Experimental Joint Contracture Correction with Low Torque—Long Duration Repeated Stretching

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Tension is necessary to maintain and restore the mechanical properties of soft connective tissues. Conversely, reduced tension states such as produced by immobilization weaken mechanical properties and facilitate joint contracture. We assessed the effect of low torque-long duration stretching to increase the range of motion (ROM) and to restore the mechanical properties of contracted joints in 66 rat knees immobilized for 40 days. After remobilization, we randomly divided the contracted knees into four treatment groups treated with repeated stretches of diverse torques and duration: stretching with low-torque and long-duration, high-torque and short-duration, high-torque and long-duration, low-torque and short duration. We included control and natural recovery groups. Phase lag in all treatment groups recovered to the same range as in the normal controls. Dynamic stiffness, which was not altered by joint immobilization, increased in all treatment groups. Deformation and load to failure improved substantially only in the low-torque and long-duration stretching group. Low-torque and long-duration repeated stretching leads to a greater restoration of ROM with more normal mechanical properties compared to high-torque and short duration stretching.

Tension is necessary to maintain normal metabolism and the mechanical properties of tendon and periarticular connective tissue. Tension positively influences tendon repair by increasing fibroblast proliferation, migration, protein synthesis, and new collagen synthesis. Within three weeks, a time when collagen fibers begin to mature and establish cross-links, loaded tendons in vitro are stronger compared to unloaded tendons. Increases in DNA, protein, glycosaminoglycan, and collagen synthesis relative to unloaded tendons occur in loaded embryonic chicken tendons. Periodontal ligament fibroblasts exposed to 5% biaxial deformation strain at a frequency of 30 times per minute for 24 hours exhibited statistically substantial increases in type II collagen and fibronectin synthesis.

Controlled stretching of repaired tendons accelerates collagen synthesis, fibril neoformation, and proper fiber alignment leading to increased final tensile strength of the tendon. In one in vivo experiment load to failure, deflection, and stiffness were enhanced in mobilized tendons relative to immobilized tendons. Reduced tension states, such as immobilization, promote weakening of the mechanical properties of connective tissues and result in joint contracture. Stretching procedures of resisting the tensile stresses may pose a conflict of interest in connection with the submitted article. Each author certifies that he or she has no commercial associations (e.g., consultancies, stock ownership, equity interest, patent/licensing arrangements, etc) that might pose a conflict of interest in connection with the submitted article. Each author certifies that his or her institution has approved the animal protocol for this investigation and that all investigations were conducted in conformity with ethical principles of research. Correspondence to: Mariko Usuba, PT, PhD, Course of Physical Therapy, Department of Health, Tsukuba University of Technology, 4-12-7 Kasuga, Tsukuba, Ibaraki 305-0298, Japan. Phone: 81-29-858-9554; Fax: 81-29-858-9554; E-mail address: usuba@k.tsukuba-tech.ac.jp.

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We hypothesized a reduced tension state associated with immobilization would result in weakening of the tissue with increased phase lag (corresponds to the viscosity of the joint tissues) and joint deformation and decreased maximum knee extension angle, dynamic stiffness, stiffness, and maximum load after 40 days of joint immobilization. We also hypothesized low-torque and long-duration repeated stretching of the resulting moderately developed flexion contractures would result in a decreased phase lag and deformation, and increased maximum knee ROM, dynamic stiffness, stiffness, and maximum load, relative to high torque and/or short duration repeated stretch treatments.

MATERIALS AND METHODS

We randomly divided rats with experimental knee flexion contractures into one of six treatment groups: an immobilization group (Group I), in which specimens were sampled immediately after surgical remobilization; an untreated group (Group II) where no stretch treatment was given to observe the natural recovery for 4 weeks after surgical remobilization; a high-torque and short-duration stretching group (Group III); a high-torque and long-duration stretching group (Group IV); a low-torque and short-duration stretching group (Group V); and a low-torque and long-duration stretching group (Group VI). The unoperated, contralateral knees served as controls (Group VII). Each group then had tendons tested mechanically after sacrifice. The College Animal Care Committee and the Institutional Ethics Committee approved the experimental design for this study.

