Scand J Med Sci Sports 2005:
Printed in Denmark · All rights reserved
DOI: 10.1111/j.1600-0838.2005.00450.x

COPYRIGHT © BLACKWELL MUNKSGAARD 2005
SCANDINAVIAN JOURNAL OF
MEDICINE & SCIENCE
IN SPORTS

Effects of isometric training at different knee angles on the muscle–tendon complex *in vivo*

K. Kubo[1], K. Ohgo[2], R. Takeishi[2], K. Yoshinaga[2], N. Tsunoda[2], H. Kanehisa[1], T. Fukunaga[3]

[1]Department of Life Science, University of Tokyo, Meguro, Tokyo, Japan, [2]Department of Physical Education, Kokushikan University, Tokyo, Japan, [3]Department of Human Sciences, Waseda University, Tokorozawa, Saitama, Japan
Corresponding author: Keitaro Kubo, PhD, Department of Life Science (Sports Sciences), University of Tokyo, Komaba 3-8-1, Meguro-ku, Tokyo 153-8902, Japan. Tel: +81 3 5454 6860, Fax: +81 3 5454 4317, E-mail: kubo@idaten.c.u-tokyo.ac.jp

Accepted for publication 30 December 2004

The purpose of this study was to investigate the influences of isometric training at different joint angles on the muscle size and function of the human muscle–tendon complex *in vivo*. Furthermore, we tried to gain a better understanding of the mechanisms involved in angle specificity after isometric training from the aspect of neuromuscular adaptation and the changes in the properties of the muscle–tendon complex. Nine males completed 12-week unilateral training program (70% of maximal voluntary contraction (MVC) × 15 s × six sets) on the knee extensors at 50° (shorter muscle length: ST) and 100° (longer muscle length: LT). The internal muscle force (mechanical stress) is higher at 100° than at 50° because of the difference in the moment arm length, although there were no difference in the relative torque level, contraction and relaxation times, and repetition between ST and LT. Before and after training, isometric strength at eight angles and muscle volume were determined. Tendon elongation of knee extensors was measured by ultrasonography. There was no significant difference in the rate of increment of muscle volume between the protocols. Tendon stiffness increased significantly for LT, but not for ST. Although significant gain was limited to angles at or near the training angle for ST, increases in MVC at all angles were found for LT. These results suggest that only mechanical stress (internal muscle force imposed on muscle and tendon) contributes to adaptation in the tendon stiffness, although metabolic (relative torque level, etc.) and mechanical stress relate to muscle hypertrophy. Furthermore, increment of tendon stiffness for LT might contribute to increase torque output at smaller angles other than the training angle.

It has been generally known that heavy resistance exercise has an effect for muscle hypertrophy and strength gains. In addition to this, the high mechanical stress imposed on the muscle may lead to a stimulus for the changes in neuromotor control, metabolic demands, and endocrine activities. On the other hand, previous findings obtained from animal experiments demonstrated that the influences of physical training on the tendon properties differ between the exercises protocols used (Woo et al., 1981; Simonsen et al., 1995). Furthermore, some recent observations have shown that the training regimens used led to differences in the effects on the human tendon properties based on cross-sectional and longitudinal studies (Kubo et al., 2001, 2003; Hansen et al., 2003). According to the findings of Kubo et al. (2003) and Hansen et al. (2003), the low-load resistance training and running training did not change the tendon stiffness. Considering these findings from animal and human experiments, it is hypothesized that adaptation of the tendon structures to physical training varies with the exerted force level during exercise.

Changes in muscle length, determined by joint angle, can affect external torque production. In addition, the moment arm length is an important factor when the exerted muscle force is converted to the joint torque. Previous studies demonstrated that the moment arm length changes with joint angles (Marshall et al., 1990; Maganaris et al., 1998). Therefore, the internal muscle force levels were different if the exerted joint torque values were the same at different joint angles (Ng et al., 1994). For example, the knee extension torque – knee joint angle curve was different from the knee extensor force – knee joint angle curve, because the moment arm length for knee extensor muscles increased from knee flexed position to knee extended position (e.g. Marshall et al., 1990). Considering these points, isometric training at two different joint angles would result in unique adaptations in the morphological and/or functional properties of the exercising muscle–tendon complex because of the difference in the internal muscle force level in spite of the same joint torque level.

It is well known that strength increases induced by isometric training are specific to the joint angle at the point where exercise is performed (Thepaut-Mathieu et al., 1988; Kitai & Sale, 1989). Thepaut-Mathieu et al. (1988) showed that electromyographic activities (EMGs) increased at the joint angles used in training. In addition, Kitai and Sale (1989) did not find any increases in the maximal twitch torque at joint angles exhibiting increases in maximal voluntary torque. These results would indicate that "neural adaptation" was associated with joint angle specificity. On the contrary, the linkage between strength and EMG changes after isometric training was not found by Garfinkel and Cafarelli (1992) and Weir et al. (1994). Therefore, the mechanisms resulting in the joint angle specificity are still unclear. Furthermore, only a few studies have ever tried to investigate the effects of isometric training at two different joint angles (Gardner, 1962; Thepaut-Mathieu et al., 1988). Concerning the joint angle selected for isometric training, angular specificity is more marked when the selected joint angle places the involved muscles in a shortened position (Gardner, 1962; Thepaut-Mathieu et al., 1988). However, the mechanisms for the differences in the training effects of trained muscle length, i.e. joint angle, are also unknown.

In the present study, the elongation of the tendon structures of the vastus lateralis (VL) muscle *in vivo* was directly measured using ultrasonography before and after 12 weeks of isometric training at different knee joint angles. The purposes of this study were (1) to consider the mechanisms of "angular specificity" from the effects of training with different joint angles on muscle strength, tendon properties and neural activation, (2) to investigate the effect of training with different internal muscle force (in spite of same joint torque level) on tendon stiffness.

