), force (4,29,30), speed or velocity (18,30), number of actions (9,17,27), and total work (8) during eccentric actions have been proposed as factors to determine the level of eccentric exercise-induced muscle damage.

In animal studies, Hunter and Faulkner (8) investigated the effects of mechanical variables (initial fiber length, final fiber length, displacement of stretch, and work) on force deficit immediately after single stretch of the maximally activated extensor digitorum longus (EDL) muscles of mice. They concluded that the initial fiber length of the stretch and the work during the stretch (8) best explained the differences in force deficit among conditions. MacPherson et al. (19) demonstrated that sarcomeres in the regions with the longest lengths before the stretch were the most susceptible to contraction-induced injury, and the initiating event in the development of the injury occurred when longer sarcomeres in series with shorter sarcomeres were stretched excessively. It was hypothesized by Morgan (21) that eccentric contractions at longer fiber lengths produces greater degree of inhomogeneity of sarcomere length, and this causes a greater chance to disrupt stretched, weaker sarcomeres. On

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the other hand, Warren et al. (30) showed peak forces produced during eccentric contractions not the initial fiber length were most closely related to the decrement in force generation ability immediately after eccentric contraction-induced injury protocol in isolated rat soleus muscle.

Compared with the animal studies, only two studies investigated the effect of muscle length on eccentric exercise-induced muscle damage using human subjects. Jones et al. (12) and Newham et al. (23) showed that maximal eccentric exercise of the elbow flexors at a long length (elbow joint angle: approximately 2.36–3.14 rad/135–180°) developed more muscle soreness and low frequency fatigue than that at a short length (elbow joint angle: approximately 0.52–1.05 rad/30–60°). They speculated that there is a length-dependent component in the development of pain and decrease in force after eccentric exercise. However, it is not clear whether changes in other muscle damage indicators such as ROM and plasma CK activity are also larger after eccentric exercise at a long length compared with at a short length. It is also important to demonstrate how the findings from the animal studies can apply to the human muscle system *in vivo.*

Therefore, the purpose of this study was to further investigate the effect of elbow joint angle on development of muscle damage with respect to the magnitude of changes in muscle damage indicators. The present study compared two eccentric exercise regimens in which the range of motion during the eccentric action was the same (1.4 rad = 80°) but the starting position was different (0.87 rad = 50°; *Small* angle condition: *S* condition vs 1.74 rad = 100°; *Large* angle condition: *L* condition).

METHODS

Subjects. Ten male students who were nonathletes and not involved in a regular resistance training program were used as subjects after having the subjects read and sign an informed consent document consistent with the policy statement by *Medicine and Science in Sports and Exercise*. Their mean age, height, and weight were 19.8 ± 1.9 yr, 169.7 ± 2.8 cm, and 58.9 ± 4.9 kg, respectively. Subjects were not allowed to perform any vigorous physical activities and unaccustomed exercises during the experiment period.

Exercise. One arm performed 24 maximal eccentric actions of the elbow flexors at the elbow joint angle from 0.87 to 2.27 rad (50–130°: *S* condition) and the other arm at the angle from 1.74 to 3.14 rad (100–180°: *L* condition) on a modified arm curl machine (Fig. 1). Because the elbow flexors generate maximal force at the elbow joint angle around 2 rad (14,31), it was expected that the peak force generated during the eccentric actions would not be different between the *S* and the *L* conditions, and that effects of peak force on the development of muscle damage could be eliminated. The strain (1.4 rad, 80°), speed (0.35 rad·s^{-1}), number of actions (24 actions) were the same for both conditions. The differences between the conditions were thought to be the initial and final fiber length, and in any case the total work during the eccentric actions. The arm used for the *S* and *L* conditions, and the order of the exercise

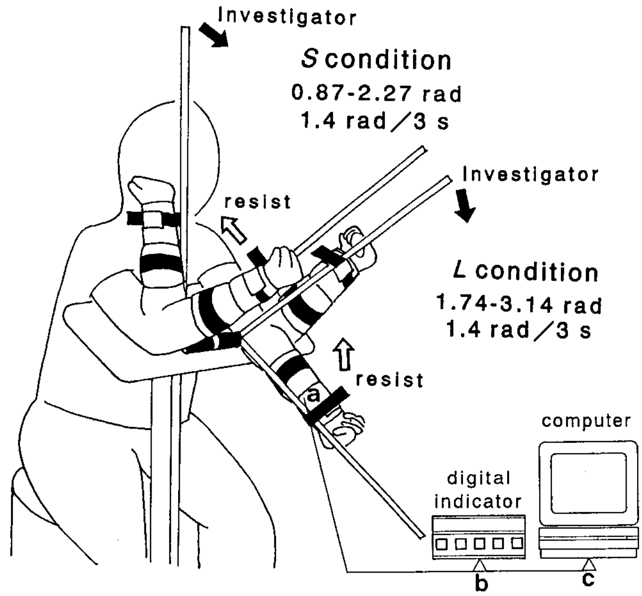

FIGURE 1—Eccentric exercise in the *S* condition and the *L* condition. In this illustration, the right arm was used for the *S* condition, and the left arm was used for the *L* condition. a, Load transducer installed in a specially designed wrist attachment. "a" is connected to a digital indicator (b) and a computer (c). The *large arrows* indicate the direction of the eccentric action.

