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Effects of Prolonged Stretching and Thermotherapy on Muscle Contracture of Immobilized Rat Soleus Muscle

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Abstract. [Purpose] We examined the effects of prolonged stretching and thermotherapy on muscle contracture of immobilized rat soleus muscles by determining ankle joint range of motion (ROM), collagen fibril arrangement in the endomysium and insoluble collagen content. [Methods] In the experimental group, bilateral ankle joints of each rat were fixed in full plantar flexion with plaster casts for four weeks. Then, the experimental group animals were randomly partitioned into five groups: 1) immobilization alone; and 2) spontaneous recovery, 3) prolonged stretching, 4) thermotherapy, and 5) prolonged stretching immediately following thermotherapy for 2 weeks after cast removal. Prolonged stretching of the soleus muscle (30 min/day) was conducted by maintaining the dorsiflexion position of the ankle joint. Thermotherapy consisted of immersion of bilateral hindlimbs (20 min/day) in hot water (42 °C). Under anesthesia, both treatments were performed six days per week during the two-week remobilization. [Results] Immobilization led to decreased ROM, collagen fibril movement in the endomysium and increased insoluble collagen. Prolonged stretching and the combination of stretching and thermotherapy accelerated amelioration of the ROM limitation and diminished collagen fibril movement. [Conclusion] Our findings suggest that while thermotherapy does not exert a specific effect on muscle contracture, prolonged stretching can promote recovery.

Key words: Stretching, Thermotherapy, Muscle contracture

INTRODUCTION

Clinically, cases involving bed rest for prolonged periods or immobilization of a joint are characterized by decreased muscle elasticity and reduced range of motion (ROM). This condition, known as muscle contracture, is quite possibly the most frequently encountered complication among rehabilitation professionals. Muscle contracture is thought to result from changes in intramuscular connective tissue. Intramuscular connective tissue displays a three-tier organization: the epimysium or fascia surrounds whole muscles, the perimysium binds muscle fibers into bundles, and the endomysium outlines individual muscle cells. Collagen is the main fibrous protein in intramuscular connective tissue, and collagen elasticity depends not only on intra- and intermolecular cross-links but also on the arrangement of fibrils. Purslow and Trotter reported that the orientation of collagen fibril distribution in the endomysium exhibits a progressive shift in the circumferential direction at short sarcomere length and in the longitudinal direction at long sarcomere length. Therefore, collagen fibrils in the endomysium run in various directions during muscle relaxation, and move longitudinally to the axis of the muscle fiber in muscle stretching. This re-orientation of the fibrils may reflect the role of the endomysium in terms of providing mechanical support to the fiber’s surface and its action as an elastic device for contraction-relaxation cycles. Moreover, fibril arrangement in the endomysium is believed to be related to muscle elasticity. Our previous studies demonstrated changes in collagen with respect to the mechanism underlying muscle contracture based on morphological and biochemical analysis. A morphological assessment by Okita et al. disclosed that collagen fibril arrangement in the endomysium 1 and 2 weeks after immobilization was longitudinal to the axis of the muscle fibers, whereas at 4, 8 and 12 weeks after immobilization, the fibril arrangement was circumferential. Such changes in collagen fibril arrangement are indicative of decreased collagen fibril movement in the endomysium of immobilized muscle. The biochemical approach of Hibino et al. revealed that
in an earlier investigation, the extensibility of connective tissue was attributed to warming administered prior to stretching exercise because increased related to the mechanism governing muscle contracture. In terms of changes in intramuscular connective tissue, little has been reported on the effect of prolonged stretching for 15 min per day during a 10-day immobilization period. Furthermore, Williams demonstrated that intermittent stretching for 15 min per day during a 10-day immobilization period prevented increase in connective tissue. However, little has been reported on the effect of prolonged stretching in terms of changes in intramuscular connective tissue related to the mechanism governing muscle contracture.

In general, thermotherapy for muscle contracture is often administered prior to stretching exercise because increased extensibility of connective tissue was attributed to warming in an earlier investigation. In particular, Lehman et al. described a greater increase in residual length in rat tail tendon under increasing loading in a 45 °C hot water bath, whereas progressive lengthening was not observed in a 25 °C water bath. In addition, the tension of rat tail tendon dropped to very low values within minutes in a 45 °C bath whereas very little tension decrease was detected at 25 °C. However, thermotherapy which warms soft tissue to 45 °C is difficult in the clinical setting as it may induce tissue injury and/or the degeneration of protein. Therefore, we concluded that evidence supportive of prolonged stretching and thermotherapy for muscle contracture is incomplete.