Methods

Subjects

Nine healthy males (age: 24 ± 1 years, height: 172 ± 6 cm, body mass: 70 ± 9 kg, mean ± SD) voluntarily participated as subjects. The subjects were fully informed of the procedures to be utilized as well as the purpose of the study. Written informed consent was obtained from all the subjects. This study was approved by the office of the Department of Sports Sciences, University of Tokyo, and complied with their requirements for human experimentation.

Training

The subjects completed four times per week for 12 weeks of a unilateral isometric knee extension-training program on a dynamometer (Myoret, Asics, Tokyo, Japan). One leg was trained at 50° (shorter muscle length: ST) and the other leg was trained at 100° (longer muscle length: LT). In each subject, the right and left legs were randomly allocated to the training protocols. Both protocols consisted of 70% of maximal voluntary contraction (MVC) with six sets of contraction for 15 s with a 30 s rest between each. To acclimatize to the training protocol, slightly lower loads corresponding to 50% of MVC were used for the first week and 60% of MVC for the second week. The measurement of MVC was made every 2 weeks to adjust the training load. In a training session a subject would train the LT protocol leg first then the ST protocol leg, and in the next session the order would be reversed.

Elasticity of tendon structures

Each subject was seated on a test bench of a dynamometer with the hip joint angles of 80° flexed (full extension = 0°). The axis of the lever arm of the dynamometer was visually aligned with the center of rotation of the knee joint. The foot was firmly attached to the lever arm of the dynamometer with a strap and fixed with the knee joint angles of 80° flexed (full extension = 0°). After a standardized warm-up and submaximal contractions to become accustomed to the tests, the subjects exerted isometric knee extension torque from zero (relax) to MVC within 5 s. The task was repeated twice per subject with at least 3 min between trials. Torque signals were A/D converted at a sampling rate of 1 kHz (MacLab, AD Instrument) and analyzed by a computer (model Powerbook G4, Apple, Tokyo, Japan). The measured values shown below are the means of two trials.

An ultrasonic apparatus (SSD-2000, Aloka, Tokyo, Japan) with an electronic linear array probe (7.5-MHz wave frequency with 80 mm scanning length; UST 5047-5, Aloka) was used to obtain a longitudinal ultrasonic image of the VL muscle at the level of 50% of the thigh length, i.e. the distance from the greater trochanter to the lateral epicondyle of the femur. The width and depth resolutions of ultrasonography with this probe are 0.67 and 0.4 mm, respectively. The probe was longitudinally attached to the dermal surface by adhesive tape, which restrained the probe from sliding (Kubo et al., 2001). The ultrasonic images were recorded on videotape at 30 Hz, and synchronized with recordings of a clock timer for subsequent analyses. The tester visually confirmed the echoes from the aponeurosis and VL fascicles. The point at which one fascicle was attached to the aponeurosis (P) was visualized on the ultrasonic image. We carefully chose these points, confirming that they showed clear echoes throughout the muscle contraction. The P moved proximally during isometric torque development up to a maximum. The displacement of P (L) is considered to indicate the lengthening of the deep aponeurosis and the distal tendon (Kubo et al., 2001).

The knee joint torque (TQ) measured by the dynamometer was converted to muscle force (F_m) by the following equation:

$$F_m = k \text{ TQ MA}^{-1}$$

where k is the relative contribution of VL to the quadriceps femoris muscles in terms of the ratio of the muscle volume, and MA is the moment arm length of the quadriceps femoris muscles at 80° of knee flexion, which is estimated from the thigh length of each subject as described by Visser et al. (1990). In the present study, the F_m and L values above 50% MVC were fitted to a linear regression equation, the slope of which was adopted as an index of the stiffness (Kubo et al., 2001).

It has been shown that passive angular rotation about a joint results in considerable tendon displacement (Marshall et al., 1990). Therefore, the tendon displacement will be attributed to both angular rotation and contractile tension, because any angular joint rotation occurs in the direction of knee extension during an "isometric" contraction. Thus, angular joint rotation needs to be accounted for to avoid an overestimation of tendon displacement during an isometric

contraction (Magnusson et al., 2001; Maganaris & Paul, 2002). To monitor knee joint angular rotation an electrical goniometer (Penny & Giles, Biometrics Ltd, Gwent, UK) was placed on the lateral aspect of the knee. To correct the measurements taken for the tendon elongation, additional measurements were taken under passive conditions. The displacement of the tendon structures caused by rotating the knee from 80° to 60° was digitized in sonographs taken, as described in the above section. Thus, for each subject the tendon elongation obtained from the ultrasound images could be corrected for that attributed to joint rotation alone.

Muscle volume and tendon cross-sectional area (CSA)

Measurements of muscle and tendon CSAs were carried out by magnetic resonance imaging scans (AIRIS II, HITACHI Medical Cop., Tokyo, Japan). Details of the methodology employed have been described elsewhere (Kubo et al., 2001). T1-weighted spin-echo, and 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 0 mm. The subjects were imaged in a prone position with the knee kept at 0°. The muscles investigated were as follows: rectus femoris (RF), VL, vastus intermedius (VI), and vastus medialis (VM). In each cross-sectional image, outlines of the quadriceps femoris muscles were traced, and the anatomical CSA of each muscle was measured. The muscle volume was determined by multiplying the anatomical CSA of each image by the thickness (10 mm). In addition, the tendon CSA was measured 0 and 10 mm above the patella. The average CSA at the two positions was calculated as the representative of the tendon CSA.

Torque–angle relationship

The posture of the subject and setup were similar to those for the measurement of the tendon properties as mentioned above. The participants were asked to perform two 3 s maximal voluntary isometric contractions of the quadriceps femoris. The mean of two peak values was calculated and if the two values differed by more than 10%, the subject was requested to perform a third. We examined eight different knee angles, 40°, 50°, 60°, 70°, 80°, 90°, 100°, 110°. Joint angle order was randomized in order to avoid any systematic effects. The pre-training order of testing was also followed during the post-training test session. The peak torque for each 3 s contraction was recorded and the mean of the two contractions at each joint angle was used as the performance measure. The coefficient of variance of the two measurements was in the range of 0–6.9% (2.7 ± 1.7%).

