# EFFECTS OF FORCE ON THE BIOMECHANICAL PROPERTIES OF HEALING PATELLAR TENDONS IN THE RABBIT AFTER REMOVAL OF THE CENTRAL PORTION

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## INTRODUCTION

The central one-third of the patellar tendon (PT) is a common substitute for ligament reconstruction. A number of studies have been done on the chronic changes of structural properties of the whole PT after the resection of the central portion [1, 2]. However, much less studies have been done on the properties of each of the tissue regenerated in the defect and the unresected, residual tissue, with the exception of, for example, the study done by Tohyama et al. [3].

Biological tissues change their dimensions and mechanical properties in response to changes in mechanical stress. This phenomenon is referred to as tissue remodeling, which often occurs during disuse, exercise, and healing. We have developed an experimental method of stress shielding, by which the tension applied to the PT can be completely or partially released during normal knee motion. This method was used to study the effects of stress removal and reduction on the biomechanical properties of the rabbit PT [for example, 4, 5], and it has been demonstrated that stress shielding markedly changes the mechanical properties of the PT.

In the present study, the rabbit PT that was resected its central portion was stress-shielded with the above method for a prescribed period, and then physiologic tension was applied again. Using this model, we studied the effects of force on the biomechanical properties of the healing PT, distinguishing between the regenerated tissue and the residual tissue.

### MATERIALS AND METHODS

Forty-three mature female Japanese White rabbits were used. In the right knee, a full-thick, 3-mm wide, 10-mm long defect was made at the central location of the PT. The width of the defect was almost equal to the one-third of the whole width of the PT.

In order to quantitatively adjust the amount of force applied to the PT, we used the above-mentioned stress shielding technique. Briefly, in the completely stress-shielded group (CSS), the tension applied to the PT in each right knee was completely released with a stainless steel wire installed between the patella and the tibial tubercle [4]. After surgery, it was confirmed that the PT was relaxed at all knee

angles. For the partially stress-shielded group (PSS), the tension was reduced to around 30% of the normal value, with the same technique as used for CSS but by using a polymer-made strand and a buckle transducer [5]. In the restressing group (CSS/NSS), first, the PT tension was completely released for 3 weeks in the same way as that for CSS. Then, for restressing, a reoperation was performed to cut and remove the stainless steel wire installed for CSS [6]. No postoperative immobilization was applied to the knee joint. The contralateral left knees from arbitrarily chosen 12 rabbits were used to obtain control data. All the rabbits were allowed unrestricted activities in cages, and were euthanized by a lethal injection of pentobarbital at 3, 6, and 12 weeks after the operation for stress shielding. The results obtained from these animals were compared with those from non-stress-shielded animals (NSS) [3].

Immediately before euthanasia, blood flow and blood mass were measured in both PTs under anesthesia using a laser Doppler flow meter. For biomechanical testing, each patella-PT-tibia complex was divided into the medial (residual tissue), central (regenerated tissue), and lateral (residual tissue) portions. Then, a bone-tendon or a regenerated tissue-bone preparation having the width of approximately 2 mm was made from each portion. The cross-sectional area of each tissue was measured with an optical, non-contact method with a dimension analyzer (VDA) [3]. During tensile testing, the bone-tendinous tissue-bone complex was immersed in a physiological saline solution of  $37^{\circ}$ C. After preconditioning, tensile testing was done at a rate of 20mm/min until the tissue failed. Strain of the tissue substance was measured with a VDA. In addition, the number of fibroblasts in each tissue was determined from histological sections stained with hematoxylin and eosin.

#### **RESULTS AND DISCUSSION**

Blood flow in the regenerated tissues in all the experimental groups were about 150% of that in the non-treated, contralateral PT (left knee); however, their blood mass were similar to a contralateral level.

Histologically, at each period, the number of fibroblasts per cross-sectional area (fibroblast density) in each of the regenerated and the residual tissues was much larger than that in the control PT. In the regenerated tissue, it showed a tendency of decreasing with time; however this was not the case in the residual tissue. The histological appearance of regenerated tissues was very different from that of the normal PT; no longitudinally aligned collagen fibers were observed in all the groups. On the other hand, the histology of residual tissues was influenced by stress conditions. That is, in the residual tissues of CSS and NSS groups, fragmentation and misalignment of collagen bundles were usually and occasionally observed, respectively, which is considerably different from the histology of the normal PT, possibly because of stress deprivation and overstress, respectively. However, the histology of PSS group was rather similar to that of the normal PT.