(S/L) were counterbalanced among the subjects; 5 subjects used the left arm for the *S* (1st bout: $N = 3$, 2nd bout: $N = 2$) and the right arm for the *L* (1st bout: $N = 2$, 2nd bout: $N = 3$), and *vice versa* for the other 5 subjects. In each eccentric action, the subjects were asked to generate maximal isometric force at the starting position (0.87 rad for the *S* condition, 1.74 rad for the *L* condition) for 1 s, then the forearm was forcibly extended 1.4 rad in 3 s, and this action was repeated every 15 s. During the eccentric action, the arm was positioned in front of the body on a padded support adjusted to 0.79 rad (45°) shoulder flexion, and the forearm was supinated and the wrist was placed against the lever arm (Fig. 1). During the eccentric actions, force of the elbow flexors transduced at the wrist were measured by a load transducer (9E01-L43, NEC San-ei, Japan) installed in a specially designed wrist attachment and monitored and recorded by a digital indicator (F360A, UNIPULSE, Japan) and a computer (Macintosh Performer 5410, U.S.). The peak force of each eccentric action was recorded from the digital indicator, and the work in each eccentric action was calculated as the integrated force for 3 s using a software program (LabVIEW, National Instruments, Texas) on the computer. The total work during 24 eccentric actions was the sum of each work.

Criterion measures. Maximal isometric force of the elbow joint angle at 1.57 rad (90°), range of motion (ROM) of the elbow joint, circumference of the upper arm, and B-mode ultrasound pictures (US) of the elbow flexors were measured immediately before and after and for 5 d after each exercise condition. Muscle soreness and plasma CK activity were also assessed at the same time course of the other measures except immediately after exercise. Magnetic resonance image (MRI) of the transverse and longitudinal scans of the upper arm was taken at 4 d after exercise.

Maximal isometric force was measured twice by a dynamometer at an elbow joint of 1.57 rad for 3 s and the mean value was used. Relaxed and flexed elbow joint angles were measured by a goniometer, and the angle subtracting the flexed angle from the relaxed angle was used as ROM (5,24). Circumferences on the upper-arm at 3, 5, 7, 9, and 11 cm from the elbow joint were measured by a tape measure when letting the arm hang down by the side (5). A visual analog scale that had a 50-mm line with "no pain" on one end and "extremely sore" on the other end (23) evaluated soreness levels during palpation on the upper-arm and extension of the forearm. Approximately 5 mL of blood was drawn from the antecubital vein and centrifuged for 10 min to obtain plasma. Plasma samples were stored at −20° C until analysis, and plasma CK activity was determined spectrophotometrically by the VP-Super (Dinabott Co. Ltd., Japan) using a test kit (Dinabott Co. Ltd., Japan). The normal reference ranges of plasma CK activity for male adults by the method was 45–135 $IU \cdot L^{-1}$.

B-mode ultrasonography with a 7.5 MHz probe (Aloka Co. Ltd., Japan) was used to obtain the transverse and longitudinal images of the elbow flexors. Changes in thickness of the biceps brachii and brachialis, and changes in echo signal intensity were observed. T2 images of MRI were obtained from the upper-arm 4 d after exercise, because our previous study showed that swelling peaked 4–5 d after exercise, and changes in MRI also became striking 3–6 d after exercise (24,26). Transverse images of 12 sections with 8-mm thickness and 2-mm intersection gap were taken by using a 0.5-T 21.3 MHz superconducting magnet (SMT-50X, Shimadzu Co. Ltd., Japan). T2 relaxation times of four regions of interest for the biceps brachii, brachialis, and triceps brachii were determined (24).

Statistical analysis. A repeated-measures ANOVA was used to analyze the main effects, i.e., conditions (*S* and *L*), time (pre, post, D1–5), and the interaction effect (conditions × time) for all criterion measures. A Fisher's PLSD *post hoc* test was used to detect differences in the measures between the conditions at different time points. Statistical significance was set at $P < 0.05$.