EMG

The EMG was recorded during the measurement of the tendon properties and torque–angle relationship. The bipolar surface electrodes (5 mm in diameter) were placed over the bellies of RF, VL, VI, VM and the long head of the biceps femoris (BF) muscles with a constant interelectrode distance of 25 mm. The electrodes were connected to a preamplifier and differential amplifier with a bandwidth of 5–500 Hz (model 1253A, NEC Medical Systems, Tokyo, Japan). The EMG signals were transmitted to a computer at a sampling rate of 1 kHz. The EMG was full-wave rectified and integrated for the duration of the contraction for the measurement of tendon properties and for a 1.0 s period of steady-force output for the measurement of the torque–angle relationship, respectively, to give integrated EMG (iEMG). In addition, for the measurement of the torque–angle relationship, the sum of iEMG in the knee extensors (VL, RF, VM) was defined as $iEMG_{QF}$.

To quantify the antagonist muscle activity, we normalized its iEMG value at each joint angle with respect to its iEMG value at the same angle when acting as agonist at maximal effort.

Statistics

Descriptive data included means ± SD. The data were analyzed with a two factor (test times, groups) or a three factor (test times, groups, joint angles) analysis of variance. The F ratio for main effects and interactions was considered significant at $P<0.05$. Significant differences among means at $P<0.05$ were detected using Tukey's post-hoc test.

Results

There were no significant differences in the relative increase in MVC values at each trained knee angle between ST (49 ± 28%) and LT (44 ± 20%) ($P = 0.547$, Fig. 1). For ST, the MVC values suddenly increased at 4 and 6 weeks, then increased and remained constant throughout training period. On the other hand, the MVC values for LT increased significantly at 4 weeks, then steadily increased to the end of training period. Furthermore, the MVC values at 6 and 8 weeks were significantly higher for ST than for LT.

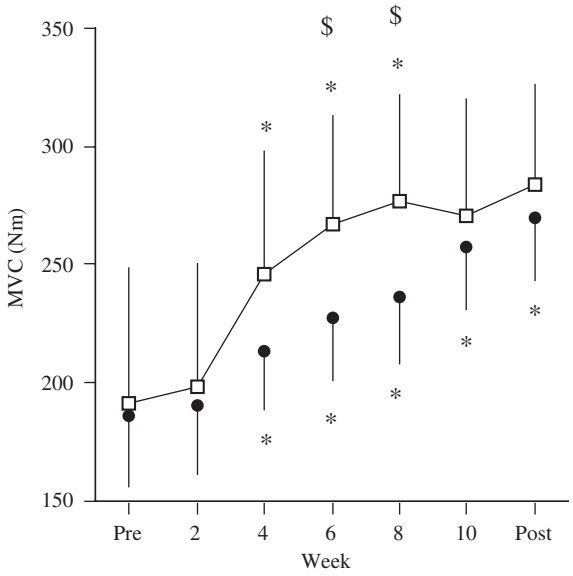

Fig. 1. The maximal voluntary contraction (MVC) values at each trained knee angle for shorter muscle length (ST) (open square) and longer muscle length (LT) (closed circle) during the 12-week training period. There were no significant differences in the relative increase in MVC values at each trained knee angle between ST (49 ± 28%) and LT (44 ± 20%). The MVC values at 6 and 8 weeks were significantly higher for ST than for LT. *Significantly different from previous week, $significantly different between ST and LT.

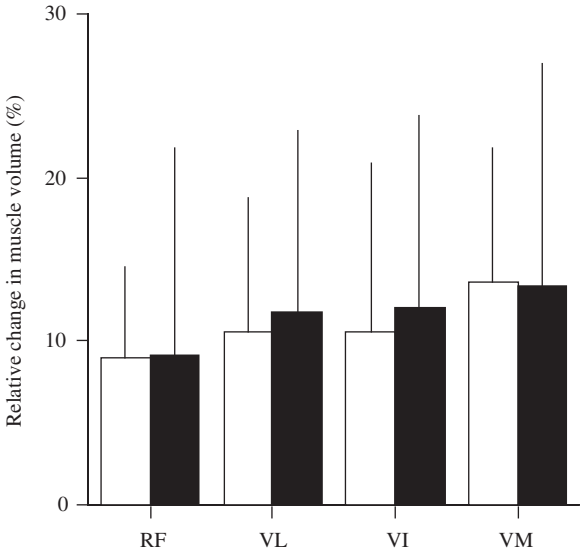

Fig. 2. The relative changes in the muscle volumes of m. rectus femoris (RF), m. vastus lateralis (VL), m. vastus intermedius (VI) and m. vastus medialis (VM) before and after training. Open bars show the shorter muscle length protocol and closed bars show the longer muscle length protocol. All the muscle volumes increased significantly. However, there seemed to be no differences in the degree of increase in the muscle volumes among the knee extensor muscle.

The muscle volumes of the knee extensor muscles increased significantly from 1858 ± 242 to $2049 \pm 224\,cm^3$ ($+10 \pm 1\%$; $P = 0.020$) for ST and from 1913 ± 224 to $2152 \pm 213\,cm^3$ ($+11 \pm 2\%$; $P = 0.017$) for LT. No significant difference in the relative increase in muscle volume was found between ST and LT. There were no significant differences in the relative increase in the muscle volume among the constituents of the quadriceps femoris muscles (Fig. 2). Furthermore, no significant changes in the tendon CSA were found between both ST and LT (Table 1).

