Acta Physiol Scand 2001, **172**, 269–278

Inactivity and muscle: effect of resistance training during bed rest on muscle size in the lower limb

H. AKIMA,[1] K. KUBO,[1] M. IMAI,[1] H. KANEHISA,[1] Y. SUZUKI,[2] A. GUNJI[2] and T. FUKUNAGA[1]

1 Department of Life Sciences (Sports Sciences), Graduate School of Arts and Sciences, The University of Tokyo, Meguro, Tokyo, Japan
2 Seigakuin University, Tosaki 1-1, Ageo, Saitama, Japan

ABSTRACT

The present study aimed to investigate the effect of dynamic leg press training on the physiological cross-sectional areas (PCSAs) of human lower limb muscles during 20 days of 6° head-down tilt bed rest. Five healthy men comprised the resistance training group (BR-Tr) and data from two previous studies were used to derive a 10-man control group (BR-Cont). The BR-Tr performed two sessions (morning and afternoon session) of dynamic leg press action including knee extension and plantar flexion daily for the bed rest period: (1) three sets of 10 repetitions at 90% of maximum load and (2) 40% of maximum load to exhaustion. The PCSAs of the knee extensor (KE), knee flexor (KF), plantar flexor (PF), and dorsiflexor muscle groups were estimated using serial axial magnetic resonance (MR) images of the right-thigh and leg. After the bed rest period, the BR-Tr showed a significant increase in the PCSA of the KE. Although PCSA of the KF in two groups significantly decreased after bed rest, percentage of change in PCSA of the biceps femoris (long head) and semitendinosus muscles in the BR-Tr, which occupied approximately 70% of the KF, was significantly higher than those in the BR-Cont. Both the BR-Tr and BR-Cont groups showed significant decreases in the PCSA of PF with similar magnitude of 11.6% ($P < 0.001$) and 11.9% ($P < 0.001$), respectively. These results suggest that dynamic leg press training during bed rest can prevent deteriorating of the KE and a part of KF, but not the calf muscles.

Keywords human, inactivity, magnetic resonance imaging, muscle size.

Received 5 June 2000, accepted 12 January 2001

It is well known that muscle atrophy is caused by disuse, such as bed rest (Gogia *et al.* 1988, LeBlanc *et al.* 1988, 1992, Duvoisin *et al.* 1989, Hikida *et al.* 1989, Berg *et al.* 1992, Suzuki *et al.* 1994, Ferrando *et al.* 1995, Bloomfield 1997, Ferretti *et al.* 1997, Akima *et al.* 1997a, 2000b, Tabata *et al.* 1999) or unilateral lower limb suspension (ULLS) (Berg *et al.* 1991, Dudley *et al.* 1992, Hather *et al.* 1992, Ploutz-Snyder *et al.* 1995), as well as spaceflight (Edgerton *et al.* 1995, LeBlanc *et al.* 1995, Widrick *et al.* 1999, Akima *et al.* 2000b) in human skeletal muscles. However, as far as we know, few investigations have been made on the effects of physical activity, e.g. resistance training, during bed rest on the morphological properties of skeletal muscles (Bamman *et al.* 1998, Akima *et al.* 2000c). Previously, we demonstrated that 20 days of bed rest induces 7–10% atrophy in the lower limb muscles of healthy men and women (Akima *et al.* 1997b, Tabata *et al.* 1999). More recently, we have shown that isometric leg press exercises during 20 days of bed rest prevents atrophy of the knee extensors (KE), but not of the knee flexor (KF) or plantar flexors (PF) (Akima *et al.* 2000c). Most notably, the physiological cross-sectional area (PCSA) of the PF decreased significantly by about 12% in both the training and control (non-training) groups over the 20 days. As there was no significant difference in the degree of atrophy displayed by the two groups, suggesting that isometric exercise regimen used in our previous study (Akima *et al.* 2000c) was of little effect in the prevention of atrophy in the KF and PF, we speculated that there was less involvement of these muscles in isometric leg press exercises than other muscles covered in the study.

Previous attempts have been made to show the effect of resistance training on strength and/or morphological properties in skeletal muscles during bed rest

Correspondence: H. Akima, Department of Life Sciences (Sports Sciences), Graduate School of Arts and Sciences, The University of Tokyo, 3-8-1 Komaba, Meguro, Tokyo 153-8902, Japan.

(Germain *et al.* 1995, Bamman *et al.* 1997, 1998, Koryak 1998, Akima *et al.* 2000c). For example, Germain *et al.* (1995) and Bamman *et al.* (1997) reported that muscle strength in lower limbs could be maintained as a result of resistance training during 6° head-down tilt bed rest. Bamman *et al.* (1997) demonstrated in eight volunteers that resistance training during bed rest reduced fibre atrophy in the vastus lateralis muscles. Although these studies showed that resistance exercise during bed rest prevented muscle deconditioning, it is yet to be determined as to what extent each region of the related muscle groups and which individual muscles develop as a result of such training.

In dynamic leg press exercise, three lower limb joints (hip, knee and ankle) are simultaneously involved both concentrically and eccentrically (Escamilla *et al.* 1998). Recent studies have shown that the metabolic cost of dynamic exercise is greater than that of isometric (Ameredes & Clanton 1990, Price *et al.* 1998); and that it might reduce bed rest induced atrophy in the lower limb muscles. Sale *et al.* (1992) demonstrated that CSA of the KE increased after 19 weeks of dynamic leg press exercise. Moreover, Dudley *et al.* (1991) demonstrated that concentric and eccentric actions during resistance training induces greater muscle strength than concentric actions alone. Thus, in this study, we endeavoured to investigate whether or not dynamic leg press training could prevent atrophy of the thigh and leg muscles during 20 days of 6° head-down tilt bed rest.

MATERIALS AND METHODS

Subjects

Fifteen healthy men participated in this study after giving their informed consent to the experimental protocol, which had been approved by the Ethical Committee of the Faculty of Medicine, The University of Tokyo. These subjects were assigned to two groups, i.e. resistance training (BR-Tr: $n = 5$) and non-training during bed rest (BR-Cont: $n = 10$). All data of BR-Cont was derived from our two previous reports (Akima *et al.* 1997b, 2000c). Permission to republish the data was obtained from Springer-Verlag (Akima *et al.* 2000c) and from *Journal of Gravitational Physiology* (Akima *et al.* 1997b). The physical characteristics of the subjects were shown in Table 1.