Sixty-six 6-week-old young adult male Wistar rats, each initially weighing about 200 g, were subjected to the experimental surgical procedure to create knee flexion contractures. Under intraperitoneal anesthesia with a mixture of ketamine hydrochloride 57.6 mg/mL and xylazine 23.3 g/mL (Ketalar 50 and Celenal for 0.15 mL per body weight of animal), each animal had intraperitoneal anesthesia with a mixture of ketamine hydrochloride 57.6 mg/mL and xylazine 23.3 g/mL (Ketalar 50 and Celenal for 0.15 mL per body weight of animal), each animal had intraperitoneal anesthesia with a mixture of ketamine hydrochloride 57.6 mg/mL and xylazine 23.3 g/mL (Ketalar 50 and Celenal for 0.15 mL per body weight of animal), each animal had intraperitoneal anesthesia with a mixture of ketamine hydrochloride 57.6 mg/mL and xylazine 23.3 g/mL (Ketalar 50 and Celenal for 0.15 mL per body weight of animal), each animal had intraperitoneal anesthesia with a mixture of ketamine hydrochloride 57.6 mg/mL and xylazine 23.3 g/mL (Ketalar 50 and Celenal for 0.15 mL per body weight of animal), each animal had intraperitoneal anesthesia with a mixture of ketamine hydrochloride 57.6 mg/mL and 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animal), each animal had intraperitoneal anesthesia with a mixture of ketamin...
We thawed the specimens at room temperature just before the mechanical analysis.

We performed stretching with the anesthetized animal in a supine position on a heating pad, with the pelvis stabilized by an elastic tube attached to the treatment table. The hip on the experimental side was in approximately 100° to 120° of flexion. The ankle of the experimental side was taped and tied to a jig of a digital force gage (DPS-0.5; IMADA, Toyohashi, Japan). The direction of the stretch was set toward extension with traction applied to the whole lower extremity. The hip was maintained in a neutral position with respect to rotation and abduction-adduction. We monitored rectal temperature to keep the temperature 36°C with the heating pad.

To apply a fixed amount of torque (T) to the knee in every treatment session, the length between the knee and the ankle tape (L), and the angle between the traction line and the extended line from the lower leg (θ) was measured. Calculations were performed to adjust the tensile force (W) at each treatment as follows (Fig 2):

\[ T = L \cdot W \cdot \sin \theta \]
\[ W = \text{Tensile force} \]
\[ \text{Tensile force of previous treatment session: } W_1 \]
\[ \text{Tensile force of present treatment session: } W_2 \]
\[ \theta = \text{Angle between the pulling tape and the extended line from the lower leg} \]

High torque was applied as a force of 0.045 Nm and low torque was applied as 0.02 Nm. We calculated the intensity of high torque from the readings of the force gage measuring the force an experienced therapist applied to maximally stretch the contracted knee of a rat. The intensity of the low torque was calculated in the same way when the therapist applied mild to moderate stretch. The stretching time for a single treatment was set at 40 minutes for long duration, and 20 minutes for short duration, considering a possible duration with stable anesthetic condition.

We measured the maximum passive knee extension angle under anesthesia, defined as the angle between the extension line from the thigh and the lower leg, expressed in minus degrees (Fig 1). A rat’s maximum passive knee extension angle on the normal side ranges between -20 and -30°. The angle was measured using a plastic goniometer with the animal on its side, the thigh in a right angle to the trunk and the talocrural joint passively plantar-flexed. All goniometer tests were performed by one individual (MU) who was blinded to the results. One arm of the goniometer was placed parallel to the line between the greater trochanter and the knee, which had been premarked with a felt-tip marker. The fulcrum was centered over the lateral knee, the space that can be felt as the soft tissue depression just posterior to the lateral tibial plateau. Another arm of the goniometer was placed parallel to the longitudinal axis of the lower leg and over the ankle at midwidth. The tensile force applied to the knee during the goniometer measurement was approximately 80 to 100 g, and the distance between the knee and the therapist’s finger placement on the animal’s foot was about 5 cm (Fig 3).

After harvest and preparation we mounted the proximal end of the specimen’s femur in a custom jig for the mechanical tests.
Fig 3. The knee extension angle was measured using a plastic goniometer with the animal on its side. Position of goniometer and therapist’s hand are demonstrated.