Figure 3 shows the relationships between F_m and corrected L before and after training. There were no significant differences in the L values at all the force production levels and stiffness value before training between ST and LT. During the graded knee

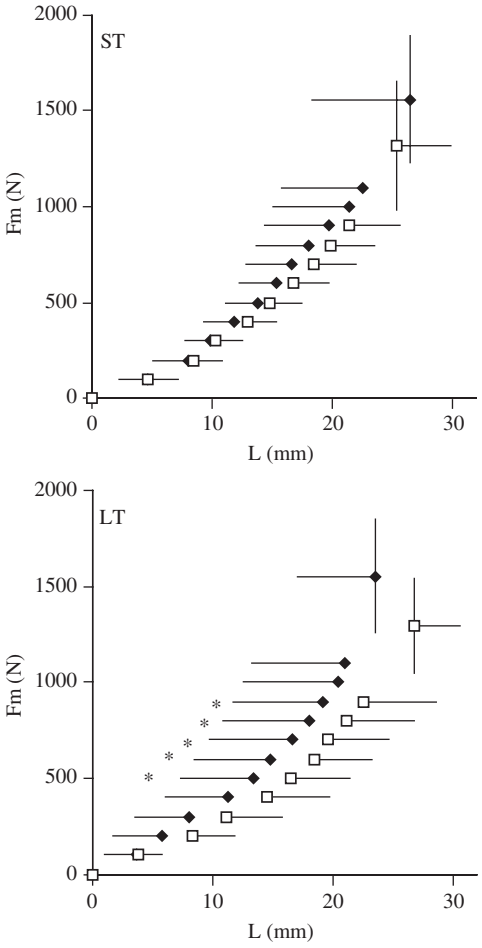

Fig. 3. The relationship between F_m and corrected L before (open) and after (after) the two kinds of isometric training for 12 weeks. The shorter muscle length (ST) protocol produced no significant differences in the L values at all the force production levels between before and after. For the longer muscle length (LT) protocol, the L values above 500 N were significantly shorter after training. *Significantly shorter than before.

Table 1. The measured parameters before and after training (mean ± SD)

	MVC (N m)		Maximum L (mm)	
	Before	After	Before	After
ST	257 ± 65	304 ± 63*	25.4 ± 4.6	26.4 ± 8.2
LT	253 ± 48	303 ± 57*	26.8 ± 3.8	23.5 ± 6.5*

	Stiffness (N/mm)		Tendon CSA (mm^2)	
	Before	After	Before	After
ST	78.7 ± 21.4	86.3 ± 35.8	204 ± 19	207 ± 22
LT	80.8 ± 25.8	121.9 ± 39.9*	202 ± 13	205 ± 17

MVC, maximal voluntary contraction; ST, shorter muscle length; LT, longer muscle length; CSA, cross-sectional area.
*Significantly different from before.

Table 2. The iEMG values (mV s) during ramp isometric contraction

	RF	VL	VM
ST			
Before	1.35 ± 0.22 (30.8 ± 5.5)	1.55 ± 0.23 (35.4 ± 5.7)	1.47 ± 0.29 (33.6 ± 6.5)
After	1.46 ± 0.28* (31.5 ± 5.8)	1.60 ± 0.17* (34.5 ± 4.9)	1.57 ± 0.30* (33.9 ± 6.6)
LT			
Before	1.34 ± 0.25 (31.0 ± 5.7)	1.51 ± 0.21 (34.9 ± 5.4)	1.47 ± 0.20 (34.0 ± 5.4)
After	1.47 ± 0.29* (31.2 ± 6.0)	1.65 ± 0.18* (35.1 ± 5.2)	1.58 ± 0.24* (33.6 ± 5.7)

Mean ± SD (relative value of each iEMG to the sum of iEMG of the three muscles).

*Significantly difference from before.

iEMG, integrated electromyographic activity; ST, shorter muscle length; LT, longer muscle length; RF, rectus femoris; VL, vastus lateralis; VM, vastus medialis.

extension effort the maximal knee joint angular displacement was 12 ± 3° before and 14 ± 5° after training. There were no significant differences in the maximal knee joint angular displacement between before and after training ($P = 0.211$). In addition, there was no significant difference in the relative increase of iEMG among the three muscles (RF, VL, VM) and no changes in the relative iEMG values (to the sum of iEMG of RF, VL, VM) were found after training (Table 2). The MVC value at 80° of knee angle increased significantly 20.6 ± 17.3% ($P < 0.001$) for ST and 20.3 ± 11.7% ($P < 0.001$) for LT. The ST protocol produced no significant differences in the L values at all the force production levels between before and after. In the case of the LT protocol, the L values above 500 N were significantly shorter after training. In addition, the maximal L decreased significantly 13.4 ± 10.8% ($P = 0.034$) (Table 1). A two-way ANOVA on the stiffness showed a significant effect ($P = 0.021$) of groups × test time interaction. The stiffness increased significantly for LT ($P = 0.014$), but not for ST ($P = 0.181$) (Table 1). The relative increase in stiffness was significantly greater for LT than for ST ($P = 0.033$).

Figure 4 shows the relationship between torque and knee joint angle before and after training. For ST, training did not cause a significant overall increase in the strength (test times main effect, $P = 0.152$); however, there was a significant ($P = 0.010$) test times × joint angles interaction, indicating specificity of joint angle after training. Post-hoc analysis indicated that a significant strength improvement was found only for the training angle and the adjacent angles (40–80°, $P < 0.05$). On the contrary, the least specificity was observed for LT. Significant increases of MVC values were found at all the measured angles ($P < 0.05$).

The $iEMG_{QF}$ values at all joint angles increased significantly for ST (39 ± 6%; 27–47%) and LT (37 ± 3%; 32–43%) (Fig. 5). However, there were no significant differences in the rate of increase in $iEMG_{QF}$ values among the measured joint angles (test times × joint angles interaction, $P = 0.472$).