Table 1 Physical characteristics of subjects

	BR-Tr	BR-Cont
Age (years)	23.8 ± 4.2	19.6 ± 1.3
Hight (cm)	173.5 ± 4.9	171.7 ± 4.9
Weight (kg)	68.5 ± 10.3	68.1 ± 12.0

Values are mean ± SD. BR-Tr: resistance training during bed rest, BR-Cont: non-training during bed rest. The data for BR-Cont were derived from two previous reports (Akima *et al.* 1997b, 2000c). Republished with permission from Springer-Verlag and *Journal of Gravitational Physiology*.

Bed rest procedures

Bed rest procedures used in this study have been already reported elsewhere (Tabata *et al.* 1999, Akima *et al.* 2000c). Briefly, subjects remained in a 6° head-down tilt bed rest at all times throughout the bed rest period except for resistance training for BR-Tr, and did not permit any weight-bearing posture and any physical activities were restricted to a minimum for BR-Cont. During 20 days of bed rest, they used a movable bed when they were transferred. The room temperature of the wards did not surpass 25 °C. All tests were conducted before re-ambulation.

Resistance training

Using a horizontal leg press training device (VR-4100, Cybex, Medway, ME, USA), bilateral leg press resistance exercises were performed daily from the supine position for the duration of the 20-day bed rest period. Resistance training consisted of one morning session and one afternoon session per day.

In the morning session, subjects performed three sets of 10 repetitions with a 1-min rest between sets. As shown in Fig. 1, the angle of the hip, knee and ankle joints were, respectively, positioned to approximately 110°, 90° and 80° at the start of each action. During repetitions, the subjects' hip, knee and ankle joints were fully extended against the load. To ensure involvement of the PF in the exercise, the subjects' heels were prevented from touching the board during execution. The exercise was performed in 3-s cycles where the lower legs were extended for 1 s, followed by a 2-s flexion. This exercise procedure was designed to maintain the maximum voluntary contraction and muscle mass of the lower limbs.

In the afternoon session, isotonic leg press exercises at 40% of maximum load were performed to volitional exhaustion. This training was designed to maintain the muscular endurance. The starting posture for this training was same as that for the morning session, in which the hip, knee and ankle joints were positioned to approximately 110°, 90° and 80°, respectively. Endurance time to fatigue was measured using a stopwatch. Subjects were encouraged to continue the training as long as possible.

Magnetic resonance (MR) imaging

Magnetic resonance images were collected pre- and post-bed rest. Pre-measurement were performed 3 days before bed rest, and post-measurement before

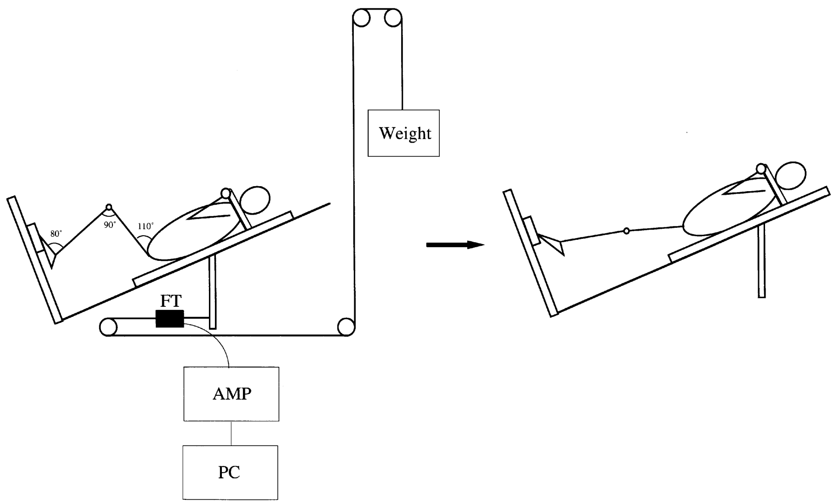

Figure 1 Schematic illustration of dynamic leg press resistance training.

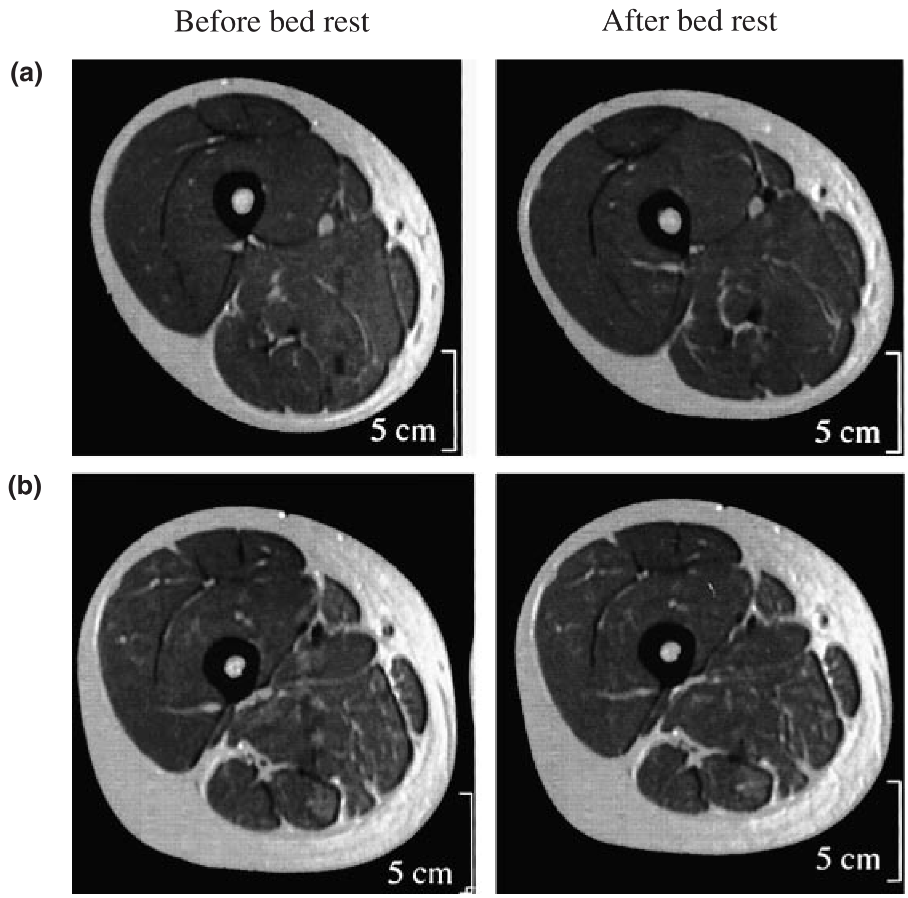

Figure 2 Representative MR images of the mid-thigh in training (a) and control (b) groups before and after bed rest.

