The objectives of this study are to introduce the use of a photodiode camera for measuring surface strain on soft tissue and to present some representative responses of the tendon. Tendon specimens were obtained from the hindlimbs of canines and frozen to \(-70^\circ\) C. After thawing, specimens were mounted in the immersion bath at a room temperature (22°C), preloaded to 0.13 N and then subjected to 3% of the initial length at a strain rate of 2%/sec. In tendons which were tested in two blocks of seven repeated extensions to 3% strain with a 120 seconds wait period between, the surface strains were measured with a photodiode camera and near the gripped ends generally were greater than the surface strains in the middle segment of the tendon specimens. The recovery for peak load after the rest period was consistent but the changes in patterns of surface strains after the rest period were not consistent. The advantages of a photodiode measurement of surface strains include the followings: 1) it is a noncontacting method which eliminates errors and distortions caused by clip gauges or mechanical/electronic transducers; 2) it is more accurate than previous noncontact methods, e.g. the VDA and the high speed photographic method; 3) it is a fully automatic, thus reducing labor for replaying video tapes or films and potential errors from human judgement which can occur during digitizing data from photographs. Because the photodiode camera employs a solid state photodiode array to sense black and white images, scan targets (black image) on the surface of the tendon specimen and back lighting system (white image), and stored automatically image data for surface strains of the tendon specimen on the computer during cyclic extensions.

**Key Words:** Bone End Section, Mid-Portion, Muscle End Section, Segment, Photodiode Measurement, Surface Strain, Tendon, Video Dimensional Analyzer (VDA) System

### 1. Introduction

Local surface strain near the bone attachment sites of human patellar tendons appeared to be larger than local surface strain in the mid-region during stretching by using a high speed film camera\(^{1,2}\). Strain measurement with high speed photography is laborious and there is potential for error in human judgement during film analysis. A video dimensional analyzer (VDA) system was used for measuring surface strain to eliminate the errors introduced by contacting the tissue such as with clip gauges or mechanical/electronic transducers\(^{3-6}\). However, the VDA system is limited in the number of regions in which strain can be accurately measured. Also, this VDA system is not fully automatic and needs some laborious work for replaying video tapes.

The objectives of this study are to introduce the use of a photodiode camera for measuring surface strain on soft tissue and to present some representative responses of the tendon.

### 2. Materials and Methods

Tendon samples were dissected from hindlimbs of adult canines which had been sacrificed in veterinary surgery classes. Within an hour post-mortem, the whole limbs were refrigerated at near freezing, and tendons were dissected within one day. After dissection, each tendon specimen was wrapped in Ringer’s lactate soaked paper...
towel and sealed in small plastic bags with the name of their anatomical location and date of dissection. Thereafter, groups of tendons from each canine were put into a larger plastic bag, and these larger plastic bags were put into an air-tight container and stored in a freezer at $-70^\circ$C. This packing method prevented tendon dehydration and decay during storage\(^7\)\(^-\)\(^9\). Each specimen was 45 mm or longer with a near constant cross-sectional area. Thick specimens with major diameters larger than 5 mm were avoided, since it was thought that large cross-sections would not insure the uniform pressure between interior and exterior fibers during gripping.

At the beginning of each test, a tendon specimen was soaked in the Ringer’s lactate solution for a minimum of 30 minutes during which there was complete thawing. Tests were conducted using a computer controlled, servo-hydraulic Instron testing system (Model 1331) with the hydraulic cylinder in the upper crosshead. For gripping tendon samples, flat-plate clamp type grips were employed with waterproof 100 grit silicon carbide abrasive paper on the inner surface. Both sides of each end of all specimens were marked with a water resistant pen and these marks were placed just inside of the grips. These marks were observed and photographed with a WILD MPS 55 stereomicroscope and its camera during extensions. Both sides of each end of all specimens were marked with a water resistant pen and these marks were placed just inside of the grips. These marks were observed and photographed with a WILD MPS 55 stereomicroscope and its camera during extensions. The marks were not detected by the microscope and shown by photographs, indicating that no detectable slippage occurred with this gripping method\(^7\),\(^9\). Histological examinations showed that the tendon fibers within the grips were continuous and compressed together but neither were torn nor fractured. Grip motion was measured with an LVDT mounted in the hydraulic actuator of the Instron testing machine. The load was measured with a fully submersible Interface load cell (Model SSM-A5-100) which has a maximum 444.82 N load and was mounted in the immersion bath and to the lower, fixed base of the testing machine. The initial length of the specimen was measured between grips by a micrometer with an accuracy of 0.01 mm at a preload of 0.13 N on the specimen. Tests were performed at a 2%/sec strain rate with the maximum strain level of 3% in two 21 seconds long blocks of seven cycles each separated by one rest period (120 seconds). This testing sequence made it possible to investigate recovery effect of the surface deformations. During testing, the specimen was immersed in a Ringer’s lactate solution bath at a room temperature (22$^\circ$C). This bath was constructed of clear plastic with a clear, flat front quartz plate and rear windows for a good camera image.