The tensile strength of all regenerated tissues were significantly lower than that of the normal, control tendon (Table 1). However, it progressively increased with time, and became 13% in CSS group at 6 weeks, 41% (PSS), 67% (CSS/NSS), and 58% (NSS) of that of the normal PT at 12 weeks. The tensile strength and tangent modulus of regenerated tissues were higher as applied force was larger. That is, they were larger in PSS than in CSS groups, and larger in NSS than in PSS groups at every period. Furthermore, the tensile strength of CSS/NSS group was much higher than that of CSS group at 6 weeks, and almost the same as those of NSS group at 6 and 12 weeks. The strain at failure of regenerated tissues were significantly larger than that of the normal, control PT, which was remarkable in CSS and PSS groups. It was lower in CSS/NSS than in CSS groups.

The tensile strength of residual tissues were also lower than that of the normal, control PT in almost all groups (Table 2). CSS group had markedly lower strength than the other groups; its strength was approximately 10% of the control PT at 3 and 6 weeks. The strength in NSS group gradually decreased until 6 weeks, possibly because of overstress. However, PSS group showed a decrease in the strength to the level in NSS group at 3 weeks, but almost no changes between 3

Table 1 Tensile strength of regenerated tissues (MPa, Mean  $\pm$  S.D.).

3	6	12
$1.8 \pm 0.5^{*,**}$	$4.0 \pm 1.3*,**$	-
$2.6 \pm 2.1^{*,**}$	$8.1 \pm 3.5*$	$12.4\pm3.9*$
-	$15.4\pm5.0*$	$18.4 \pm 13.8*$
$11.5 \pm 4.7*$	$12.7 \pm 5.1*$	$17.3 \pm 7.6*$
	$3$ $1.8 \pm 0.5^{*,**}$ $2.6 \pm 2.1^{*,**}$ $-$ $11.5 \pm 4.7^{*}$	36 $1.8 \pm 0.5^{*,**}$ $4.0 \pm 1.3^{*,**}$ $2.6 \pm 2.1^{*,**}$ $8.1 \pm 3.5^{*}$ - $15.4 \pm 5.0^{*}$ $11.5 \pm 4.7^{*}$ $12.7 \pm 5.1^{*}$

Control,  $29.9 \pm 6.3$ ; \* p < 0.05 vs. Control; \*\* p < 0.05 vs. NSS at the same period (One-way ANOVA and multiple comparison).

Table 2 Tensile strength of residual tissues (MPa, Mean  $\pm$  S.D.).

Period (weeks)	3	6	12
CSS	$2.9 \pm 1.3^{*,**}$	3.4 ± 2.1*,**	-
PSS	$21.6 \pm 9.2^{*}$	$22.1 \pm 7.1$	$19.2\pm9.8*$
CSS/NSS	-	$15.4 \pm 3.0*$	$16.2 \pm 4.3*$
NSS	$24.4\pm7.9$	$16.3 \pm 6.9*$	$21.8\pm8.7$

Control,  $29.9 \pm 6.3$ ; \* p < 0.05 vs. Control; \*\* p < 0.05 vs. NSS at the same period (One-way ANOVA and multiple comparison).

and 12 weeks. This result is attributable to the treatment of partial stress shielding, which suppressed the overstress condition occurring in NSS group. The strength in CSS/NSS group at 6 weeks markedly increased from that in CSS group at 3weeks because of restressing; however, it did not change much between 6 and 12 weeks. The tangent modulus showed the results similar to the tensile strength; the strain at failure was larger than the normal PT value, but the differences were not much compared to the regenerated tissues.

#### CONCLUSIONS

1) Complete stress shielding has adverse biomechanical effects on both of the regenerated and residual tissues.

2) Partial stress shielding has adverse effects on the regenerated tissue, but minimal effects on the residual tissue.

3) Restressing is effective to restore the strength of not only the regenerated tissue but the residual tissue which were reduced by complete stress shielding.

These results suggest that some adequate stress should be applied to the patellar tendon after partial resection for the reconstruction of the anterior cruciate ligament.

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