re-ambulation. All images were taken after 15–30 min rest to avoid fluid shifts that might induce interstitial and/or intracellular volume changes. The MR imaging was performed with a 1.0 T (GYROSCAN T10-NT, Philips Medical Systems, Best, Netherlands). T1-weighted spin echo, axial-plane imaging was performed with the following variables: TR 450 ms, TE 20 ms, matrix 256 × 172, field of view 300 mm, slice thickness 10 mm and interslice gap 7 mm (Fig. 2). The subjects were imaged in a prone position with the knee and ankle kept at 180° and ~120°, respectively, with 180° being full extension of each joint. Coronal plane images were taken to identify spina iliaca anterior superior which is the origin of sartorius. Consecutive axial images were obtained from spina iliaca anterior superior to extremitas distalis of tibia. The number of axial images obtained for each subject was 43–48. The muscles investigated were as follows: KE: m. rectus femoris (RF), m. vastus lateralis (VL), m. vastus intermedius (VI), and m. vastus medialis (VM); KF: m. biceps femoris, short head (BFs), m. biceps femoris, long head (BFl), m. semitendinosus (ST), m. semimembranosus (SM), m. gracilis (Gr), and m. sartorius (Sar); PF: m. medial gastrocnemius (MG), m. lateral gastrocnemius (LG), and m. soleus (Sol), and finally the dorsiflexors: m. tibialis anterior (TA). From the series axial images, outlines of each muscle were traced, and the traced images were transferred to a Macintosh computer (Power Macintosh 8600/200, Apple Computer, Cupertino, CA, USA) for calculation of the anatomical cross-sectional area (ACSA), which represents the end-on view of the muscle area at each level that the section has been made, using a public domain National Institutes of Health (NIH) image software package (written by Wayne Rasband at the NIH and available on the Internet by anonymous ftp from zippy.nimh.nih.gov or on floppy disk from NITS, 5285 Port Royal Road, Springfield, VA, USA). The muscle volume was determined by summing the ACSA of each image times the thickness (10 mm) and interslice gap (7 mm) of each section. Test–retest reliability of muscle volume measurement was 1.6% (Akima *et al.* 1997b). Muscle fibre length was calculated as muscle length times the ratio of fibre length to muscle length reported by Wickiewicz *et al.* (1983). It was reported that the PCSA of each muscle was as given in the following equation (Wickiewicz *et al.* 1983, Fukunaga *et al.* 1992, 1996, Akima *et al.* 1997a, 2000c):

$$\text{PCSA} = \text{muscle volume} \times \cos\theta \times (\text{fibre length})^{-1}$$

where θ is the muscle fibre pennation angle derived from Wickiewicz *et al.* (1983).

Statistics

All data were presented as mean and its standard deviation (SD). The PCSA data were analysed with a three-way (treatment group × time × muscle) analysis of variance (ANOVA) with repeated measures over time. The percentage change of PCSA in each muscle group was analysed with a two-way (treatment group × muscle) ANOVA with repeated measures over time. To determine percentage change of PCSA in each muscle groups, we used two-way (treatment group × muscle group) ANOVA. Significant main effects and interactions were compared using the least squares difference (LSD) *post hoc* test. All analysis was performed using the SuperANOVA/Mac (Version 1.11) statistical package. The level of significance was set at $P < 0.05$.

RESULTS

Table 2 shows the PCSA of the thigh and leg muscles in BR-Tr and BR-Cont. There was a three-way inter-

Table 2 Physiological cross-sectional area of the thigh and leg muscles for training (BR-Tr) and control (BR-Cont) group

	BR-Tr		BR-Cont	
	Pre	Post	Pre	Post
RF	37.2 ± 2.8	36.4 ± 6.1	41.9 ± 9.3	39.9 ± 8.7
VL	87.4 ± 8.9	93.2 ± 13.9	96.8 ± 15.3	91.9 ± 14.8*
VI	63.8 ± 6.5	71.2 ± 9.6*	74.7 ± 9.3	67.4 ± 7.2*
VM	58.7 ± 7.4	61.1 ± 12.0	65.4 ± 8.7	59.6 ± 6.6
KE	247.0 ± 22.3	261.9 ± 39.6****	278.8 ± 37.1	258.9 ± 32.7****
BFs	6.5 ± 0.5	6.2 ± 0.5	7.0 ± 1.5	6.8 ± 1.5
BFl	28.2 ± 7.5	28.6 ± 10.1	28.1 ± 4.8	26.0 ± 4.6**
ST	10.1 ± 0.4	9.5 ± 0.5	12.1 ± 2.7	11.3 ± 2.3
SM	35.3 ± 8.1	33.2 ± 10.0	34.6 ± 5.9	30.4 ± 5.4***
Sar	2.9 ± 0.5	2.8 ± 0.5	3.4 ± 0.6	3.1 ± 0.6
Gr	2.9 ± 0.4	3.0 ± 0.8	3.5 ± 0.5	3.4 ± 0.5
KF	86.0 ± 13.5	83.4 ± 20.4*	88.7 ± 12.5	80.9 ± 11.8****
MG	43.0 ± 12.0	37.7 ± 7.7**	27.3 ± 6.0	23.9 ± 4.0*
LG	28.5 ± 6.4	23.7 ± 3.7**	18.1 ± 2.7	15.9 ± 2.5
Sol	56.9 ± 18.1	51.3 ± 17.6**	40.3 ± 7.4	35.4 ± 5.2**
PF	128.4 ± 34.1	112.7 ± 26.4****	85.8 ± 14.6	75.2 ± 10.3****
TA	20.3 ± 4.4	18.4 ± 3.8	12.4 ± 1.9	12.3 ± 2.1

Values are mean ± SD. RF: rectus femoris, VL: vastus lateralis, VI: vastus intermedius, VM: vastus medialis, KE: knee extensors, BFs: biceps femoris, short head, BFl: biceps femoris, long head, ST: semitendinosus, SM: semimembranosus, Sar: sartorius, Gr: gracilis, KF: knee flexors, MG: medial gastrocnemius, LG: lateral gastrocnemius, Sol: soleus, PF: plantar flexors, TA: tibialis anterior. *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$, ****$P < 0.0001$ vs. pre. The data for BR-Cont were derived from two previous reports (Akima *et al.* 1997b, 2000c). Republished with permission from Springer-Verlag and *Journal of Gravitational Physiology*.

action, group × time × muscle ($P = 0.0002$). The PCSA of the VI and KE in BR-Tr increased after bed rest ($P < 0.05$ and $P < 0.0001$, respectively). The other individual muscles within the KE showed no change in BR-Tr. The PCSA values of the VL, VI and KE in BR-Cont decreased after bed rest ($P < 0.05$, $P < 0.05$ and $P < 0.0001$, respectively). The individual muscle of the KF in BR-Tr showed no significant changes in PCSA, however, the KF decreased significantly after bed rest ($P < 0.05$). In BR-Cont, BFl, SM and KF showed significant decreases in the PCSA after bed rest ($P < 0.01$, $P < 0.001$ and $P < 0.0001$, respectively). In the lower leg, the PCSA of the MG, LG, Sol, and PF in BR-Tr and MG, Sol, PF decreased significantly after bed rest. No significant change was found in TA in both BR-Tr and BR-Cont groups.