The co-activation levels of BF varied significantly across joint angles (joint angle main effect, $P < 0.001$) (Fig. 6). The co-activation levels of BF were significantly higher at 90–110° of the knee joint angles than

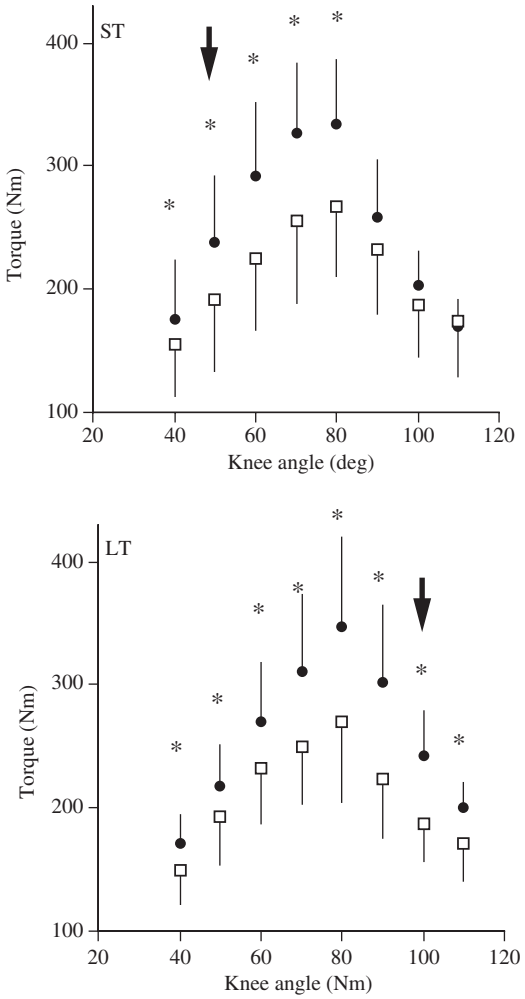

Fig. 4. The relationships between maximal voluntary contraction (MVC) and knee joint angles before (open square) and after (closed circle) training. The arrows show the trained angles. Although the significant gain was limited to angles at or near the training joint angle for shorter muscle length (ST), increases in MVC at all angles were found for longer muscle length (LT).

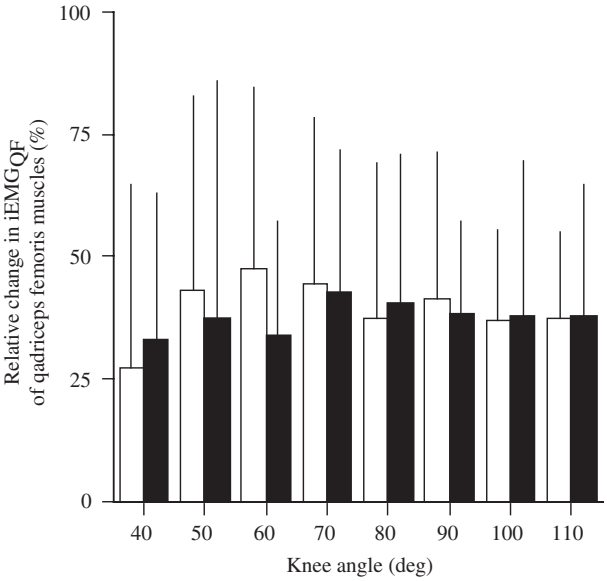

Fig. 5. The relative increase in integrated electromyographic activity ($iEMG_{QF}$) values for shorter muscle length (ST) (open) and longer muscle length (LT) (closed) protocols.

at the other knee joint angles. For both protocols, there were no significant differences in the co-activation levels of BF between before and after training (test times × joint angles interaction, $P = 0.651$).

Discussion

The present study showed that the increment of tendon stiffness after isometric training was greater using longer muscle length than using shorter muscle length. Furthermore, significant increases in MVC at all knee angles were found after isometric training using longer muscle length, while significant gain was limited to angles at or near the training angle after isometric training using shorter ones.

While the external torques exerted were the same, alterations of the knee joint angle must have produced different internal muscle forces by the effect of the moment arm length (Ng et al., 1994). Some previous studies showed that the moment arm length of the quadriceps tendon was longer at 50° than at 100° (Marshall et al., 1990; Spoor & Van Leeuwen, 1992). This indicates that for the same joint torque, the muscle force is higher at 100° than at 50°. In other words, the imposed mechanical stress on the muscle for LT (100°) was higher than that for ST (50°). According to the calculation using the previously reported moment arm lengths (Spoor & Van Leeuwen, 1992) and average MVC values at 50° and 100° before training, the internal VL force at 100° (2090 N) was 2.3 times greater than that at 50° (908 N). The high mechanical stress placed on the muscle as a result of this type of exercise may act as a stimulus for hypertrophy (e.g. McDonagh & Davies,

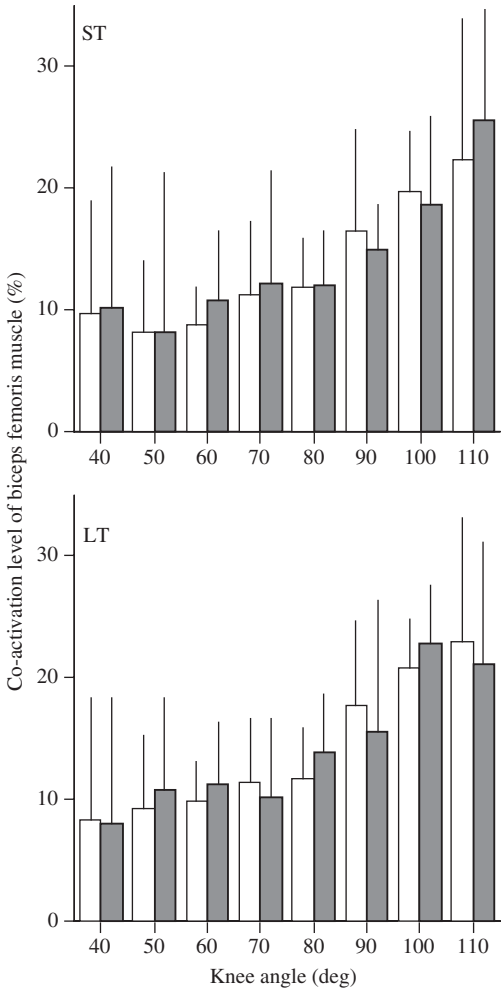

Fig. 6. Co-activation level of the biceps femoris muscles for shorter muscle length (ST) (upper) and longer muscle length (LT) (lower) protocols before (open) and after (dash) training. There were no significant differences between before and after training at all knee angles.