RESULTS

The peak force during eccentric exercise decreased significantly ($P < 0.01$) over 24 actions, and the decrease from the first to the last action was 34% for the *S* condition and 36% for the *L* condition. Changes in peak force during the eccentric exercise were not significantly different between the *S* and *L* conditions; however, the total work during the eccentric actions for the *S* condition (14,892 ± 1,286 N·s) was significantly larger than in the *L* condition (13,165 ± 1,189 N·s) (Fig. 2).

Decreases in maximal isometric force were significantly smaller in the *S* condition than the *L* condition. The force dropped to 45% of the preexercise level immediately after exercise for the *L* condition, but only 69% for the *S* condition. However, the recovery rates of force from immediately post to D5 were not significantly different between the *S* (83% of the preexercise value) and *L* (84% of the preexercise value) conditions (Fig. 3).

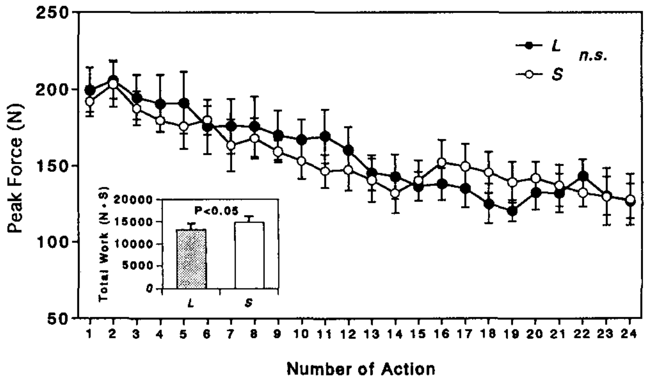

FIGURE 2—Changes in peak force during 24 eccentric actions in the *S* and *L* conditions. No significant difference between the *S* and *L* conditions. In the inserted figure, the total work in the 24 actions is shown. The total work was significantly ($P < 0.05$) larger for the *S* compared with the *L* condition. Mean (±SE) values of 10 subjects are shown.

Relaxed elbow joint angle decreased significantly after exercise in both conditions; however, the recovery was significantly faster for the *S* condition compared with the *L* condition. Flexed elbow joint angle increased significantly after both exercises, but the amount of increase was significantly larger for the *L* condition than the *S* condition. Significantly larger changes in ROM were observed after exercise for the *L* condition compared with the *S* condition (Fig. 4).

Increases in upper arm circumference were found at all measurement sites, and larger increases were observed at the distal portions. Although increases in the circumference immediately to 2 d postexercise were not significantly different between the conditions, larger increases occurred after day 3 postexercise in the *L* condition compared with the *S* condition (Fig. 5). This was confirmed by the changes in muscle thickness of US pictures. The distance between the skin and the edge of the humerus in the transverse images increased after

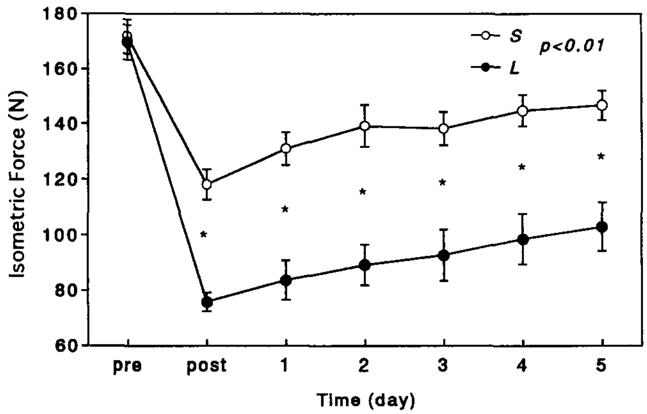

FIGURE 3—Comparison of changes in MIF after eccentric exercise between the *S* and *L* conditions. The changes with time were significantly different ($P < 0.01$). Mean (±SE) values of 10 subjects are shown. * $P < 0.05$.

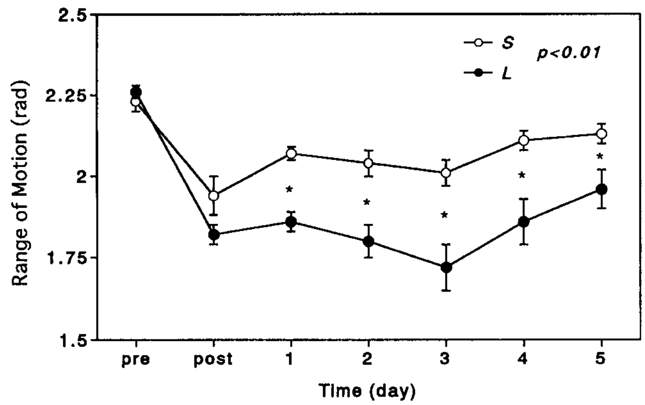

FIGURE 4—Comparison of changes in ROM after eccentric exercise between the *S* and *L* conditions. The changes with time were significantly different ($P < 0.01$). Mean (±SE) values of 10 subjects are shown. * $P < 0.05$.

exercise, and the amount of the increase was significantly larger for the *L* condition (11.2 ± 2.4 mm) compared with the *S* condition (5.1 ± 1.6 mm). Echo intensity increased in the brachialis for all subjects in both conditions, but some of the subjects showed increased echo intensity in the biceps brachii in the *L* condition (Fig. 6).