The objective of this study was to clarify the effects of prolonged stretching and thermotherapy on muscle contracture of immobilized rat soleus muscles.

SUBJECTS AND METHODS

Thirty 8-week-old male SPF Wistar rats (weight, 287.3 ± 7.0 g) obtained from Kyudo (Tosu, Saga, Japan) were randomly divided into the experimental (n = 25) and control (n = 5) groups. Control rats were untreated. Animals of the experimental group were anesthetized with pentobarbital sodium (40 mg/kg), and their bilateral ankle joints were fixed in full plantar flexion with plaster casts for four weeks with the soleus muscles immobilized in a shortened position. The plaster cast, which was positioned from above the knee joint to the distal foot, was changed weekly to reduce loosening due to muscle atrophy. Rats in the experimental group were randomly divided into five groups: 1) immobilization alone (group I, n = 5); 2) spontaneous recovery (no treatment) for 2 weeks after cast removal (group NT, n = 5); 3) prolonged stretching exercise for 2 weeks after cast removal (group S, n = 4); 4) thermotherapy for 2 weeks after cast removal (group H, n = 6); and 5) prolonged stretching immediately following thermotherapy for 2 weeks after cast removal (group SH, n = 5).

Animals were housed in cages inside a room with a 12 h-12 h light-dark cycle. The temperature and relative humidity of the room were maintained at 25 °C and 50%, respectively. Food and water were available ad libitum. Animal care and experimental procedures were performed in accordance with the Guidelines for Animal Experimentation of Nagasaki University with approval of the Institutional Animal Care and Use Committee.

The prolonged stretching exercise followed to that described by Williams. Both soleus muscles of group S and SH rats were stretched by dorsiflexion of the ankle joint with a tensile force of 0.9 N using a spring scale, which was installed vertical to the plantar, and this position was fixed with non-elastic tape. This exercise was conducted for 30 min each day, 6 days per week over two weeks following the immobilization period. Thermotherapy was performed via the following methods. Bilateral hindlimbs of group H and SH rats were immersed in hot water (42 °C) for 20 min. Our pilot study confirmed that the muscle temperature of the triceps surae gradually increased during immersion in hot water, reaching 40.0 °C after 20 min. Therefore, we concluded that adequate heating was applied to the soleus by this method. The frequency of thermotherapy was based on that of prolonged stretching (6 days per week over 2 weeks). In group SH, the prolonged stretching exercise was performed immediately after thermotherapy. All treatments were administered under pentobarbital sodium anesthesia (40 mg/kg). Furthermore, rats of group NT were anesthetized with the identical frequency.

After the 4-week immobilization and the subsequent 2-week remobilization periods, animals of all groups were anesthetized with pentobarbital sodium (40 mg/kg). Following body weight measurements, the range of motion (ROM) of dorsiflexion of the ankle joint was measured with a goniometer as described in a previous report.

Measurement of ROM was defined as the angle (0 to 180 degrees) between a straight line connecting the fifth metatarsal and the malleolus lateralis of the fibula to a line connecting the malleolus lateralis of the fibula and the center of the knee joint when the ankle was passively dorsiflexed under a tensile force of 0.3 N using a spring scale with the knee joint in the fully flexed position. For each group, a comparison between the 4-week immobilization and the subsequent 2-week remobilization values was conducted with the paired Student’s t-test. Differences among groups were assessed employing one-way analysis of variance (ANOVA) followed by Scheffe’s F post hoc test. Differences were considered significant at p <0.05.