(Fig 4). We performed two series of mechanical tests. These were nondestructive, dynamic forced vibration methods to examine viscoelasticity (phase lag and dynamic stiffness) and static destruction test using tensile force. The first mechanical test performed was to evaluate viscoelasticity of the periarticular connective tissue at the primary phase of lengthening. The testing protocol for the viscoelasticity of the bone-joint-bone complex was identical to a previously published study by Akai et al. This method is designed to evaluate viscoelasticity of the periarticular connective tissue and the intraarticular architecture. The viscoelasticity of the specimen’s knee was analyzed using forced vibration, a method that uses spectral analysis based on the fast Fourier transform of displacement, in which mechanical signals are modified in amplitude and phase as they pass through the knee. A small rod, connected to a load cell, applied vertical force providing a forced vibration at a frequency of 35Hz, a static load of 3 g, and a dynamic load of 1 g, to the distal end of the tibia. A spectrum analyzer (3582A, Hewlett Packard, Corvallis, OR) worked as a dual-channel Fast Fourier Transform machine and provided electrical driving signals to the viscoelastic spectrometer (DDV-VMF, Orientec Co., Tokyo, Japan), which were converted into random mechanical noises. The complex transfer function H(f) was defined as a ratio of the cross power spectrum G_{yx} and the autopower spectrum G_{xx}:

\[ H(f) = \frac{G_{yx}}{G_{xx}} = \frac{Y(f)}{X(f)} \]

Where X(f): input signal function
X*(f): the conjugate function of X(f)
Y(f): output signal function

The transfer functions (the ratio of output/input of the dynamic stiffness and the phase lag) were shown on a display of the analyzer (Fig 5). For quantitative measurement of the actual value of viscoelastic properties, another sinusoidal vibratory load of amplitude 0.03 N was added.

Load: \( F = F_0 + F_1 \sin(\omega t) \)
Deformation: \( D = D_0 + D_1 \sin(\omega t - \delta) \)
\( F_0 = 0.05N \), \( F_1 = 0.03N \)

where \( \omega \): angular frequency, \( t \): time, \( \delta \): phase lag

This test indicated phase lag (\( \tan(\delta) \)) and a dynamic stiffness \( (F_1/D_1) \). Phase lag indicates the shock-absorbing ability of a joint when fibers start to resist tension at the primary phase of lengthening the tissue. Dynamic stiffness is an indication of transform-resistant at the primary phase of stretching the tissue.

Another mechanical test, the tensile-testing of the bone-joint-bone complex, was determined from the load-deformation curves. A load cell, attached to a traction (TensilonUTM-10T; Dual channel FFT analyzer
Channel A | Channel B

Drive signal

\[ X(f) \]
Sample
\[ H(f) \]
\[ Y(f) \]
Transfer function

Fig 5. The schema of fast Fourier transform testing is illustrated.
Orientec, Tokyo, Japan) that moved at velocity of 3 mm/min, applied at the distal end of the tibia, provided vertical force to hyperextend the joint. The test started the analysis from the knee in maximally extended position. A load cell was set perpendicular to tibia shaft so there was no change in the angle of force input. Position of femur was adjusted during the test so a load cell was touching tibia at right angle. Load indicates resistance force of the knee. Deformation indicates the total distance load cell moved from the point of initiation to sudden drop of the resistance force. Maximum load is the largest resistance force recorded just before the drop. The load and deformation of each joint was continuously recorded with a xy-recorder. The liner form the statistical analyses. Knee ROMs at the removal of the wire (remobilization) and at the 12th treatment session and mechanical outcomes were compared between all groups with the exception of knee ROMs at the 12th treatment session of Group I, which was sampled before treatment started. Post-hoc analyses of significant comparisons were conducted with Fisher’s Protected Least Significant Difference (p ≤ 0.05).