Figure 3 shows the relative change of the PCSA of individual muscles and muscle groups of the thigh and leg in BR-Tr and BR-Cont. There was a three-way interaction, group × time × muscle ($P = 0.0002$). Significant difference in percentage change of PCSA of the VL ($P < 0.01$), VI ($P < 0.001$), VM ($P < 0.01$) and KE ($P < 0.001$) was observed between BR-Tr and BR-Cont. There was no difference in percentage change of PCSA in the KF and PF and their individual muscles between BR-Tr and BR-Cont. The relative change in RF in BR-Tr was significantly lower than those in the VL and VI.

Figure 4 shows the relative change of the PCSA of the KE, KF and PF muscle group in BR-Tr and BR-Cont. There was a three-way interaction, group × time × muscle ($P = 0.011$). Significant differences in relative change in PCSA were observed between KE for BR-Tr and KE for BR-Cont, and between KF for BR-Tr, and PF for BR-Tr. No significant differences in relative change in PCSA were found between KF for BR-Tr and KF for BR-Cont, and between PF for BR-Tr and PF for BR-Cont.

Figures 5–7 show serial ACSAs from the insertion to termination of the KE, KF and PF in BR-Tr and BR-Cont. No significant change in ACSA was observed in the KE and KF of BR-Tr throughout the length of the thigh after bed rest. In BR-Cont, there were significant decreases of ACSA at around the region of peak ACSA in the KE and KF. In the PF, significant decreases in ACSAs at around the region of peak ACSA were also observed in both BR-Tr and BR-Cont after bed rest.

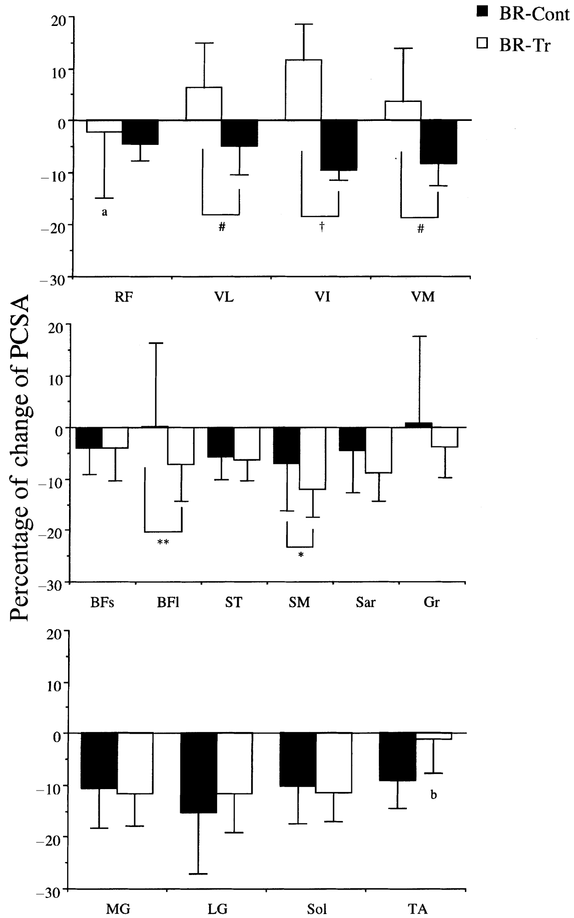

Figure 3 Percentage of changes in physiological cross-sectional area (PCSA) of individual muscles of thigh and leg muscle groups for training (BR-Tr) and control (BR-Cont) group. RF: m. rectus femoris, VL: m. vastus lateralis, VI: m. vastus intermedius, VM: m. vastus medialis, BFs: m. biceps femoris, short head, BFl: m. biceps femoris, long head, ST: m. semitendinosus, SM: m. semimembranosus, Sar: m. sartorius, Gr: m. gracilis, MG: m. medial gastrocnemius, LG: m. lateral gastrocnemius, Sol: m. soleus, TA: m. tibialis anterior. *$P < 0.05$, **$P < 0.01$, $^{\#}P < 0.001$, $^{\dagger}P < 0.0001$, $^{a}P < 0.01$ vs. VL and VI in BR-Tr, $^{b}P < 0.05$ vs. MG and Sol in BR-Cont. The data for BR-Cont were derived from two previous reports (Akima *et al.* 1997b, 2000c). Republished with permission from Springer-Verlag and *Journal of Gravitational Physiology*.

DISCUSSION

Many studies have shown that deconditioning (atrophy and loss of strength) in human skeletal muscles is caused by bed rest or other prolonged disuse (Gogia *et al.* 1988, LeBlanc *et al.* 1988, 1992, Duvoisin *et al.* 1989, Hikida *et al.* 1989, Berg *et al.* 1992, Suzuki *et al.* 1994, Ferrando *et al.* 1995, Bloomfield 1997, Akima *et al.* 1997a, 2000b, Ferretti *et al.* 1997, Tabata *et al.* 1999). It is generally accepted that bed rest or ULLS is usable as a practical simulation of spaceflight. However, few attempts have been made to evaluate countermeasures of disuse-induced deconditioning of skeletal muscle thus far (Germain *et al.* 1995, Bamman *et al.* 1997, 1998, Koryak 1998, Akima *et al.* 2000c). In particular, details of regional morphological adaptations in muscle groups and individual muscles resulting from resistance training during bed rest have not yet been established. We designed this study to evaluate the response of lower limb muscle groups and individual muscles to dynamic resistance training during bed rest. In our previous study (Akima *et al.* 2000c), we demonstrated that isometric leg press training could prevent atrophy and decline of strength in the KE; however, after 20 days of bed rest nine healthy men showed no prevention of atrophy of the KF and PF. We feel that isometric exercise is the best method of preventing muscle deconditioning in astronauts during spaceflight. As it requires only simple equipment, it would be relatively easy to perform this type of exercise while in orbit. Unfortunately, positive results have only been observed in the KE thus far (Akima *et al.* 2000c). Because of this, in our re-designed current study, we ensured that more muscles and muscle groups would be employed by the dynamic leg press exercises performed during bed rest.