At the end of each experimental period, the left soleus muscle was excised, stretched with a 4 g sinker as described in our previous study and fixed in 3% glutaraldehyde in 0.1 M cacodylate buffer (pH 7.4). The cell maceration method of Ohtani et al. was utilized. After initial fixation...
in 3% glutaraldehyde, left soleus muscles were cut into 3 × 3 × 3 mm blocks and immersed in 10% aqueous sodium hydroxide for 14 days at room temperature. Specimens were then rinsed in distilled water for 3 days. These samples were placed in a 1% aqueous tannic acid solution for 2 h and rinsed in distilled water for 1 h, followed by post-fixing in a 1% aqueous solution of osmium tetroxide for 2 h. Subsequently, specimens were dehydrated in a series of graded concentrations of ethanol and dried by the t-butyl alcohol freeze-drying method. The dried specimens were mounted on metal stubs and coated with gold, after which the collagen fibril arrangement in the endomysium was examined and micrographs produced with a scanning electron microscope (SEM; JSM-6700F/IV, JEOL, Tokyo, Japan) at a final magnification of ×20,000. SEM micrographs of the longitudinal surfaces of the cut strips were generated. Care was taken to ensure that micrographs used to analyze collagen fibril orientation in the endomysium were obtained from specimens oriented completely perpendicular to the line of view. The upper acute angles (0 to 90 degrees) formed by the two lines of the collagen fibril segment and the direction parallel to the muscle fiber axis on the photomicrographs were determined as described by Purslow and Trotter. Samples, which were lyophilized for 24 h, were hydrolyzed in 6 N HCl for 15 h at 110 °C. Next, the samples were hydrolyzed in alkali for 20 min at 90 °C. The hydrolyzed specimens were then mixed with buffered chloramine-T reagent, and left to stand to allow oxidation at room temperature. The chromophore was developed by adding Ehrlich’s aldehyde reagent, after which the absorbance of each sample was measured at 540 nm with a spectrophotometer. Absorbance values were plotted against the concentration of standard hydroxyproline; the presence of hydroxyproline in sample extracts was determined from the standard curve. The hydroxyproline concentration of samples was calculated as the content per wet weight (µg/mg wet weight). ANOVA was utilized for statistical evaluation. When ANOVA established a significant F value (p<0.05), pair-wise comparisons were conducted with Scheffe’s F method.

**RESULTS**

Table 1 presents the data of ROM of dorsiflexion of each group. The ROM of dorsiflexion in the control group was 160 degrees. Means ± SD of ROM of dorsiflexion immediately after the 4-week immobilization period were 74.5 ± 4.4 degrees in group I, 78.0 ± 4.8 degrees in group NT, 78.1 ± 4.6 degrees in group S, 78.8 ± 6.1 degrees in group H, and 79.8 ± 6.1 degrees in group SH. After two weeks of remobilization, ROM of dorsiflexion of all the experimental groups was significantly smaller than that of the control group; additionally, there were no significant difference among the experimental groups.

Means ± SD of ROM of dorsiflexion at the end of the 2-week remobilization period were 118.5 ± 4.8 degrees in group NT, 129.4 ± 9.4 degrees in group S, 134.5 ± 9.8 degrees in group H, and 120.0 ± 9.8 degrees in group SH. After two weeks of remobilization, ROM of dorsiflexion had increased significantly compared to that observed at the end of immobilization in each group. Furthermore, ROM of dorsiflexion in groups S and SH was significantly

<table>
<thead>
<tr>
<th>Groups</th>
<th>Range of Motion (degrees)</th>
<th>Hydroxyproline concentrations of insoluble collagen (µg/mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>immediately after 4 weeks of immobilization</td>
<td>after 2 weeks of remobilization</td>
</tr>
<tr>
<td>Control group</td>
<td>160</td>
<td></td>
</tr>
<tr>
<td>Group I</td>
<td>74.5 ± 4.4 *</td>
<td>118.5 ± 4.8 †</td>
</tr>
<tr>
<td>Group NT</td>
<td>78.0 ± 4.8 *</td>
<td>129.4 ± 9.4 †</td>
</tr>
<tr>
<td>Group S</td>
<td>78.1 ± 4.6 *</td>
<td>120.0 ± 9.8 †</td>
</tr>
<tr>
<td>Group H</td>
<td>78.8 ± 6.1 *</td>
<td>134.5 ± 9.8 †</td>
</tr>
<tr>
<td>Group SH</td>
<td>79.0 ± 6.1 *</td>
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Values are mean ± SD; * vs. control group (p<0.05); † vs. immediately after immobilization (p<0.05); ‡ vs. group NT after 2-week remobilization (p<0.05); ¶ vs. group H after 2-week remobilization (p<0.05); §§ vs. Group I (p<0.05)
greater than that in groups NT and H; however, there was no significant difference between groups S and SH.

A representative scanning electron micrograph of collagen fibril arrangement in the endomysium is exhibited in Figure 1. The muscle fiber axis runs horizontally. Many longitudinal collagen fibril components are present in the control group. Among the experimental groups, this arrangement is apparent only in groups S and SH. Group I exhibits increased circumferential collagen fibril components. Groups NT and H also display increased circumferential collagen fibril components.