RESULTS

Knee ROMs improved gradually in all treated and untreated groups (Fig 7). After the 12 treatment sessions and when compared with the untreated Group II, knee ROMs increased most in low torque-long duration Group VI (p < 0.0001), followed by high torque-long duration Group IV (p < 0.0001) and high torque-short duration Group III (p < 0.0017). Knee ROM of low torque-long duration Group VI was larger than high torque-short duration Group III and low torque-short duration Group V (p < 0.0001) and high torque-long duration Group IV (p = 0.0002). Groups of low torque-short duration V and untreated Group II and groups of high torque-short duration III and high torque-long duration IV were similar (Table 1).

In a forced vibration method to measure viscoelastic properties of the sample, dynamic stiffness indicates elastic resistance against load. Phase lag (loss tangent) represents the amount of dissipation of energy, ie, its viscous nature. Phase lag of Groups immobilization I and untreated II were higher (p = 0.047 and 0.0071, respectively) than the normal control Group VII; Groups immobilization I and untreated II were similar. Although phase lag for treatment groups high torque-short duration III, high torque-long duration IV, low torque-short duration V, and low torque-low duration VI were similar to the normal control Group VII, phase lag of high torque-long duration Group IV was lower (p = 0.0312) than Immobilization Group I and phase lag of high torque-long duration Group IV and low torque-short duration Group V were lower (p = 0.0078 and 0.0134, respectively) than untreated Group II. Phase lag of the joint, which increased as a result of immobilization but not altered by natural recovery for 4 weeks remobilization, was decreased by stretching treatments, regardless of torque and duration used in this study (Table 2, Fig 8).

The dynamic stiffness among Groups immobilization I, untreated II, and control VII was similar. Furthermore, dynamic stiffness increased (p = 0.0083, 0.0143, 0.0014 and 0.0465, respectively) in all of treatment groups high torque-short duration III, high torque-long duration IV, low torque-short duration V, and low torque-long duration VI, instead of decreasing to get closer to the same value as in normal control. Reduced tension status, as in groups immobilization I and untreated II, did not alter dynamic stiffness of the joint, while the joints received stretching signals as did all treatment groups (Table 2, Fig 8).

The stiffness of the untreated Group II was higher (p < 0.0001) than the immobilization Group I, but was lower (p < 0.0001) than the normal control. The stiffness of each treatment group was similar to untreated Group II. Stretching signals did not affect the stiffness of the joint contracture any more than the natural recovery during the 4-week treatment period (Table 3, Fig 9).

Deformation of groups low torque-long duration VI and control VII was smaller (p = 0.0274, p < 0.0001) than group immobilization I, while those of groups untreated II, high torque-short duration III, high torque-long duration IV, and low torque-short duration V remained large and were similar to group immobilization I (Table 3, Fig 9).

Peak maximum load was smaller (p = 0.005) in groups immobilization I through low torque-short duration V than control Group VII; groups untreated II, high torque-short duration III, high torque-long duration IV, low torque-short duration V, and low torque-long duration VI were similar. Among the latter groups, group low torque-long...
Fig 7. After remobilization, maximum knee extension angle in each group improved gradually over time. I = immobilization; II = untreated; III = high torque-short duration stretching; IV = high torque-long duration stretching; V = low torque-short duration stretching; VI = low torque-long duration stretching; VII = control. Duration VI was the only one similar to control Group VII (Table 3, Fig 9).

DISCUSSION

Our data suggest 20 minutes and/or 40 minutes of a stretching procedure per day, three times a week, contributes to an increase in ROM more than natural recovery. Low torque-long duration stretching increased ROM more than all of the treatment settings, suggesting the tension applied clinically in stretching procedures should be gentle and within patient's tolerance. Furthermore our data also suggest for effective outcomes long durations are crucial.

We note several limitations; more attention should have been given to the reliability of knee angle measurement. The method of measurement was blinded and carefully planned; however, repeated measurements were not performed at each treatment session. Anesthesia with a mixture of ketamine and hydrochloride was effective for only 60 to 80 minutes, which confined the long duration stretching to 40 minutes because body weight and knee angle measurements and treatment setup required 20 minutes.

