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Effect of Partial Defect on Biomechanical Property of Tendon

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= Abstract = Tendon, which is a specialized connective tissue made of collagen with complex three-dimensional structures, shows variable biomechanical changes with species, age, activity levels, testing environments, testing rate, gripping technique and storage methods. This study was conducted to determine the biomechanical changes of tendon due to partial defect.

Forty long flexor digitorum profundus tendons of chicken were divided into four groups, each group consisting of 10 specimens. Tension tests were performed with an Instron 1000 testing machine with various partial defects of 0%(Group A), 30%(Group B), 60%(Group C) and 90%(Group D) of the longest diameter at a tension speed of 10 mm/min. Mechanical parameters, such as yielding stress, maximum stress, modulus of elasticity and total energy absorption capacity were determined. Yielding stress and maximum stress increased siginificantly in Group D ($P < 0.01$). Young's modulus and total energy absorption to failure (modulus of toughness) were significantly higher in Groups C and D than Groups A and B. Seven out of ten failed at the defect site in Group B while all failed at the defect site in Groups C and D. These findings suggest that partial defect more than certain proportion (30% in this study) would be better protected from vigorous activities until healing is well advanced in clinical situations. Although Young's modulus and modulus of toughness seemed to increase probably due to three dimensional cross linkage of both intact and damaged portion, absolute decrease in collagen fibril rendered failures at the defect site.

Key words: ***Tendon, Partial defect, Biomechanical changes***

INTRODUCTION

Tendon is a specialized connective tissue made of collagen with complicated three-dimensional structures, and it transfers the force generated from muscle contraction to the skeleton, thus making human motion possible. Many attempts have been made to determine the biomechanical properties of tendon. Tendon is now known to show viscoelastic behavior when it is stressed at tension. Along with viscoelastic behavior, the biomechanical properties of tendon are affected by species, age of the specimen, exercise, gripping technique, temperature, water content and tension speed. (Butler *et al.*, 1986; Carlstedt and Skagervall, 1986; Noyes and Grood, 1976; Proske and Morgan, 1987; Sanjeevi *et al.*, 1987; Viidik, 1968; Welsh *et al.*, 1971; Woo, 1982).

Injuries of tendon and their treatments are common practice in the field of orthopedic surgery, and partial injuries of tendon or ligament are often a matter of judgment regarding either conservative or surgical treatment. The authors conducted this study to determine the biomechanical changes of tendon due to partial defect by comparing biomechanical parameters such as yielding stress, maximaum stress, modulus of elasticity and energy absorption capacity.