Muscle soreness during palpation and extension developed significantly after exercise in both conditions, and the extension soreness had higher sustained values compared with palpation. Soreness in the *L* condition was significantly higher than the *S* condition (Fig. 7).

Plasma CK activity increased significantly after exercise in both conditions, however the amount of increase was significantly different between the conditions. Peak plasma CK activity level for the *L* and *S* condition was 10,640 ± 2,876, and 2,891 ± 1,261 $IU \cdot L^{-1}$, respectively (Fig. 8). The amount of increase in plasma CK activity varied among subjects in the both conditions, but all subjects showed higher peak plasma CK activity in the *L* condition (989–32,490 $IU \cdot L^{-1}$) compared with the *S* condition (238–12,372 $IU \cdot L^{-1}$).

MRI demonstrated abnormality of the elbow flexors for all subjects. The area that showed increased T2 signal was larger

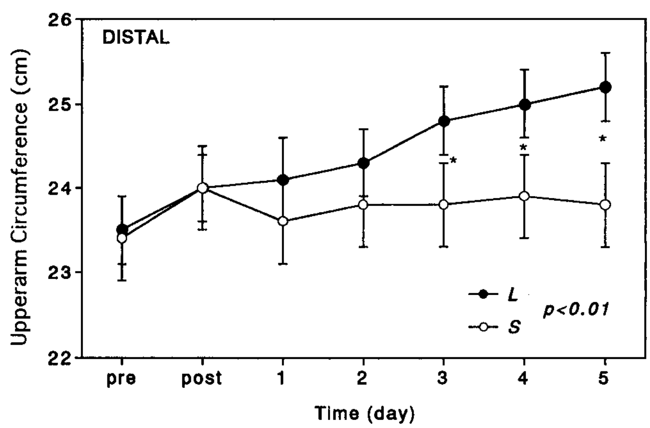

FIGURE 5—Comparison of changes in CIR (distal; 5 cm above the elbow joint) after eccentric exercise between the *S* and *L* conditions. The changes with time were significantly different ($P < 0.01$). Mean (±SE) values of 10 subjects are shown. * $P < 0.05$.

for the *L* condition compared with the *S* condition for all subjects. Abnormality in the biceps brachii was only observed in the *L* condition. The increased T2 signal area was seen in both the brachialis and biceps brachii for five out of 10 subjects (A, B, C, F, G) in the *L* condition; however, this was not the case in the *S* condition. The other five subjects (D, E, H, I, J) whose changes were small in the *S* condition showed conspicuous changes in the brachialis in the *L* condition (Fig. 9). T2 relaxation times of the biceps brachii (37.5 ± 3.2 s vs 29.3 ± 0.4 s) and brachialis (46.1 ± 2.6 s vs 36.8 ± 1.7 s) were significantly larger ($P < 0.05$) for the *L* condition compared with the *S* condition. There was no change for the triceps brachii (Fig. 10).

DISCUSSION

The present study confirmed the results of the study by Jones et al. (12) and Newham et al. (23), who reported that development of pain and decrease in force after eccentric exercise were dependent on muscle length. The present study added new information that changes in other muscle damage indicators (flexed and relaxed elbow joint angles, ROM, upper arm circumference, and CK) were also larger for exercise performed at a long length compared with a short length (Figs. 3–5, 7, and 8). Moreover, this study showed that the differences in the magnitude of changes in the measures seemed to be related to the muscles that were affected by the eccentric exercise (Figs. 6 and 9).

Peak forces generated during eccentric exercise were not significantly different between the *S* and the *L* conditions (Fig. 2). The larger total work during eccentric actions for the *S* condition was likely due to the ROM of the *S* condition that lay much more within the optimal functional length of the elbow flexors than that of the *L* condition. If the peak force during eccentric exercise is a main factor in determining the degree of muscle damage, changes in the criterion measures should have been similar between the *S* and *L* conditions. However, changes in all criterion measures after exercise were greater in the *L* condition compared with the *S* condition (Figs. 3–5, 7, and 8). Although the total work during exercise was greater in the *S* condition compared with the *L* condition, this did not seem to be a factor either. The present study showed that the initial and/or final fiber length is a critical factor in determining the development of eccentric-exercise induced muscle damage of human muscles *in vivo*.