Table 1 presents the data of hydroxyproline concentrations of insoluble collagen in the soleus muscle for each group. Means ± SD values of hydroxyproline concentration were 0.4 ± 0.1 µg/mg wet weight in the control group, 1.4 ± 0.4 µg/mg wet weight in group I, 0.6 ± 0.3 µg/mg wet weight in group NT, 0.4 ± 0.3 µg/mg wet weight in group S, 0.6 ± 0.2 µg/mg wet weight in group H and 0.5 ± 0.2 µg/mg wet weight in group SH. The hydroxyproline concentration of group I had increased significantly compared to that of the control group. Furthermore, the hydroxyproline concentration of the four intervention groups decreased significantly relative to that of group I; however, no significant differences were detected among the four intervention groups.

DISCUSSION

The current findings demonstrated a reduction in ROM of dorsiflexion in group I to half of the control value, as reported by Okita et al. A recent review proposed that
myogenic limitation predominates during the first 90 days of immobility, whereas the limitation is mainly arthro-
genic beyond 90 days of immobility. According to this
description, the limitation in ROM after four weeks of
immobilization in this investigation would be the result of
myogenic change.

Purslow and Trotter reported that collagen fibrils’ orienta-
tion in the endomysium display a progressive shift in the
circumferential direction at short sarcomere lengths and
in the longitudinal direction at longer sarcomere lengths. Namely, collagen fibrils in the endomysium are oriented
in various directions during muscle relaxation and move
longitudinally toward the axis of the muscle fiber during
muscle stretching. In the current study, muscle samples
were stretched with a 4 g sinker, then fixed for comparison
of the collagen fibril arrangement in the endomysium among
all the groups during stretching under the same force. Many
collagen fibrils in the endomysium of the control group were
longitudinal. However, the majority orientation of collagen
fibrils in group I had shifted to the circumferential direction,
a result which is consistent with that of our previous
investigation. This change is suggestive of decreased
collagen fibril movement and reduced extensibility in the
endomysium.

An earlier report noted that intermolecular cross-link
formation in collagen fibers reduces the flexibility of the
tissue. Generally, enhancement of intermolecular cross-
links affects collagen solubility and induces an increase in
insoluble collagen. In the present study, the insoluble
collagen content of group I increased significantly in
comparison with that of the control, a result which is
consistent with the findings of Hibino et al. This result is
indicative of an increase in intermolecular cross-links with
a stronger molecular structure at four weeks of immobili-
ze. Therefore, given that the limitation in ROM and
various changes in collagen occurred as described in previous
reports, we conclude that group I affords an appropriate
experimental model for muscle contracture.

ROM of dorsiflexion in the four treatment groups
immediately after four weeks of immobilization showed
no significant differences relative to group I. Based on
this result, we expected various changes in intramuscular
collagen related to the mechanism of muscle contracture in
the four intervention groups after four weeks of immobili-
ze. Accordingly, we examined the effect of prolonged
stretching and thermotherapy on muscle contracture.

Our findings demonstrate that ROM of dorsiflexion in
group S after 2 weeks remobilization was significantly larger
than that in group NT. This result suggests that prolonged
stretching accelerates amelioration of limitation of ROM.
On the other hand, Okita et al. also examined whether
prolonged stretching of rat ankle joints in full plantar
flexion promoted recovery from limitation of ROM after 4
weeks of immobilization. Prolonged stretching was applied
for 30 min per day for two weeks (6 days/week) as in the
current study. In the study of Okita et al., however, no
significant difference was observed between the stretching
group and the spontaneous recovery group in terms of ROM
of dorsiflexion, and this result was distinct from that of our
present study. Consequently, we speculate that establishing
the conditions for the angle of dorsiflexion under prolonged
stretching plays an influential role. Specifically, Okita et
al. applied prolonged stretching daily at the maximal
angle of dorsiflexion, but the conditions for this angle are
vague. In contrast, we clearly defined the conditions under
which prolonged stretching was conducted: the ankle joint
was dorsiflexed by a tensile force of 0.9 N.

In group S, many collagen fibrils in the endomysium
exhibited longitudinal orientation toward the axis of the
muscle fiber, and a peak of 20 to 50 degrees in the percent
distributions of the form angle of the direction parallel to
the muscle fiber axis was observed. These results are similar
to those of the control group. In group NT, however, many
collagen fibrils displayed circumferential orientation; in
addition, the percent distributions of the form angle of
the direction parallel to the muscle fiber axis were similar
to those of group I. Therefore, these data suggest that
prolonged stretching may improve diminished collagen
fibril movement in the endomysium due to immobilization.