TABLE 1. Maximum Knee Extension Angle (degrees) after Remobilizing Operation and after the Twelfth Treatment Session

<table>
<thead>
<tr>
<th>Group</th>
<th>After Remobilization</th>
<th>After the 12th Treatment Session</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>-123.9 ± 17.8</td>
<td>-66.1 ± 12.4</td>
</tr>
<tr>
<td>II</td>
<td>-131.2 ± 5.1</td>
<td>-56.6 ± 10.6</td>
</tr>
<tr>
<td>III</td>
<td>-127.2 ± 10.9</td>
<td>-52.5 ± 7.0§</td>
</tr>
<tr>
<td>IV</td>
<td>-125 ± 10.6</td>
<td>-63.1 ± 9.2§</td>
</tr>
<tr>
<td>V</td>
<td>-129.3 ± 8.2</td>
<td>-40.0 ± 5.7§</td>
</tr>
<tr>
<td>VI</td>
<td>-123.1 ± 21.2</td>
<td>-22.1 ± 2.5*</td>
</tr>
<tr>
<td>VII</td>
<td>-22.1 ± 2.5*</td>
<td>-24.6 ± 1.3*</td>
</tr>
</tbody>
</table>

Values are means ± SD in degrees; *larger than Group I–VI (p < 0.0001); 1 larger than untreated Group II (p = 0.0017); larger than untreated Group II (p < 0.0001); smaller than Group VI (p < 0.0001); smaller than Group VI (p = 0.0001)
TABLE 2. Phase Lag and Dynamic Stiffness from Viscoelastic Analysis in Each Group

<table>
<thead>
<tr>
<th>Group</th>
<th>Phase Lag (Tanα)</th>
<th>Dynamic Stiffness (10⁻² N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I  Immobilization (n = 9)</td>
<td>0.26 ± 0.05*1</td>
<td>4.18 ± 1.62</td>
</tr>
<tr>
<td>II Untreated (n = 9)</td>
<td>0.26 ± 0.01*2</td>
<td>4.36 ± 1.04</td>
</tr>
<tr>
<td>III High torque-short duration (n = 9)</td>
<td>0.25 ± 0.02</td>
<td>6.13 ± 2.82*5</td>
</tr>
<tr>
<td>IV High torque-long duration (n = 8)</td>
<td>0.23 ± 0.03*3</td>
<td>6.08 ± 1.66*5</td>
</tr>
<tr>
<td>V  Low torque-short duration (n = 8)</td>
<td>0.23 ± 0.02*4</td>
<td>6.84 ± 6.32*5</td>
</tr>
<tr>
<td>VI  Low torque-long duration (n = 8)</td>
<td>0.24 ± 0.01</td>
<td>6.57 ± 1.72*5</td>
</tr>
<tr>
<td>VII Control (n = 51)</td>
<td>0.24 ± 0.02</td>
<td>3.65 ± 1.04</td>
</tr>
</tbody>
</table>

Values are means ± SD. *1 = significantly larger than Group VII (p = 0.047); *2 = significantly larger than Group VII (p = 0.0071); *3 = significantly smaller than Group I (p = 0.0312) and Group II (p = 0.0078); *4 = significantly smaller than Group II (p = 0.0134); *5 = all treatment groups were significantly larger than the control (p < 0.05).

We immobilized the rat knees for 40 days to create the flexion contracture model in this study because it is the longest period of immobilization allowing reversal of the loss of ROM, and it does not cause cartilage change. According to Yaoita,23 who immobilized rat knees up to 20 days ROM returned to normal if the period of immobilization was less than 40 days. It was not reversible if the immobilization period exceeded 60 days, as degeneration of cartilage developed. It took 30 days after remobilization to regain full of range of motion of the knee previously immobilized for 30 days. When the duration of immobilization increased to 40 days, ROM did not fully recover within 40 days after remobilization. In pilot studies we found limited ROM of rat knees returned to normal if the immobilization period was only for 14 days, whereas it took 60 days after remobilization to restore normal ROM if the immobilization period was 40 days.

By 40 days of immobilization, we found decreased alterations in ROM, stiffness, and maximum load to failure, increased alterations in phase lag and deformation. Dynamic stiffness was the only parameter unaltered after 40 days of immobilization. Dynamic stiffness is an indication of transform-resistance at the primary phase of stretching the tissue. Unlike humans, the maximum extension angle of rat knees is 20 to 30° in flexion. Lack of mechanical stress to the posterior portion of the joint as in flexed knee position of both normal and immobilized status could be the reason for no alteration in dynamic stiffness in Groups I and II. Therefore it is assumed dynamic stiffness may increase only when tensile force is applied to joint in full extended position. It is also assumed dynamic stiffness may not decrease even if there is lack of tensile force applied to the tissue. This idea corresponds to the result dynamic stiffness increased in all of the treatment Groups III thru VI.