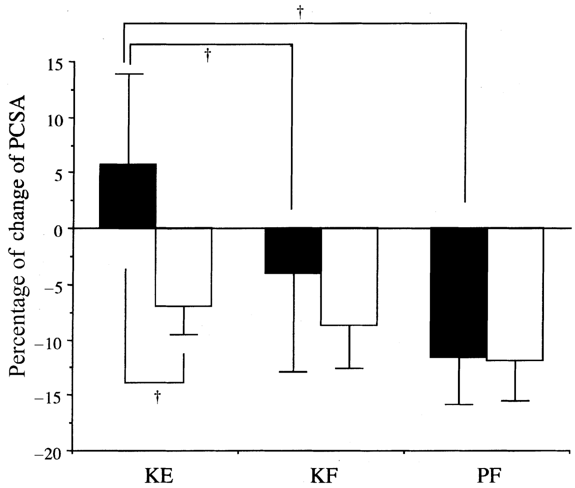

Figure 4 Percentages of changes in physiological cross-sectional area (PCSA) of the knee extensor (KE), knee flexor (KF), and plantar flexor (PF) muscle groups for training (BR-Tr) and control (BR-Cont) group. †$P < 0.0001$. The data for BR-Cont were derived from two previous reports (Akima *et al.* 1997b, 2000c). Republished with permission from Springer-Verlag and *Journal of Gravitational Physiology*.

We did not find a significant difference in percentage change in the KF PCSA between the BR-Tr and BR-Cont (Fig. 4). However, reduction of the vasti muscle PCSA in the KE and the BFl/SM PCSA in the KF was minimized through dynamic leg press exercises during the 20 days of head-down tilt bed rest (Fig. 3). These results support, in part, our previous study (Akima *et al.* 2000c). In that study, we speculated that the KF would be relatively unutilized during training, allowing atrophy to occur in this muscle group (Akima *et al.* 2000c). Based on integrated electromyographic

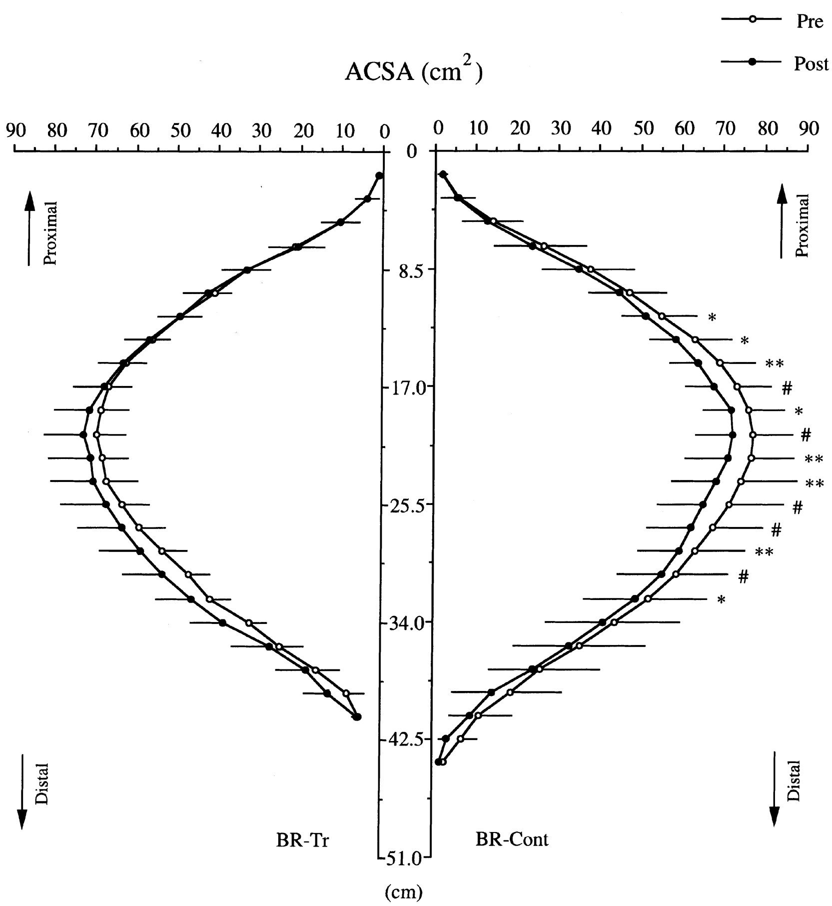

Figure 5 Serial anatomical cross-sectional area (ACSA) of the knee extensor muscles before and after bed rest in training (BR-Tr) and control (BR-Cont) group. *$P < 0.05$, **$P < 0.01$, #$P < 0.001$ vs. pre. The data for BR-Cont were derived from two previous reports (Akima *et al.* 1997b, 2000c). Republished with permission from Springer-Verlag and *Journal of Gravitational Physiology*.

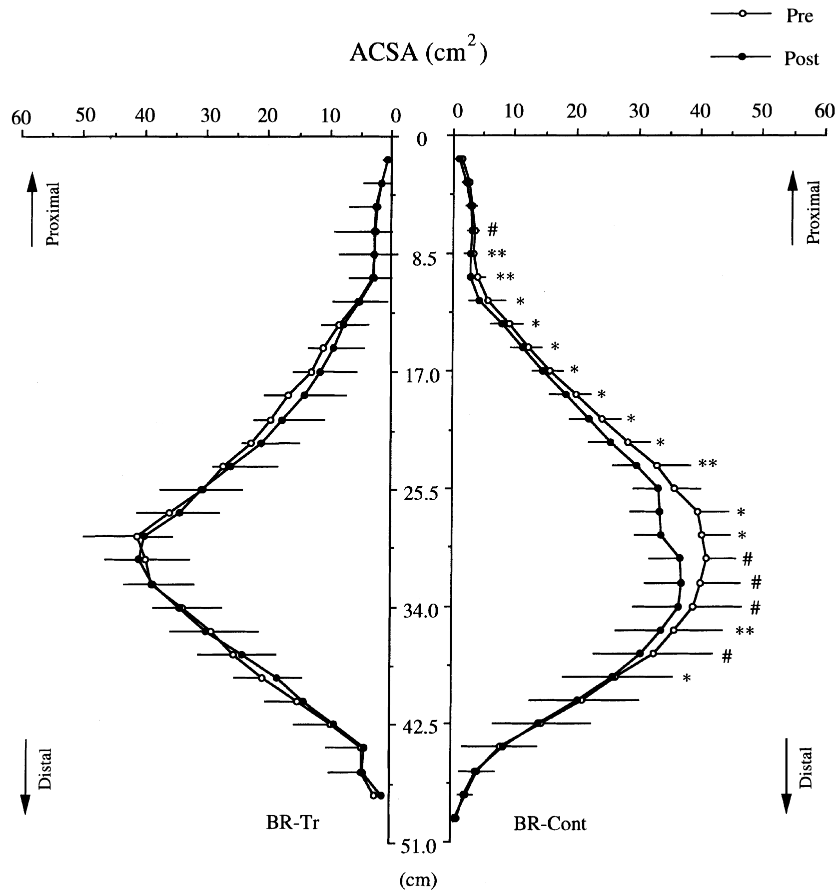

Figure 6 Serial anatomical cross-sectional area (ACSA) of the knee flexor muscles before and after bed rest in training (BR-Tr) and control (BR-Cont) group. *$P < 0.05$, **$P < 0.01$, #$P < 0.001$ vs. pre. The data for BR-Cont were derived from two previous reports (Akima *et al.* 1997b, 2000c). Republished with permission from Springer-Verlag and *Journal of Gravitational Physiology*.