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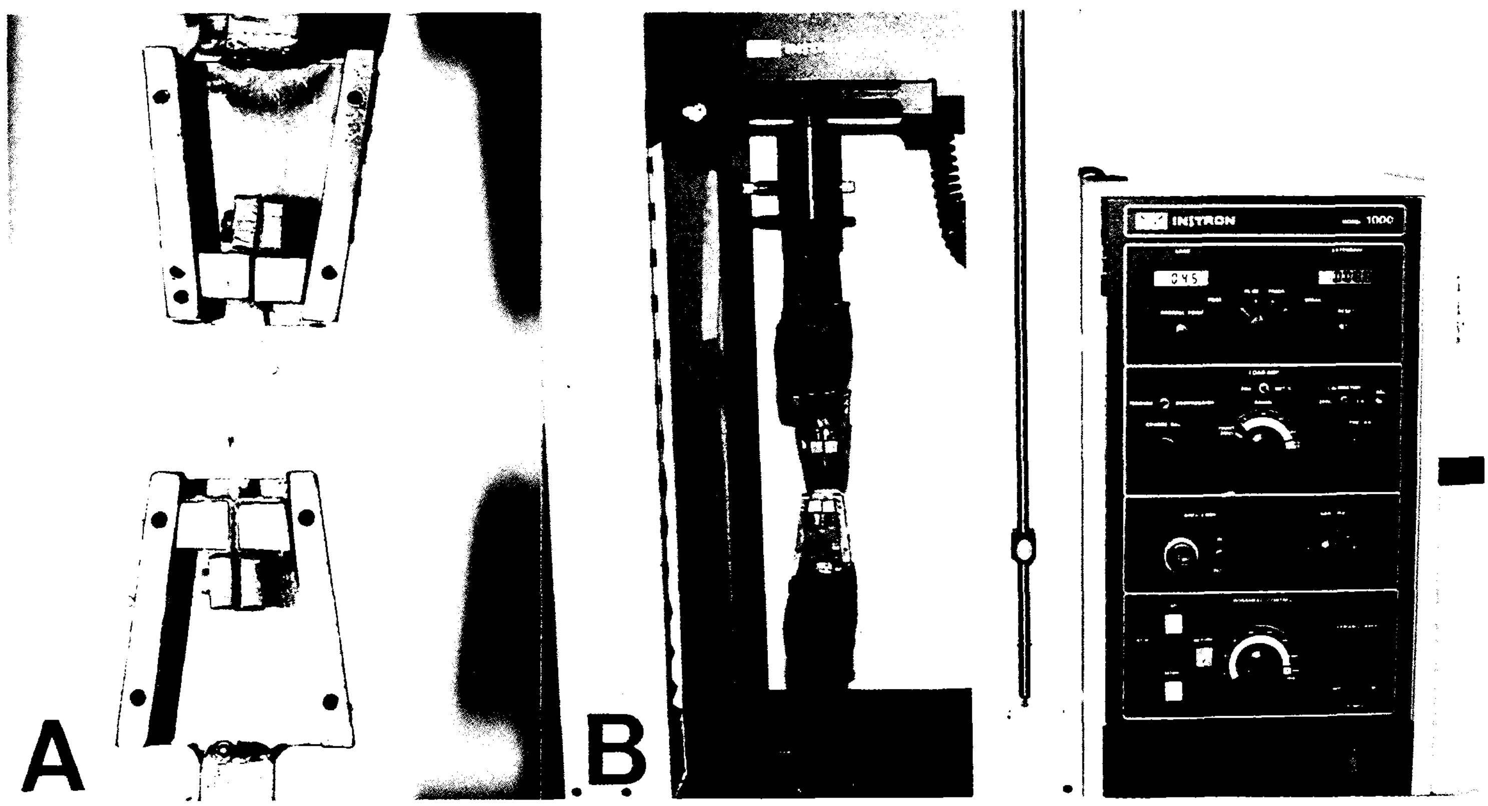


Fig. 1. A. Modified double-wedge action grip. Cotton cloth was used to minimize grip failure. B. The specimens and grips were attached to an Instron 1000 universal material testing machine.

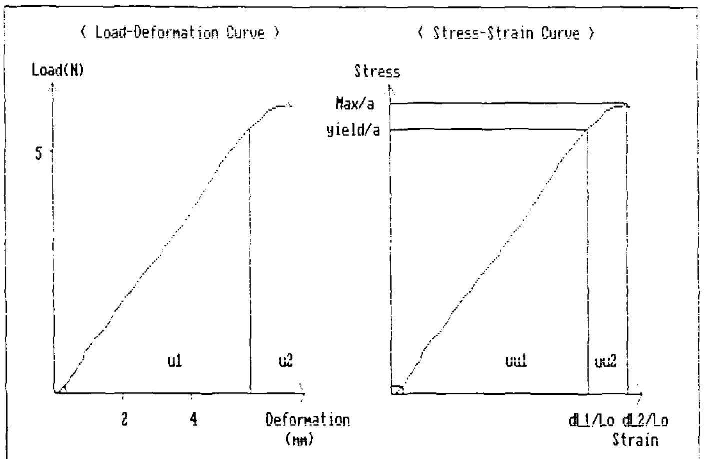
MATERIALS AND METHODS

Preparation of specimesn: After sacrificing Harvard chickens with an average age of forty days and average weight of 1.7 Kg, below-the-knee amputations were performed. The whole legs were wrapped with saline gauze and stored in a deep freezer at $-75°$, and the average storage was three days. After thawing at room temperature for two hours, the flexor digitorum profundus tendons to the middle toe were dissected atraumatically with micro-instruments and were kept moist by wrapping them with saline-soaked gauze. All the experiments were performed within two hours.