1984). In the present study, however, there were no differences in the increment of MVC and muscle volume. In addition to this, as shown in Fig. 1, the MVC values at 6 and 8 weeks were significantly higher for ST than for LT. This implies that the leg for LT may be tired at the middle phase of the training period because of higher "mechanical stress". Accordingly, if the subjects continue this training protocol for a longer period than 12 weeks, the increment of MVC and muscle volume for the LT protocol would be greater than that for ST.

The high mechanical stress on the muscle fibers and connective tissue used in strength training will cause metabolic changes within the muscle. There will be metabolite changes in the muscle and the stimulus for adaptation may arise as a result of these changes or indirectly through hormonal or growth factor release (Kraemer et al., 1990; Schott et al., 1995). Schott et al. (1995) reported that using nuclear magnetic resonance spectroscopy the changes in

phosphate metabolites and pH were greater for long isometric contractions than short contractions, and that strength improvement after 14 weeks training was greater long isometric contractions. Kraemer et al. (1990) showed that high-intensity exercise with an interest interval as short as 1 min induced more than a 100-fold increase in the plasma concentration of growth hormone, whereas the same exercises with a longer interest interval (3 min) did not. Previous studies demonstrated that the growth hormone played crucial roles in growth, development, and maintenance of skeletal muscle (Palmiter et al., 1983; Takarada et al., 2000). On the other hand, the relative torque level (70% of MVC), contraction and relaxation times (15, 30 s) and repetitions (six sets) were same for both the training protocols (ST and LT) in the present study. Furthermore, we confirmed that there was no significant differences in the relative decrease of MVC and increase muscle thickness after exercise between ST and LT protocols in a preliminary study. Accordingly, it is likely that the metabolite changes within muscle and tendon after exercises (i.e. metabolic stress) were same between the two types of training protocols. However, we cannot deny the possibility that the effects of hormonal release for the observed adaptations were subjected in the opposite leg, because the two types of training were performed within the same subjects.

On the other hand, the stiffness of the tendon structures increased significantly for LT (+47%), but not for ST (+5%) (Table 1). As mentioned above, ''metabolic stress'' would be the same between the two protocols because of the same relative torque levels, contraction and relaxation times, and repetitions. However, ''mechanical stress'' was higher at LT than at ST by the difference in the moment arm length. As far as we know, a few studies have ever tried to investigate the effects of ''metabolic stress'' to tendon (Klein et al., 2001; Yalamanchi et al., 2004). Some previous studies using animal have demonstrated that the mechanical stress and stretch play important roles in the remodeling process of the tendon structures (Langberg et al., 1999, 2001; Kim et al., 2002). Recent studies using the microdialysis technique showed that exercise-induced increases in the production of type 1 collagen of Achilles tendon were found in response to both 11 weeks of strength training and acute long distance running (Langberg et al., 1999, 2001). Unfortunately, we have no information concerning the collagen turnover of the tendon structures. According to our previous findings, the low-load resistance training, i.e. using body weight, did not change the tendon stiffness, although the high-load resistance training (70% of MVC, 70% of 1RM) made the tendon stiffness increase (Kubo et al., 2001, 2002). Similarly, Hansen et al. (2003) reported that the running training (relatively low load) for 9 months did not change the mechanical properties of the triceps surae tendon–aponeurosis complex and the dimensions of Achilles tendon. Taking these previous findings into account together with the present results, we may say that only mechanical stress contributes to adaptation in the tendon structures whereas metabolic and mechanical stress relates to muscle hypertrophy. However, these discussions are speculative and await additional data for clarification.

The effects of isometric training are specific to the joint angle selected for training; increases in strength are exclusive to or greater at the joint angle trained, in comparison with other joint angles (Lindh, 1979; Kitai & Sale, 1989). However, only a few studies have ever tried to investigate the effects of isometric training at two different joint angles (Gardner, 1962; Thepaut-Mathieu et al., 1988). Thepaut-Mathieu et al. (1988) reported that after isometric training of the elbow flexors in a shortened position, the increase in strength at trained angle was much greater than that at other angles. On the other hand, when training was carried out in a lengthening position of the muscles, the increase in strength was more equally distributed over the angular range. In other words, angular specificity is usually more marked when training has occurred at shorter muscle length (Gardner, 1962; Thepaut-Mathieu et al., 1988). The present result agreed with these previous findings (Gardner, 1962; Thepaut-Mathieu et al., 1988). Considering these findings, it would be desirable that the isometric training performed at longer muscle length, although the mechanisms involved in these findings are still unclear.

Angular specificity in isometric training has been attributed to some form of neural adaptation (Lindh, 1979; Thepaut-Mathieu et al., 1988; Kitai & Sale, 1989). For example, Thepaut-Mathieu et al. (1988) showed that EMGs increased at the joint angles used in training. On the contrary, Weir et al. (1994) reported that the strength increases were localized to the trained joint angle, whereas the iEMG increases were not observed. Changes in neural drive may be because of increases in motor unit recruitment, increases in motor unit firing rate, and/or decreases in neuromuscular inhibition (Sale, 1988). In the present study, the iEMG values at all joint angles increased significantly for ST and LT (Fig. 5). Furthermore, there were no significant differences in the rate of increase in iEMG values among the measured joint angles. Therefore, the linkage between MVC and EMG changes after training was not found for ST. A similar conclusion was reached by Garfinkel and Cafarelli (1992) and Weir et al. (1994). However, it is not to be denied that the changes in EMG activity at the various muscle lengths are caused by the changes in the recording

from different volume and numbers of muscle fibers because of electrode–muscle configuration changes (e.g. Farina et al., 2004).