Many studies have investigated what the dominant factor might be that produced eccentric exercise-induced muscle damage by using different animal models. Some studies used a single muscle fiber model (3,18,19) and others used a *in situ* model for mouse EDL (4,8), the tibialis anterior of rat (9) or rabbit (17), rat soleus (30), rat adductor longus (29), and toad sartorius (27). The findings of these animal studies should be carefully compared with human eccentric exercise, because these animal models are not necessarily compatible with the human eccentric exercises with regard to the exercise system.

MRI and US demonstrated that muscle damage in the brachialis was more conspicuous in the *L* condition, and

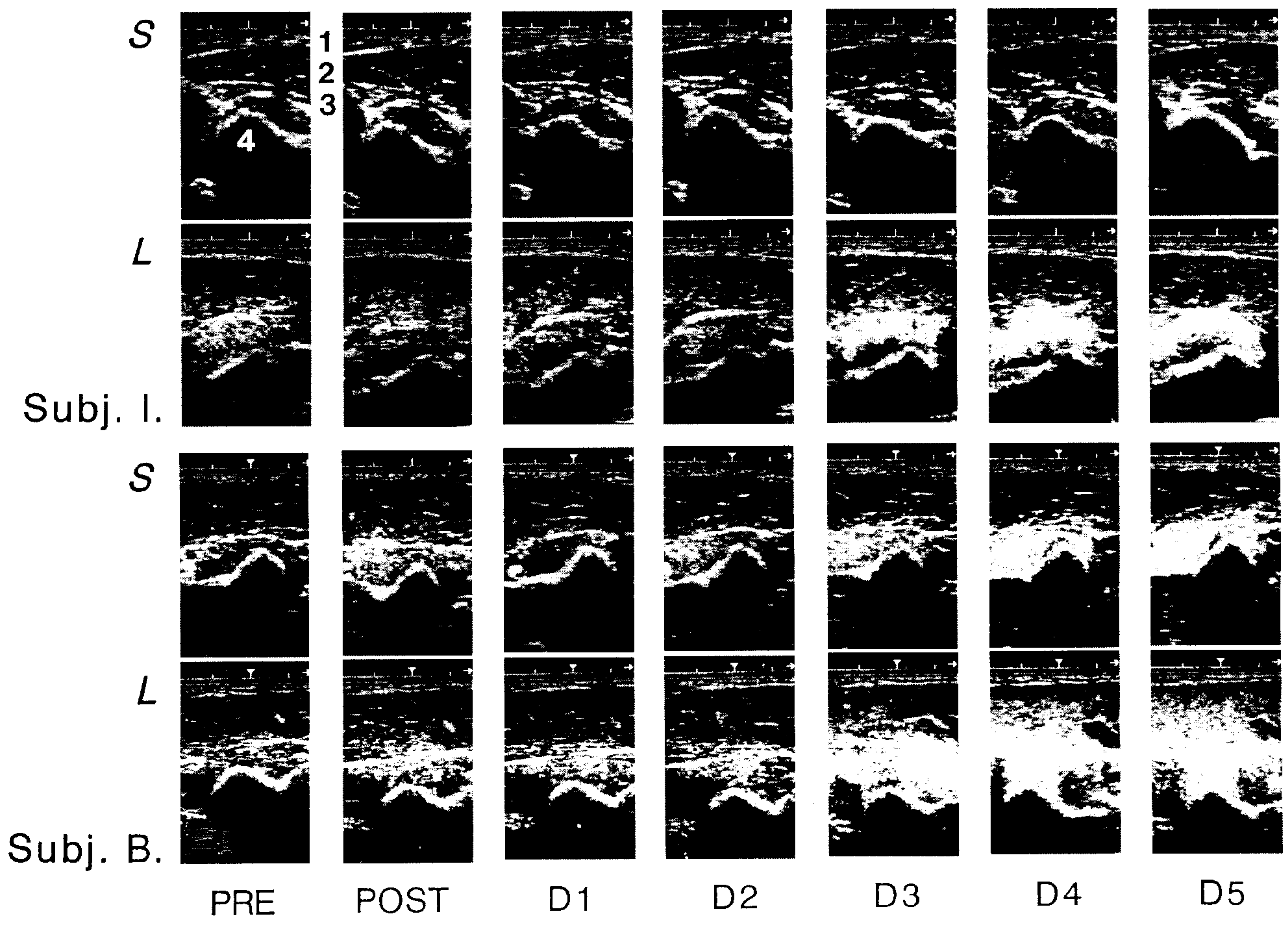

FIGURE 6—Time course of changes in US images (transverse images) taken at 7 cm above the elbow joint for two subjects (I and B). Increased echo intensity is seen in the brachialis in the *L* condition for one subject (I) and in the both brachialis and biceps brachii for the other subject (B). In the case of Subj. B, increased echo is seen in the brachialis for the *S* condition as well. 1: subcutaneous layer, 2: biceps brachii, 3: brachialis, 4: humerus.