Measurement: Since the tendon is an elliptical cylinder rather than a rectangle, authors measured the longest and shortest diameter at three different locations with an optical micrometer(X 8) by two independent investigators. If the longest and shortest diameter of the tendon are a and b, the area will be $\pi ab/4$. The decrease of area due to partial defect can be calculated by integrating the elliptical function of $Y = b/a \sqrt{a^2 - x^2}$ after substracting the defect length from the longest diameter. The factors of remaining intact area to original area are 0.746 in 30% defect, 0.374 in 60% defect, and 0.052 in 90% defect. The average cross-sectional area was 2.37 ± 0.05 mm^2. The length of the specimen was measured after installing the specimen at the Instron at the zero point of preload. The average length of the specimen was 30.40 ± 2.11 mm. There was no significant difference in the cross-sectional area and the length of the specimen among groups ($p > 0.05$).

Tension Test: Forty tendons were divided into four groups, each group was composed of 10 specimens according to the percentage of partial defect; 0% (Group A, control), 30% (Group B), 60% (Group C), and 90% (Group D). The specimens were gripped with a modified wedge-action grip as seen in Figure 1, and each end of the grip was attached at the jig of the Instron 1000 ($\pm$ 1.0% measurement of error and speed). Tension speed was performed at 10 mm /min at room temperature, and load-deformation curve was plotted in the X-Y recorder.

Biomechanical parameters: The data of the experiment were recorded at the X-Y plotter as a load-deformation curve (Fig. 2). Break strength and elongation of the specimen were also visual-



dL1/Lo =	19.13 %	max_l/a =	7844.2	(u1+u2)/a	28.41
dL2/Lo =	23.33 %	u1 =	0.0152	slope =	7.6948215867E+06
yield =	5.48 N	u2 =	0.0067	bias =	-2.3965605538E+04
max_L =	6.04 N	u1/a =	19.68	uu1 =	655.88
yield/a =	7116.9	u2/a =	8.74	uu2 =	291.26

Fig. 2. Load-deformation curve and stress-strain curve. LO: length of the specimen; dL1: yield strain; dL2: maximum strain; yield/a: yielding stress; max 1/a: maximum stress; u1: energy absorbed during elastic phase; u2: energy absorbed during plastic phase; u1 + u2: total energy absorbed at failure; uu1 + uu2: total energy absorption density. Slope in stress-strain curve: Young's modulus

ized on the digital meter assembled in the Instron 1,000. All the values of each curve were stored in an IBM-AT computer using newly developed software and a digitizer. Mechanical parameters such as strain at yielding point (%), maximum strain (%), yielding load, maximum load, yileding stress, maximum stress, modulus of elasticity and energy absorption capacity were determined.

1. Yielding and maximal strain(%): The strain(dL1) at which shows the abrupt change of the curve pattern from the linear portion was measured and the strain(dL2) at maximum load was measured on the load-deformation curve.

2. Yielding load and mixmum load(N): The yileding load was assumed as a point where the linear portion of the curve ended and continued as curved pattern. The highest load was regarded as maximum load.

3. Yielding stress and maximum stress(N/m^2): Yeilding stress and maximum stress were calculated after dividing the yielding load and maximum load by a cross-sectional area of each specimen.

4. Modulus of elasticity(N/m^2): The conversion of the load-deformation curve into a stress-strain curve was made with the aid of a computer program, and the slope of the linear portion in the stress-strain curve was obtained by linear regression.

5. Energy absorption density(Nm/m^3 : J/m^3): the area below the linear and curved portion in the stress-strain curve was obtained by integration of the curve with the aid of a computer program. Because of the variable initial toe region of the curve, the initial point of the linear portion was considered to be the reference point instead of the point at zero strain. The cross-sectional area factor was also considered to calculate volume.