In terms of insoluble collagen content, groups S and NT
displayed significantly reduced levels in comparison with
group I; however, no significant difference was detected
between groups NT and S. Although this result indicates
that the number of collagen fibers with strong intermolecular
cross-links in the NT and S groups had decreased during the
remobilization process, prolonged stretching did not demon-
strate specific effects with respect to the enhancement of
intermolecular cross-links in intramuscular collagen.

First, in reference to the result in group H (thermotherapy
alone), no significant difference was found between groups
NT and H regarding ROM of dorsiflexion after the 2 weeks
remobilization. Moreover, in group H, many collagen fibrils
in the endomysium displayed circumferential orientation
toward the axis of the muscle fiber, and a peak of 90 degrees
in the percent distributions of the form angle of the direction
parallel to the muscle fiber axis was evident. Furthermore,
these results were similar to those of group NT. In addition,
insoluble collagen content in group H declined significantly
in comparison with group I; in contrast, group H exhibited no
meaningful difference relative to group NT. Following the
report of Lehman et al., it was believed that thermotherapy
was effective at increasing extensibility of soft tissue, and
thermotherapy has become widely utilized in current clinical
rehabilitation programs for muscle contracture. However,
few studies have examined whether thermotherapy improves
recovery from muscle contracture. From the results of the
recovery of ROM after remobilization and the changes in
intramuscular collagen related to the mechanism governing
muscle contracture, we conclude that thermotherapy alone
is not effective in the promotion of recovery from muscle
contracture.

On the other hand, Okita et al. examined the effects on
rat triceps surae of continuous mode ultrasound treatment
(frequency, 1 MHz; intensity, 1.0 W/cm²) for 15 min per
day over a 4-week immobilization period during which
ankle joints were fixed in full plantar flexion. The ultra-
sound intervention inhibited the deterioration of ROM of
dorsiflexion of the ankle joint and collagen fibril movement.
in the endomysium. Okita et al. argued that the effect of ultrasound in terms of progressive inhibition of muscle contracture was attributable exclusively to a thermal effect. In the present study, however, the effects of thermotherapy on the recovery process from muscle contracture were unclear. It is possible that the speed of heating of the soleus muscle accounts for the difference between our results and those of Okita et al., since the time required for the triceps surae to reach a temperature of 40.0 °C was approximately 20 min under our approach, whereas it was only 6 min for the continuous ultrasound method. Thus, assessment of the thermotherapy methodology will be necessary in future experiments.

Second, ROM of dorsiflexion of group SH (combination therapy with prolonged stretching and thermotherapy) was significantly larger than that of groups NT and H after the 2-week remobilization; however, no significant difference was detected between the S and SH groups. In addition, many collagen fibrils in the endomysium of group SH exhibited longitudinal orientation, and a peak of 20 to 50 degrees in the percent distributions of the form angle of the direction parallel to the muscle fiber axis was observed in the SH group. The results of group SH were similar to those of group S. Group SH displayed markedly reduced insoluble collagen content in comparison with that of group I; however, no significant difference was found among the four treatment groups. These findings suggest that recovery from muscle contracture was more striking in animals of group SH than in animals of the NT and H groups. To be sure, neither the SH nor the S group demonstrated a significant difference in recovery, based on the muscle contracture parameters examined in the present study. Therefore, we assume that the combination of prolonged stretching and thermotherapy affords little multiplier effect. Moreover, the recovery promotion factor of muscle contracture in group SH may be appropriate in relation to the influence of prolonged stretching.

In the clinical setting, combination therapy involving prolonged stretching and thermotherapy is often included in rehabilitation programs associated with muscle contracture. Several studies consisting of randomized controlled trials for this combination therapy have been conducted; however, the majority of the subjects in those studies were healthy adults and the evidence supporting the effectiveness of combination therapy for muscle contracture is unclear. Moreover, the specific effect of combination therapy on intramuscular collagen related to the mechanisms underlying muscle contracture was not proven in the present study. Therefore, we hypothesize that thermotherapy for skeletal muscle may be effective for the promotion of muscle relaxation and the enhancement of blood flow, but not for the stimulation of intramuscular collagen.

Our results suggest that prolonged stretching and combination therapy involving prolonged stretching and thermotherapy promotes recovery from muscle contracture. Little specific effect of thermotherapy on muscle contracture was evident, and the promotion factor for recovery from muscle contracture found in the combination therapy may arise from the influence of the prolonged stretching. We also speculate that the impact of thermotherapy on muscle contracture is influenced by the speed of heating of skeletal muscle. Further studies will be necessary in order to examine other thermotherapy methodologies.

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