there were some cases that not only the brachialis but also the biceps brachii were damaged for the *L* condition (Figs. 7, 9, and 10). These results indicated that the eccentric exercise in the *L* condition induced more damage to the brachialis and biceps brachii than the exercise in the *S* condition that induced damage only to the brachialis to a certain extent, although there was a large intersubject variability in the response. It is important to note that the

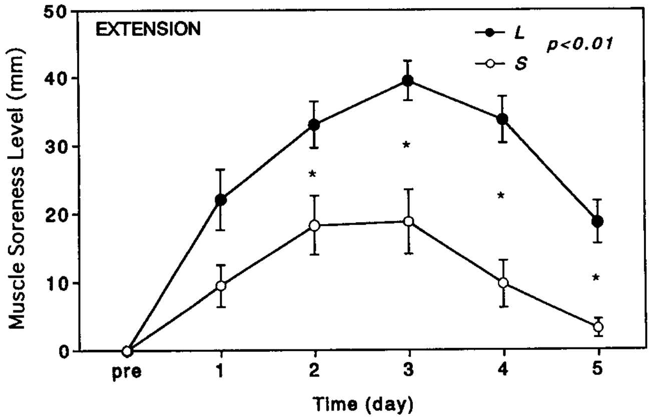

FIGURE 7—Comparison of changes in SOR (soreness when extending the elbow) after eccentric exercise between the *S* and *L* conditions. The changes with time were significantly different ($P < 0.01$). Mean (±SE) values of 10 subjects are shown. * $P < 0.05$.

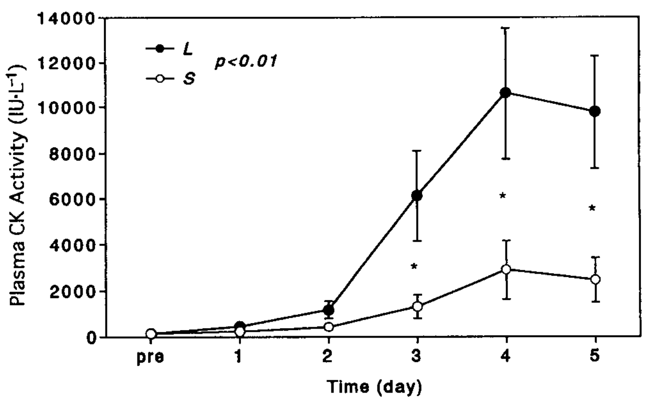

FIGURE 8—Comparison of changes in plasma CK activity after eccentric exercise between the *S* and *L* conditions. The changes with time were significantly different ($P < 0.01$). Mean (±SE) values of 10 subjects are shown. * $P < 0.05$.