6. Analysis of Data: Statistical validation was performed using "Analysis of Variance" with 16 bit IBM-AT personal computer.

RESULTS

1. Load-deformation curve and stress-strain curve: Load-deformation curves were obtained at the X-Y recorder connected to the Instron 1,000. These curves were stored in the IBM-AT computer after the values of each curve were digitized using a newly-developed software. Given each cross-sectional area, the load-deformation curves were converted to stress-strain curves (Fig. 2).

2. Elastic (yielding) strain and failure(maximum) strain are shown in Table 1. Group D showed significantly low values than Groups A, B, and C, but certain patterns of increase or decrease were not observed.

3. Yielding and maximun load: The results are illustrated in Table 1. Both parameters decreased significantly with the increased proportion of the defect($p < 0.01$, Fig. 3).

4. Yielding stress and maximum stress: The cross-sectional area was given at each proportion of defect as described earlier. The results are in Table 1. The yielding stress increased significantly with the increased proportion of the defect ($P < 0.01$). There was no difference of maximum stress between Group A and B($P > 0.05$). The maximum stress of Group D was higher than Group C ($P < 0.01$), and the overall tendency was an increasing pattern (Fig. 4).

5. Modulus of elasticity: Young's modulus increased in Group C and D ($P < 0.05$, Table 1, Fig. 5).

Table 1. Biomechanical parameters of tendon with partial defect

Parameters/Group	A	B	C	D
Strain at Yield (%)	12.39± 2.62	20.62± 3.19	16.57± 2.49	10.32± 1.55
Strain at Max. Stress (%)	18.35± 3.00	30.35± 2.98	24.94± 4.33	14.32± 3.05
Yielding Load (N)	9.63± 2.02	7.96± 0.46	4.95± 0.58	1.79± 0.23
Maximum Load (N)	12.37± 1.79	9.81± 1.31	5.91± 0.76	2.06± 0.29
Yielding Stress (MPa)▲	4.17± 0.58	5.07± 0.49	6.95± 0.74	16.93± 2.56
Maximum Stress (MPa)	5.22± 0.68	5.63± 0.49	7.54± 0.81	19.23± 2.81
Young's Modulus (MPa)	6.86± 1.14	6.61± 2.57	10.10± 4.21	40.70± 11.80
E. A. D. (Nm/m)*	566.8 ±86.0	798.8 ±123.1	899.8 ±199.1	1380.1 ±327.8

▲: Pa (1 Pascal = 1 N/m^2); *: Energy Absorption Density

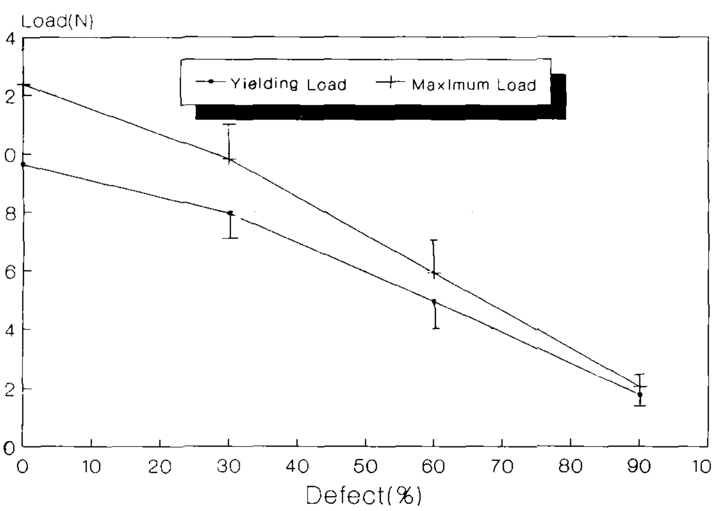


Fig. 3. Yielding and maximum load (strength) decreased significanty with the increasee proportion of the defect.