Furthermore, previous evidence indicated that the levels of antagonistic co-contraction are modifiable with training (Carolan & Cafarelli, 1992). A training-induced decrease in co-contraction of the antagonist would result in increases in measured torque production. Accordingly, as part of the "learning" after isometric training, the activation level of antagonist may decrease at the trained and adjacent joint angles (Rutherford & Jones, 1986). However, this notion was not supported in this study.

Previous studies evaluated isometric strength after a concentric training program, which is thought to shift the torque–joint angle curve to the left (Lynn & Morgan, 1994; Lynn et al., 1998). Recently, some researchers reported that the stiffness of the human tendon structures increased significantly after the resistance training (Kubo et al., 2001, 2002; Reeves et al., 2003a, b). Considering these findings, increased tendon stiffness for LT would change the "torque–angle" relationship. In fact, our recent observation has shown that more compliant tendon structures would make the higher knee extension torque exert at the longer quadriceps femoris muscle than at shorter muscle length (Kubo et al., unpublished). Ichinose et al. (1997) showed that the human VL muscle used the ascending (knee $< 70^{\circ}$), plateau (70°), and descending regions ($> 70^{\circ}$) of the force–length curve. Namely, sarcomere lengths of the VL muscle shifted to shorter lengths because of the more compliant tendon structures. Therefore, compliant subjects could exert a higher torque at longer whole muscle length than at shorter whole muscle length. Taking these previous findings into account together with the present results, it is likely that the increment of tendon stiffness for LT might contribute to increase torque output at the knee-extended position other than the training angle or near (knee flexed position), and so resulted in the increase in MVC torque at all test angles in this group.

Soderberg and Cook (1983) and Soderberg et al. (1987) showed that RF was significantly more active than VM at the straight leg raising position. Inversely, Tang et al. (2001) demonstrated that as the knee flexion angle increased, the activation level of VM was greater. Furthermore, Narici et al. (1989) found preferential hypertrophy of VM and VI with lesser effects in the RF and VL following isokinetic strength training. In the present study, we estimated the relative contribution of VL to the knee extensors in terms of muscle volume to calculate the muscle force. Considering these previous findings, as mentioned above, it is likely that the differences in the degree of hypertrophy are found among the quadriceps femoris muscles. However, the present result showed that there were no significant differences between before and after training in the relative change in the muscle volume (Fig. 2). Furthermore, there was no significant difference in the relative increase of iEMG among the three muscles (RF, VL, VM) and no changes in the relative iEMG values (to the sum of iEMG of RF, VL, VM) were found after training (Table 2). These results implied that the relative contribution of each constituent for force production was similar between before and after training.

Perspectives

This study demonstrated a greater increment of stiffness of the human tendon structures following isometric training using longer muscle length compared with shorter ones. This implied that only mechanical stress contributes to adaptation in the tendon structures whereas metabolic and mechanical stress relates to muscle hypertrophy. However, these discussions are speculative and await additional data for clarification. Concerning this point, we are investigating the effects of low-intensity resistance training with vascular occlusion (Takarada et al., 2000) on the tendon stiffness. Furthermore, while a significant strength improvement was found only for the training angle and the adjacent angles for ST, the least specificity was observed for LT; MVC improvement as significant as for the training angle was found at the other angles. These results suggest that the isometric training at longer muscle length is admirable for the field of sports, although the mechanisms involved in these findings are still unclear.

Key words: stiffness, ultrasonography, *in vivo* determination, vastus lateralis muscle.

References

Carolan B, Cafarelli E. Adaptation in coactivation after isometric resistance training. J Appl Physiol 1992: 73: 9110–9117.

Farina D, Merletti R, Enoka RM. The extraction of neural strategies from the surface EMG. J Appl Physiol 2004: 96: 1486–1495.

Gardner GW. Specificity of strength changes of the exercised and nonexercised limb following isometric training. Res Quart 1962: 34: 98–101.

Garfinkel S, Cafarelli E. Relative changes in maximal force, EMG, and muscle cross-sectional area after isometric training. Med Sci Sports Exer 1992: 24: 1220–1227.

Hansen P, Aagaard P, Kjaer M, Larsson B, Magnusson SP. Effect of habitual running on human Achilles tendon load-deformation properties and cross-sectional area. J Appl Physiol 2003: 95: 2375–2380.

Ichinose Y, Kawakami Y, Ito M, Fukunaga T. Estimation of active force-length characteristics of human vastus lateralis muscle. Acta Anatomica 1997: 159: 78–83.

Kim SG, Akaike T, Sasagawa T, Atomi Y, Kurosawa H. Gene expression of type I and type III collagen by mechanical stretch in anterior cruciate ligament cells. Cell Struct Funct 2002: 27: 139–144.

Kitai TA, Sale DG. Specificity of joint angle in isometric training. Eur J Appl Physiol 1989: 58: 744–748.

Klein MB, Pham H, Yalamanchi N, Chang J. Flexor tendon wound healing in vitro: the effect of lactate on tendon cell proliferation and collagen production. J Hnd Surg 2001: 26: 847–854.

Kraemer WJ, Marchitelli L, Gordon SE, Harman E, Dziados JE, Mello R, Frykman P, McCurry D, Fleck SJ. Hormonal and growth factor responses to heavy resistance exercise protocols. J Appl Physiol 1990: 69: 1442–1450.

Kubo K, Kanehisa H, Fukunaga T. Effects of different duration isometric contractions on tendon elasticity in human quadriceps muscles. J Physiol 2001: 536: 649–655.

Kubo K, Kanehisa H, Fukunaga T. Effects of resistance and stretching training programs on the viscoelastic properties of tendon structures in vivo. J Physiol 2002: 538: 219–226.