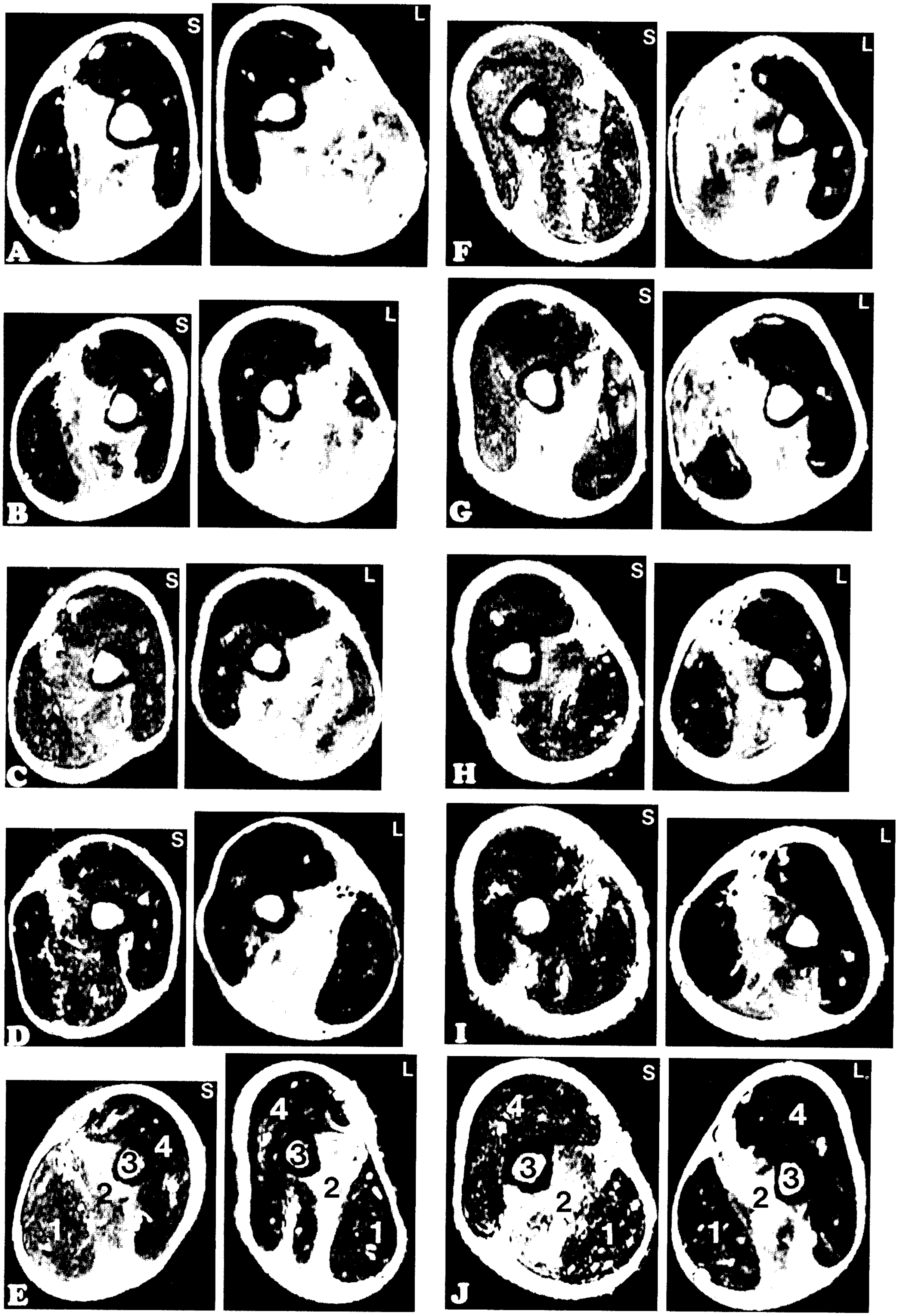

FIGURE 9—T2 MR images of 10 subjects (A-J) after eccentric exercise in the *S* and *L* conditions. Compared with the *S* condition, more conspicuous abnormality in the brachialis is seen in the *L* condition. Some subjects (A, B, C, F, G) showed abnormality in the biceps brachii as well in the *L* condition. 1: biceps brachii, 2: brachialis, 3: humerus, 4: triceps brachii.

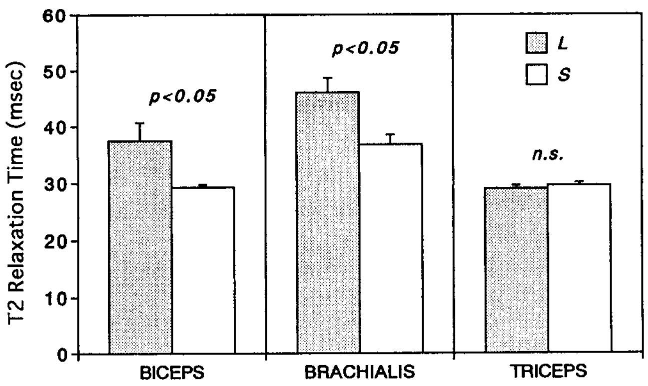

FIGURE 10—Comparison of T2 relaxation time between the *S* and *L* conditions for the biceps brachii, brachialis, and triceps brachii muscles. For the biceps brachii and brachialis, the *L* condition was significantly ($P < 0.05$) higher than the *S* condition. Mean (±SE) values of 10 subjects are shown.

differences in the amount of change in the criterion measures (maximal isometric force, ROM, circumference, soreness, CK) among subjects may also be explained by the affected area on the MRI and US. The large intersubject variability in the response to eccentric exercise of the elbow flexors (5,24,26) may be due, in part, to slight differences in the usage of muscles in the exercise regimen performed by each subject. Although this is not the main point of this study, it is noteworthy that the US demonstrated similar changes to those seen in the MRI. This would suggest that both MRI and US can be used as noninvasive quantification of muscle damage (15), and the increased T2 signal in the MRI and the increased echo signal in the US may result from a common factor—most likely edema (15). Because of the low cost and versatility of the US, the US may be a useful tool to detect muscle damage in human studies.