(iEMG) activity study, Escamilla *et al.* (1998) reported that the muscle activation level of the BF and the ST and SM during leg press exercises averaged about 35 and 20%, respectively, normalized by iEMG during maximum voluntary contraction. In our study, we also used similar forms of resistance training, and our results support their findings. However, the degree of iEMG activity in the hamstrings was smaller than that in the quadriceps femoris during leg press exercises. We speculate that no significant difference exists in percentage change in PCSA in the KF between two groups. As shown in Table 2, the BFl and SM are the largest muscles in the KF. Results showing that BFl and SM degradation was minimized by training would be important, as these two muscles occupy over 70% of the KF's PCSA. The PCSA of the VI in the BR-Tr increased significantly after training. As shown in Fig. 3, the greatest relative change in the PCSA of KE was observed in the VI of the BR-Tr group. Ploutz-Snyder *et al.* (1995) demonstrated that the vasti muscle is the major muscle exercised while performing barbell squat exercise. This was determined using exercise-induced contrast shifts in spin–spin relaxation times (T2)-weighted MR images. It has been shown that this technique is able to provide recruitment during exercise (Adams *et al.* 1992, Ploutz *et al.* 1993, Yue *et al.* 1994, Akima *et al.* 1999, 2000a, Meyer & Prior 2000, Vandenborne *et al.* 2000). This result indicated that the VI would be one of the major contributing muscle when performing dynamic leg press exercises.

In both BR-Tr and BR-Cont, a significant reduction in the PCSA was observed in the PF (i.e. MG, LG and Sol). There was also no significant difference between the two groups in percentage change of the PCSA in those muscles (Fig. 3). These results suggest that the dynamic leg press training performed during bed rest in this study had no training effect on the PCSA of the PF. The PF plays an important role in standing, walking, running and other upright physical activities, making it one of the most important antigravity muscle in humans. Muscle loss during spaceflight was greater in the PF than in the thigh muscles, such as the KE and KF, in humans (LeBlanc *et al.* 1995, 2000, Akima *et al.* 2000b). These results strongly indicate that the PF is sensitive to unloading. The degree of change in the PCSA for the PF and its individual muscles was similar in BR-Tr and BR-Cont. It would appear to be difficult to explain the variability of bed rest-induced atrophy according to fibre type composition. It has been reported that there is a marked difference in percentage

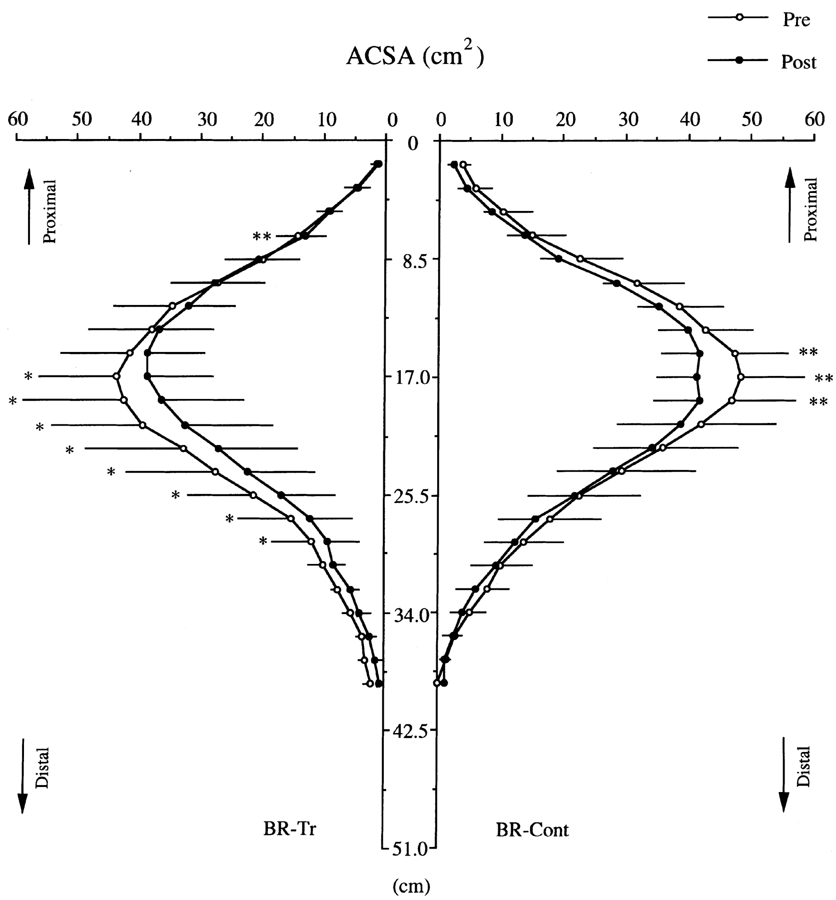

Figure 7 Serial anatomical cross-sectional area (ACSA) of plantar flexor muscles before and after bed rest in training (BR-Tr) and control (BR-Cont) group. *$P < 0.05$, **$P < 0.01$ vs. pre. The data for BR-Cont were derived from two previous reports (Akima *et al.* 1997b, 2000c). Republished with permission from Springer-Verlag and *Journal of Gravitational Physiology*.

slow-twitch fibres for the MG, LG and Sol (50.8, 50.3, and 82.3%, respectively) (Johnson *et al.* 1973). On the other hand, the atrophic responses of human skeletal muscles appear to be different from animal skeletal muscles. In animal studies, it is well known that the degree of atrophy after disuse and spaceflight in slow-twitch fibres, e.g. the Sol, is greater than in fast-twitch fibres, e.g. the plantaris and TA (Martin *et al.* 1988, Thomason & Booth 1990). These qualities have been observed in previous studies by other authors and ourselves. For example, Hather *et al.* (1992) observed that the degree of CSA loss in the gastrocnemius muscle was greater than that of the Sol after 6 weeks of ULLS. Furthermore, Edgerton *et al.* (1995) reported that in human VL muscles, the CSA of both slow-twitch and fast-twitch fibres decreased after 11 days of spaceflight (slow-twitch fibres: –17%, fast-twitch fibres: –21%).