A possible explanation for the induced dynamic stiffness in all the treatment groups when there was no alteration in Groups I and II is the effect of the stretching procedure itself. The stretching procedure provides more...
Stiffness was the only mechanical property that was not more effective in the treatment groups than in natural recovery. Substantial increase of stiffness by stretching treatments may require a longer observation period. Although several clinical studies suggest a substantial clinical effect with low-load prolonged stretch,10,13,16 few experimental studies with quantitative evidence support so-called tissue induction effect through cellular function and collagen synthesis change.13

Our data would be limited to a patient with moderate contracture without cartilage involvement. Forty-day immobilization produces a joint contracture model with more involvement of the joint capsule than soft tissue around the joint, such as muscle. Trudel and Uhthoff11 reported arthrogenic changes played an increasing role in limiting the ROM of joints after immobility, especially when the period of immobility extends beyond 2 weeks. For those with mild ROM limitation with more involvement of soft tissue, and for those with severe ROM limitation with cartilage degeneration, tissue response to stretching may differ.

The joint contracture model we used represents moderately limited ROM without cartilage and nerve involve-

### TABLE 3. Stiffness, Deformation and Peak Maximum Load from Static Tensile Test in Each Group

<table>
<thead>
<tr>
<th>Group</th>
<th>Stiffness (x10^-1 N/mm)</th>
<th>Deformation (mm)</th>
<th>Peak Maximum Load (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.7 ± 0.32^2</td>
<td>42.47 ± 5.51</td>
<td>1.83 ± 0.41^6</td>
</tr>
<tr>
<td>II</td>
<td>1.96 ± 0.8^1,2</td>
<td>37.95 ± 5.14</td>
<td>4.77 ± 0.58^5,6</td>
</tr>
<tr>
<td>III</td>
<td>1.7 ± 0.48^1,2</td>
<td>42.45 ± 7.06</td>
<td>4.5 ± 0.80^5,6</td>
</tr>
<tr>
<td>IV</td>
<td>1.59 ± 0.2^1,2</td>
<td>42.90 ± 8.58</td>
<td>4.49 ± 0.59^5,6</td>
</tr>
<tr>
<td>V</td>
<td>1.92 ± 0.43^1,2</td>
<td>39.38 ± 6.96</td>
<td>4.48 ± 0.65^5,6</td>
</tr>
<tr>
<td>VI</td>
<td>2.19 ± 0.46^1,2</td>
<td>35.60 ± 6.5^13</td>
<td>5.15 ± 0.48^5</td>
</tr>
<tr>
<td>VII</td>
<td>3.56 ± 0.69^1</td>
<td>29.80 ± 4.09^44</td>
<td>6.24 ± 1.19^15</td>
</tr>
</tbody>
</table>

Values are means ± SD. *1 = significantly larger than Group I (p < 0.05); *2 = significantly smaller than Group VII (p < 0.0001); *3 = Group VI was significantly smaller than Group I (p = 0.0274); *4 = Group VII was significantly smaller than Group I (p < 0.0001); *5 = significantly larger than Group I (p < 0.0001); *6 = significantly smaller than the control Group VII (p < 0.005)
ment. The data suggest mild and long-duration stretching is more favorable than high torque or short-duration stretching for patients with similar signs. In our previous in vivo study using a similar joint contracture animal model, heat combined stretching was more effective than stretching alone. There are many chronic cases with inflammation in peri- or intraarticular tissue or degeneration of cartilage. Response of fibroblasts to mechanical stretch may differ when inflammation is present. Although the joint is more responsible for restriction of ROM than muscle when duration of immobilization extends more than 2 weeks, contribution of muscle to contracture is indisputable. Alterations in muscle fiber type and mechanical properties of muscle, tendons and infammed joint after remobilization and stretch and heat treatments require further investigation.

References