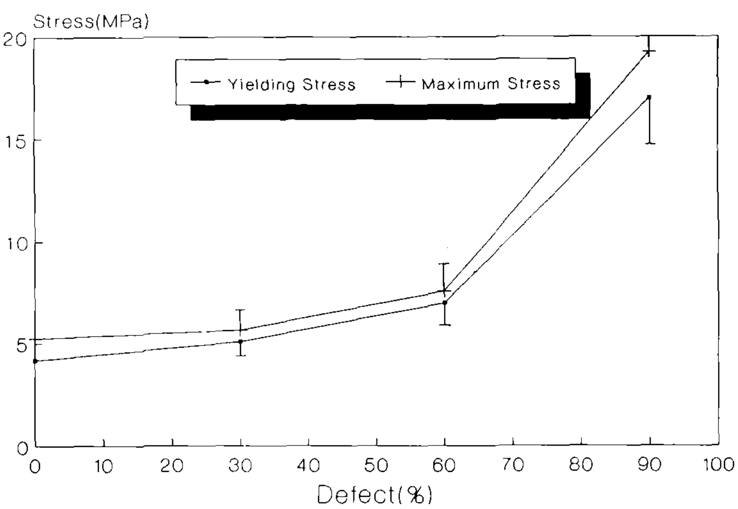


Fig. 4. Yielding stress and maximum stress increased with the increased proportion of the defect.

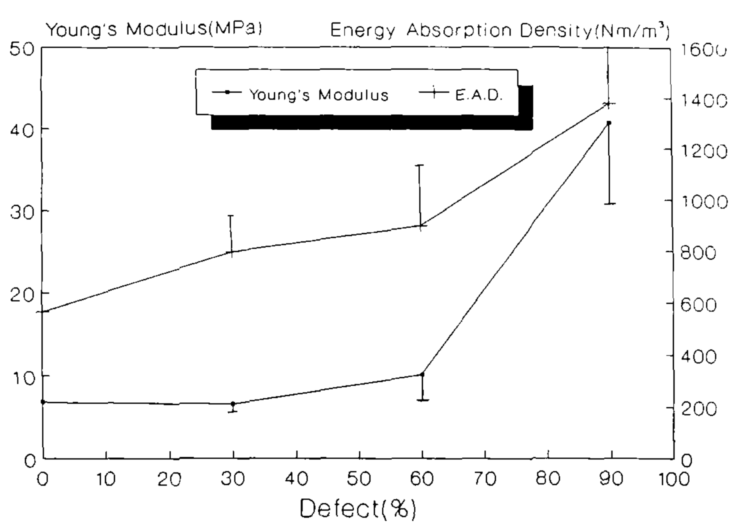


Fig. 5. Young's modulus and energy absorption density (EAD) increased significantly with the increased proportion the defect.

6. Energy absorption density: The results are shown in Table 1. The energy abosrption density increased significantly with the increased proportion of defects. ($P < 0.01$ between Group A and B, $P > 0.05$ between Group b and C, $P < 0.01$ between Group C and D, Fig. 5).

DISCUSSION

Tendon is made up of bundles of the structural protein, collagen. Collagen fibrils consist of interwining molecules of tropocollagen suspended in a mucopolysaccharide gel. The basic molecule comprises three left-handed alpha helixes joined to form a right-handed super helix. Bundles of four or five of these molecules wound together in a left-handed super super helix make up a microfibril. Microfibrials are packed into a tetragonal lattice to form fibrils, the basic-loading units. These are grouped into secondary bundles or fasciculi, which, in turn, are aggregated into tertiary bundles. Secondary and tertiary bundles are arranged in a three-dimensional network, probably as cross-branching helices with loops (Diamant, 1972; Viidik, 1973). The tendon transfers the force generated by the contraction of the muscles to the skeleton and makes joint motion possible. Tendon is known to show viscoelastic behavior during tension (Carlstedt and Skagervall, 1985; Sanjeevi *et al.*, 1982; Woo, 1982). Because of biomechanical and structureal function of the tendon in human body, biomechanical studies were performed in various conditions as described earlier.