The PCSA of the TA in BR-Cont showed a more significant difference in percentage change than that of MG, LG, and Sol. Other researchers in addition to ourselves have demonstrated that atrophy does not occur in the TA after just a few weeks of bed rest (LeBlanc *et al.* 1988, Akima *et al.* 1997b, 2000c). We speculated that the low level of atrophy in the TA might be partially because of its lower activation level during ordinary activity and physical exertion when compared with other antigravity muscles such as the PF. However, even after short duration (5 and 11 days) of spaceflight, LeBlanc *et al.* (1995) reported that in four astronauts, the muscle volume of the anterior calf significantly decreased by 4%. It has been reported that muscle fibre composition of this muscle is 74% of slow-twitch fibres (Johnson *et al.* 1973). In animal unloading studies, it seems fairly accepted that muscles with a high ratio of slow-twitch fibres such as Sol display greater atrophy than muscles such as the TA or plantaris which are dominated by fast-twitch fibres (in rats and mice, the TA is primarily composed of fast-twitch fibres). We would like to emphasis that atrophy appears not to be fibre type specific based on our observations of the PF. Rather, it seems that for human skeletal muscles, the level of activation in daily life is a greater factor in determining a muscle's susceptibility to atrophy.

Only a few attempts have been made in previous studies to show the locations of changes in muscle shape as a result of disuse (Akima *et al.* 1997b, 2000b, c). Figures 4–6 show changes in muscle shape in the BR-Tr and BR-Cont after 20 days of bed rest. In both groups and in all muscle groups, a significant change mainly occurred around the region of the peak ACSA, rather than at either edge of the muscle belly. This result supports our previous studies (Akima *et al.* 1997b, 2000b, c). The mechanism of this phenomenon after unloading is not clear, but serial ASCA measurement from the origin to the termination of groups and individual muscles accurately revealed the location of muscle atrophy caused by disuse.

In summary, we investigated the effects of dynamic leg press training on the PCSA of individual muscles and groups found in human lower limbs (KE, KF, PF, and dorsiflexor muscles) during 20 days of 6° head-down decline bed rest. Dynamic leg press exercises during bed rest prevented atrophy of the KE and KF muscles; however, decreases in PF PCSA was similar in the BR-Tr and BR-Cont groups. These results suggest that dynamic resistance training may be useful in preventing the loss of muscle mass in thigh muscle groups during short periods of disuse.

This study is funded by a part of 'Ground Research for Space Utilization' promoted by NASDA and Japan Space Forum. The authors thank Dr Y. Makita and the staffs in Makita private general hospital for their technical assistance of MR imaging measurements.

REFERENCES

Adams, G.R., Duvoisin, M. & Dudley, G.A. 1992. MRI and EMG as indices of muscle function. *J Appl Physiol* **73,** 1578–1583.

Akima, H., Kuno, S., Inaki, M., Shimojo, H. & Katsuta, S. 1997a. Effects of sprint cycle training on architectural characteristics, torque–velocity relationships, and power output in human skeletal muscles. *Adv Exerc Sports Physiol* **3,** 9–15.

Akima, H., Kuno, S., Suzuki, Y., Gunji, A. & Fukunaga, T. 1997b. Effects of 20 days of bed rest on physiological cross-sectional area of human thigh and leg muscles evaluated by magnetic resonance imaging. *J Gravit Physiol* **4,** S15–S21.

Akima, H., Takahashi, H., Kuno, S. *et al.* 1999. Early phase adaptations of muscle use and strength to isokinetic training. *Med Sci Sports Exerc* **31,** 588–594.

Akima, H., Ito, M., Yoshikawa, H. & Fukunaga, T. 2000a. Recruitment plasticity of neuromuscular compartments in exercised tibialis anterior using echo-planar magnetic resonance imaging in humans. *Neurosci Lett* **296,** 133–136.

Akima, H., Kawakami, Y., Kubo, K. *et al.* 2000b. Effect of short duration of spaceflight on thigh and leg muscle volume. *Med Sci Sports Exerc* **32,** 1743–1747.

Akima, H., Kubo, K., Kanehisa, H., Suzuki, Y., Gunji, A. & Fukunaga, T. 2000c. Leg-press resistance training during 20 days of 6° head-down-tilt bed rest prevents muscle deconditioning. *Eur J Appl Physiol* **82,** 30–38.

Ameredes, B.T. & Clanton, T.L. 1990. Increased fatigue of isovelocity vs. isometric contractions of canine diaphragm. *J Appl Physiol* **69,** 740–746.

Bamman, M.M., Hunter, G.R., Stevens, B.R., Guilliams, M.E. & Greenisen, M.C. 1997. Resistance exercise prevents plantar flexor deconditioning during bed rest. *Med Sci Sports Exerc* **29,** 1462–1468.

Bamman, M.M., Clarke, M.S.F., Feeback, D.L. *et al.* 1998. Impact of resistance exercise during bed rest on skeletal muscle sarcopenia and myosin isoform distribution. *J Appl Physiol* **84,** 157–163.

Berg, H.E., Dudley, G.A., Häggmark, T., Ohlsén, H. & Tesch, P.A. 1991. Effects of lower limb unloading on skeletal muscle mass and function in humans. *J Appl Physiol* **70,** 1882–1885.

Berg, H.E., Larsson, L. & Tesch, P.A. 1992. Lower limb muscle function after 6 wk of bed rest. *J Appl Physiol* **82,** 182–188.

Bloomfield, S.A. 1997. Changes in muscloskeletal structure and function with prolonged bed rest. *Med Sci Sports Exerc* **29,** 197–206.

Dudley, G.A., Tesch, P.A., Miller, B.J. & Buchanan, P. 1991. Importance of eccentric actions in performance adaptations to resistance training. *Aviat Space Environ Med* **62,** 543–550.

Dudley, G.A., Duvoisin, M.R., Adams, G.R., Meyer, R.A., Belew, A.H. & Buchanan, P. 1992. Adaptations to unilateral lowerlimb suspension in humans. *Aviat Space Environ Med* **63,** 678–683.

Duvoisin, M.R., Convertino, V.A., Buchanan, P., Gollnick, P.D. & Dudley, G.A. 1989. Characteristics and preliminary observations of the influence of electromyostimulation on the size and function of human skeletal muscle during 30 days of simulated microgravity. *Aviat Space Environ Med* **60,** 671–678.