The brachialis was affected more in the *L* condition compared with the *S* condition for all subjects, and the biceps brachii was affected only in the *L* condition (Figs. 9 and 10). Kawakami et al. (13) estimated from the physiological cross-sectional area and moment arm of the elbow flexors that brachialis had the greatest contribution to torque (47%), followed by the biceps brachii (34%) and brachioradialis (19%). Leedham and Dowling (14) stated that the contribution of the biceps brachii synergist muscles (brachialis and brachioradialis) might provide proportionally more force at flexed than extended elbow joint angles during isometric contractions. Nakazawa et al. (22) also reported that the contribution of the biceps brachii was higher at extended angles (i.e. 2.62–3.14 rad) compared with flexed angles (i.e. 1.57–2.09 rad) during eccentric contractions, although it was not the case for concentric contractions. It seems reasonable to assume that the brachialis contributes most during eccentric actions of the elbow flexors as well, especially when the elbow joint does not exceed 2.27 rad (130 degrees). The contribution of the biceps brachii increases in the elbow extended position, at least larger than 2.27 rad (130°). It is also important to note that one of the functions of the biceps brachii is to supinate the forearm, and the biceps brachii is activated more in the flexion and supination tasks (11). Because the forearm was kept supinated during the eccentric actions in the present study, the biceps brachii appeared to be activated more at the elbow extended position compared with the flexed position.

Saxton and Donnelly (25) reported that the greatest decline in maximal isometric force was observed at the most acute angle (0.87 rad, 50°), followed by 1.57 rad (90°) and 2.79 rad (150°) after a bout of 70 maximal eccentric actions. This seems to be in line with the findings of the present study that the brachialis was damaged more by the eccentric exercise than the biceps brachii. The force at 0.87 rad decreased more because the contribution of the brachialis is larger at this angle. The possibility that the peak force during eccentric exercise is a main factor in determining the degree of muscle damage remains, because the muscle that generates larger forces seemed to be damaged more (Figs. 9 and 10). However, the fact that the brachialis was also damaged more in the *L* condition in which the contribution of the brachialis appeared to be smaller compared with the *S* condition would suggest that the magnitude of the stretch either relative to fiber length or beyond optimum fiber length is a key factor for the eccentric exercise-induced muscle damage as demonstrated in animal studies (8,12,23,27).

The musculoskeletal geometry of the elbow flexors should be also considered with respect to the susceptibility of the muscles to damage induced by eccentric exercise. Although the moment arms of the elbow flexors change with elbow joint angle, the moment arm of the biceps brachii is always larger than that of the brachialis (1,20,28,31). Kawakami et al. (13) reported that the moment arm of the biceps brachii was approximately 1.9 times as large as that of the brachialis at the elbow joint angle 1.57 rad. If muscle fiber length is short and moment arm is large, the sarcomeres change length a great deal during joint rotation (16). The muscle fiber length of the biceps brachii is larger than that of the brachialis (biceps brachii/brachialis is approximately 1.66 based on the data by ref. 13). It can be speculated that the strain of the biceps brachii was larger than that of the brachialis during eccentric actions in both conditions, because of the larger moment arm of the biceps brachii. If so, the biceps brachii should have been more susceptible to eccentric exercise-induced muscle damage than the brachialis, but the opposite was the case (Figs. 6 and 9).

This contradiction could be explained by muscle structure. First, the longer muscle fiber length of the biceps brachii may compensate for the effects of the moment arm. Second, the biceps brachii is a two-joint muscle and has relatively long tendons at two proximal attachments (glenoid fossa and coracoid process) and one distal attachment (radial tuberosity). The tendon compliance plays a major role in protecting muscle fibers from injury associated with stretch (7). This may be why the biceps brachii was not affected by the eccentric exercise, especially in the *S* condition. Third, the structure of the brachialis and the long head of the biceps brachii is a parallel-fibered, but the short head of the biceps brachii is unipennate (1). Garrett et al. (6) demonstrated that muscles with more pennate structure tended to elongate further relative to their resting length and were more resilient to biomechanical failure under passive extension. It seems likely that the parallel-fibered structure is more susceptible to eccentric action-induced muscle damage than the pennate structure. Because of the pennate structure of the short head of the biceps brachii and the structure of two origins, it might be possible that the biceps brachii can absorb the stress produced by eccentric actions more effectively than the brachialis. Although the present study did not examine muscle damage to the brachioradialis, it should be also carefully examined in future studies.

In conclusion, this study showed that changes in all markers of muscle damage were significantly larger following eccentric exercise of the *L* condition compared with that of the *S* condition. The larger changes in the *L* condition appeared to be due to more damage to the brachialis and biceps brachii compared with the *S* condition. The *S* condition resulted in less damage to the brachialis. Eccentric exercise-induced muscle damage of the elbow flexors is dependent on elbow joint angle.

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