Tendon and ligament injuries are frequently seen, and treatments of partial laceration of the tendon or ligament are often controversial. In general, a ductile structure begins to exhibit permanent deformation when its yielding stress is exceeded. This is the progressive event with yielding occurring first in the area where the highest stress occurs under normal load. Any effect due to the distribution of structure are greatly increased by discontinuties, such as holes, sharp angles, nothes, grroves and other sudden transitions in a structure. These discontinuties are known as stress risers, and they produce a stress concentration effect. In this current study, all the Group A specimens failed at either midsubstance or near the grip. In Group B, three specimens failed near the grip despite the presence of the defect. In Groups C and D all failed at the defect site. These results suggest partial defect of tendon is mechanically compensated within substance upto certain proportion of defect, probably due to three dimensional cross-linkages, and absolute decrease in collagen mass rendered failure at defect site at certain higher defect. Although the exact proportion of the safe margin of the defect are not given in detail, it would be better to protect the partially damaged tendon from vigorous activities thus avoiding overloading. Similar studies showed partially divided tendons failed by rupture at the lacreation site with greater than 30% laceration, or at the tendon bone junction, usually less than 30% laceration (Cooney, 1985).

Yielding and maximal strain varied between groups with lowest value in Group D. Yielding and maximum load decreased significantly with the increased proportion of the defect, and these results are predictable since the strength is related with the cross-sectional area or absolute mass of collagen fibril. In terms of stress where the cross-sectional area is considered, yielding stress increased in Group B, C, and D. The maximum stress increased in Group C and D. Since stress is expressed as load per unit area, the value refers to material properties and is rather uniform although there are some discrepancies according to the location and length of the specimen. The increase apparently is regarded as stress concentration due to geometrical changes within tendon. Incresed stress might be explained in two, rather contradictory way. One is to mean the tendon itself is more stronger due to defect. This might be partly explained by three-dimensional cross-linkages between intact and defect portion of the fiber. The other is that the tension load was concentrated at the defect with resulting higher stress values. This in turn suggests the tendon is more stronger. The exact distribution of load within tendon substance, however, is not known at the present time. Young's modulus and energy absorption density (modulus of toughness) also increased at higher proportion of defect. According to the failure modes just presented, absolute decrease of collagen fibrils due to defect negates the effect of increased stress and energy absorption density.

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= 국문초록 =

부분 결손에 의한 건의 생역학적 변화

서울대학교병원 정형외과학 교실

이춘기 · 이영인 · 안재훈

건은 삼차원적 구조의 교원 섬유로 이루어져 있으며 근육의 수축으로 발생하는 힘을 전달하여 관절운동을 가능하게 해준다. 이러한 건의 역학적인 기능으로 인하여 많은 생역학적 연구가 이루어져 왔으나 건의 부분결손에 의한 결손 부위의 생역학적 변화는 잘 알려져 있지 않다. 저자들은 닭의 심부 장족지굴건 40개를 각 군 10개씩 나누어 장경의 0%, 30%, 60%, 90%에 해당하는 결손부위를 만들어 준후 Instron 1000을 이용하여 10 mm / min의 신장 속도로 생역학적 실험을 하였다. 탄성 한계 및 최대 하중은 결손이 클 수록 유의하게 감소하였으며($P < 0.01$), 탄성한계장력 및 최대장력은 유의하게 증가하였으며($P < 0.01$), 탄성계수 및 총 에너지 밀도도 결손이 클수록 증가하였다($P < 0.01$). 30%군에서는 10시편중 7개에서, 60%, 90%군에서는 전 시편에서 파열이 일어났다. 임상적으로 본 연구는 건이나 인대의 어느 정도의 부분 결손은 건 자체의 구조적인 특징으로 인한 역학적인 보상이 이루어지나, 어느 이상의 결손은 충분한 치유과정이 일어날 때까지 과하중으로부터 보호가 필요함을 시사하였다.