Edgerton, V.R., Zhou, M.-Y., Ohira, Y. *et al.* 1995. Human fiber size and enzymatic properties after 5 and 11 days of spaceflight. *J Appl Physiol* **78,** 1733–1739.

Escamilla, R.F., Fleisig, G.S., Zheng, N., Barrentine, S.W., Wilk, K.E. & Andrews, J.R. 1998. Biomechanics of the knee during closed kinetic chain and open kinetic chain exercises. *Med Sci Sports Exerc* **30,** 556–569.

Ferrando, A.A., Stuart, C.A., Brunder, D.G. & Hillman, G.R. 1995. Magnetic resonance imaging quantitation of changes in muscle volume during 7 days of strict bed rest. *Aviat Space Environ Med* **66,** 976–981.

Ferretti, G., Antonutto, G., Denis, C. *et al.* 1997. The interplay of central and peripheral factors in limiting O_2 consumption in man after prolonged bed rest. *J Physiol (London)* **501,** 677–686.

Fukunaga, T., Roy, R.R., Shellock, F.G. *et al.* 1992. Physiological cross-sectional area of human leg muscles based on magnetic resonance imaging. *J Orthop Res* **10,** 926–934.

Fukunaga, T., Roy, R.R., Shellock, F.G., Hodgson, J.A. & Edgerton, V.R. 1996. Specific tension of human plantar flexors and dorsiflexors. *J Appl Physiol* **80,** 158–165.

Germain, P., Guell, A. & Marini, J.F. 1995. Muscle strength during bedrest with and without muscle exercise as a countermeasure. *Eur J Appl Physiol* **71,** 342–348.

Gogia, P.P., Schneider, V.S., LeBlanc, A.D., Krebs, J., Kasson, C. & Pientok, C. 1988. Bed rest effect on extremity muscle torque in healthy men. *Arch Phys Med Rehab* **69,** 1030–1032.

Hather, B.M., Adams, G.R., Tesch, P.A. & Dudley, G.A. 1992. Skeletal muscle responses to lower limb suspension in humans. *J Appl Physiol* **72,** 1493–1498.

Hikida, R.S., Gollnick, P.D., Dudley, G.A., Convertino, V.A. & Buchanan, P. 1989. Structural and metabolic characteristics of human skeletal muscle following 30 days of simulated microgravity. *Aviat Space Environ Med* **60,** 664–670.

Johnson, M.A., Polgar, J., Weightman, J.D. & Appleton, D. 1973. Data on the distribution of fiber types in thirty-six human muscles. An autopsy study. *J Neurol Sci* **18,** 111–129.

Koryak, Y. 1998. Effect of 120 days of bed-rest with and without countermeasures on the mechanical properties of the triceps surae muscle in young women. *Eur J Appl Physiol* **78,** 128–135.

LeBlanc, A., Gogia, P., Schneider, V., Krebs, J., Schonfeld, E. & Evans, H. 1988. Calf muscle area and strength changes after five weeks of horizontal bed rest. *Am J Sports Med* **16,** 624–629.

LeBlanc, A., Schonfeld, E., Evans, H.J., Pientok, C., Rowe, R. & Spector, E. 1992. Regional changes in muscle mass following 17 weeks of bed rest. *J Appl Physiol* **73,** 2172–2178.

LeBlanc, A., Rowe, R., Schneider, V., Evans, H. & Hedrick, T. 1995. Regional muscles loss after short duration spaceflight. *Aviat Space Environ Med* **66,** 1151–1154.

LeBlanc, A., Lin, C., Shackelford, L. *et al.* 2000. Muscle volume, MRI relaxation times (T2), and body composition after spaceflight. *J Appl Physiol* **89,** 2158–2164.

Martin, T.P., Edgerton, V.R. & Grindeland, R.E. 1988. Influence of spaceflight on rat skeletal muscle. *J Appl Physiol* **65,** 2318–2325.

Meyer, R.A. & Prior, B.M. 2000. Functional magnetic resonance imaging of muscle. *Exerc Sport Sci Rev* **28,** 89–92.

Ploutz, L.L., Tesch, P.A., Biro, R.L. & Dudley, G.A. 1993. Effect of resistance training on muscle use during exercise. *J Appl Physiol* **76,** 1675–1681.

Ploutz-Snyder, L.L., Convertino, V.A. & Dudley, G.A. 1995. Resistance exercise-induced fluid shifts change in active muscle size and plasma volume. *Am J Physiol* **269,** R536–R543.

Price, T.B., Kennan, R.P. & Gore, J.C. 1998. Isometric and dynamic exercise studied with echo planar MRI. *Med Sci Sports Exerc* **30,** 1374–1380.

Sale, D.G., Martin, J.E. & Moroz, D.E. 1992. Hypertrophy without increased isometric strength after weight training. *Eur J Appl Physiol* **64,** 52–55.

Suzuki, Y., Murakami, T., Haruna, Y. *et al.* 1994. Effects of 10 and 20 days bed rest on leg muscle mass and strength in young subjects. *Acta Physiol Scand Supplement* **616,** 5–18.

Tabata, I., Suzuki, Y., Fukunaga, T., Yokozeki, T., Akima, H. & Funato, K. 1999. Resistance training afects GLUT-4 content in skeletal muscle of humans after 19 days of head-down bed rest. *J Appl Physiol* **86,** 909–914.

Thomason, D.B. & Booth, F.W. 1990. Atrophy of the soleus muscle by hindlimb unweighting. *J Appl Physiol* **68,** 1–12.

Vandenborne, K., Walter, G., Ploutz-Snyder, L., Dudley, G., Elliott, M.A. & Meirleir, K.D. 2000. Relationship between muscle T_2* relaxation properties and metabolic state: a combined localized ^{31}P-spectroscopy and ^{1}H-imaging study. *Eur J Appl Physiol* **82,** 76–82.

Wickiewicz, T.L., Roy, R.R., Powell, P.L., Perrine, J.J. & Edgerton, V.R. 1983. Muscle architecture of the human lower limb. *Clin Orthop Rel Res* **179,** 275–283.

Widrick, J.J., Knuth, S.T., Norenberg, K.M. *et al.* 1999. Effect of a 17 day spaceflight on contractile properties of human soleus muscle fibres. *J Physiol (London)* **516,** 915–930.

Yue, G., Alexander, A.L., Laidlaw, D.H., Gmitro, F., Unger, E.C. & Enoka, R.M. 1994. Sensitivity of muscle proton spin–spin relaxation time as an index of muscle activation. *J Appl Physiol* **77,** 84–92.