Kubo K, Kanehisa H, Miyatani M, Tachi M, Fukunaga T. Effect of low-load resistance training on the viscoelastic properties of tendon-aponeurosis structures in middle aged and elderly women. Acta Physiol Scand 2003: 178: 25–32.

Kubo K, Ohgo K, Takeishi R, Yoshinaga K, Tsunoda N, Kanehisa H, Fukunaga T. Effects of elasticity of human tendon structures on the torque-angle relationship in vivo. Res Quart (unpublished).

Langberg H, Rosendal L, Kjaer M. Training-induced changes in peritendinous type I collagen turnover determined by microdialysis in humans. J Physiol 2001: 534: 297–302.

Langberg H, Skovgaard D, Petersen LJ, Bulow J, Kjaer M. Type I collagen synthesis and degradation in peritendinous tissue after exercise determined by microdialysis in humans. J Physiol 1999: 521: 299–306.

Lindh M. Increase of muscle strength from isometric quadriceps exercises at different knee angles. Scand J Rehab Med 1979: 11: 33–36.

Lynn R, Morgan DL. Decline running produces more sarcomeres in rat vastus intermedius muscle fibers than does incline running. J Appl Physiol 1994: 77: 1439–1444.

Lynn R, Talbot JA, Morgan DL. Differences in rat skeletal muscles after incline and decline running. J Appl Physiol 1998: 85: 98–104.

Maganaris CN, Baltzopoulos V, Sargeant AJ. Changes in Achilles tendon moment arm from rest to maximal isometric plantarflexion: in vivo observations in man. J Physiol 1998: 510: 977–985.

Maganaris CN, Paul JP. Tensile properties of the in vivo human gastrocnemius tendon. J Biomech 2002: 35: 1639–1646.

Magnusson SP, Aagaard P, Rosager S, Poulsen PD, Kjaer M. Load–displacement properties of the human triceps surae aponeurosis in vivo. J Physiol 2001: 531: 277–288.

Marshall RN, Mazur SM, Taylor NAS. Three-dimensional surfaces for human muscle kinetics. Eur J Appl Physiol 1990: 61: 263–270.

McDonagh MJN, Davies CTM. Adaptive response of mammalian skeletal muscle to exercise with high loads. Eur J Appl Physiol 1984: 52: 139–155.

Narici MV, Roi GS, Landoni L, Minetti AE, Cerretelli P. Changes in force, cross-sectional area and neural activation during strength training and detraining of the human quadriceps. Eur J Appl Physiol 1989: 59: 310–319.

Ng AV, Agre JC, Hanson P, Harrington MS, Nagle FJ. Influence of muscle length and force on endurance and pressor responses to isometric exercise. J Appl Physiol 1994: 76: 2561–2569.

Palmiter RD, Norstedt G, Gelinas RE, Hammer RE, Brinster RL. Metallothionein-human GH fusion genes stimulate growth of mice. Science 1983: 222: 809–814.

Reeves ND, Maganaris CN, Narici MV. Effect of strength training on human patella tendon mechanical properties of older individuals. J Physiol 2003a: 548: 971–981.

Reeves ND, Narici MV, Maganaris CN. Strength training alters the viscoelastic properties of tendons in elderly humans. Muscle Nerve 2003b: 28: 74–81.

Rutherford OM, Jones DA. The role of learning and coordination in strength training. Eur J Appl Physiol 1986: 55: 100–105.

Sale DG. Neural adaptation to resistance training. Med Sci Sports Exer 1988: 20: 135–S145.

Schott J, McCully K, Rutherford OM. The role of metabolites in strength training II. Short versus long isometric contractions. Eur J Appl Physiol 1995: 71: 337–341.

Simonsen RB, Klitgaard H, Bojsen-Moller F. The influence of strength training, swim training and aging on the Achilles tendon and m. soleus of the rat. J Sports Sci 1995: 13: 291–295.

Soderberg GL, Cook TM. An electromyographic analysis of quadriceps femoris muscle setting and straight leg raising. Phys Ther 1983: 63: 1435–1438.

Soderberg GL, Minor SD, Arnold K, Henry T, Chatterson JK, Poppe RD, Wall C. Electromyographic analysis of knee exercises in healthy subjects and in patients with knee pathologies. Phys Ther 1987: 67: 1691–1695.

Spoor CW, van Leeuwen JL. Knee muscle moment arms from MRI and from tendon travel. J Biomech 1992: 25: 201–206.

Takarada Y, Takazawa H, Sato Y, Takebayashi S, Tanaka Y, Naokata I. Effects of resistance exercise combined with moderate vascular occlusion on muscular function in humans. J Appl Physiol 2000: 88: 2097–2106.

Tang SFT, Chen CK, Hsu R, Chou SW, Hong WH, Lew HL. Vastus medialis obliquus and vastus lateralis activity in open and closed kinetic chain exercises in patients with patellofemoral pain syndrome: an electromyographic study. Arch Phys Med Rehabil 2001: 82: 1441–1445.

Thepaut-Mathieu C, Hoecke JV, Maton B. Myoelectrical and mechanical changes linked to length specificity during isometric training. J Appl Physiol 1988: 64: 1500–1505.

Visser JJ, Hoogkamer JE, Bobbert MF, Huijing PA. Length and moment arm of human leg muscles as a function of knee and hip–joint angles. Eur J Appl Physiol 1990: 61: 453–460.

Weir JP, Housh TJ, Weir LL. Electromyographic evaluation of joint angle specificity and cross-training after isometric training. J Appl Physiol 1994: 77: 197–201.

Woo SL, Gomez MA, Amiel D, Ritter MA, Gelberman RH, Akeson WH. The effects of exercise on the biomechanical and biochemical properties of swine digital flexor tendons. J Biomech Eng 1981: 103: 51–56.

Yalamanchi N, Klein MB, Pham HM, Longaker MT, Chang J. Flexor tendon wound healing in vitro: lactate up-regulation on TGF-β expression and functional activity. Plast Reconstr Surg 2004: 113: 625–632.