As in previous studies\(^7\),\(^8\), the cross-sectional areas of the specimens were measured from histological cross-sections prepared with commonly used paraffin embedding\(^10\). The slides with the cross-sections were placed in a photographic enlarger with a precision scale and photographs were taken. From these photographs, the compact tendon cross-section was selected and measured using a digitizer which is accurate to within 0.01 mm$^2$. The test number, anatomical site, tendon status, initial length (mm), area (mm$^2$), and peak load (N) for each specimen are listed in Table 1.

A photodiode camera (Reticon Model LC 120 V2048/16), which employs a 2048 element solid state photodiode array to sense the image, was utilized to measure the surface deformations during cyclic motion. Figure 1 is an illustration of tendon segments with the camera scanning line and back lighting system. Two targets of self-adhesive, stiff, and narrow (about 0.5 mm) plastic were glued approximately 10 mm apart with cellulose nitrate to the mid-portions of the tendon specimen\(^11\). This cellulose nitrate did not cause any local dehydration of the tendon specimen. The photodiode camera scanned these targets and grips for measurement of surface deformation during cyclic extensions. It was assumed that there was no target rotation during cyclic extensions in the tendon specimen.

The accuracy of measurement was optically deter-

Table 1  Tendon specimen characteristics in cyclic tests with a photodiode camera

| Test No | Anatomical Location     | Tendon* Status | Initial Length (mm) | Area (mm$^2$) | Peak Load (N) |
|---------|------------------------|----------------|---------------------|--------------|--------------|
| 1       | Peroneus longus (m.e.s.| same           | 31.52               | 0.76         | 11.17        |
| 2       | Peroneus longus (m.p.) | same           | 31.88               | 0.66         | 10.54        |
| 3       | Peroneus longus (b.e.s.) | same       | 32.80               | 0.81         | 12.85        |
| 4       | Extensor digitorum longus | same       | 32.75               | 0.99         | 11.34        |
| 5       | Extensor digitorum longus | same       | 33.05               | 0.89         | 14.77        |
| 6       | Flexor hallucis longus   | same           | 32.68               | 1.52         | 1.38         |
| 7       | Flexor digitorum brevis  | same           | 33.58               | 1.92         | 3.71         |

*  Tendon Status means that test no.1, test no.2, and test no.3 are obtained from one long peroneus longus tendon which are divided into muscle end section (m.e.s.), mid-portion (m.p.) and bone end section (b.e.s.), and the others (test no.4-test no.7) are obtained from different tendons.

![Fig. 1 Illustration of tendon segments with the scanning line in a photodiode camera and the back lighting system](image-url)
mined by the field-of-view depending on the working distance used. In this study, position differences of 17.5 µm were resolved with about a 35 mm field-of-view. The field-of-view was imaged by the lens onto the photodiode array, which was electronically scanned to provide both analog and digital outputs to the camera data formatter and interface unit. The digital image data were created in the camera by comparing a user-settable threshold were accepted and preprocessed by the camera data formatter without a need for a computer CPU control. The formatted camera data were stored in two RAM memories on-board the camera data formatter. These two memories allowed simultaneous image data storage and computer processing of data. While one memory was acquiring image scan data, the other was available for computer processing of the data. This toggling scheme was used to accommodate the acquisition of camera data at clock rates up to 2 MHz. At this rate, a 2048 pixel scan line would take nominally 2 ms. However, the ultimate limitation on image data rate was generally dependent upon the number of transitions, complexity of the image, and the computer’s ability to accept and process image data. The back lighting system was chosen to make a good uniform light field for the photodiode camera. A 12V-DC fluorescent light was employed as the lighting system to obtain a useful image.

A computer was used for test control and data acquisition, storage, and analysis. An Instron Machine Interface Unit (MIU) and an Instron Machine Driver (IMD) enabled command and communication between the computer and the testing machine. Data were also monitored and stored on a digital oscilloscope (Nicolet, Model 210, Series 2090). A description of the test diagram for measuring surface strains with the photodiode camera and an Instron testing system is shown in Fig. 2.

3. Results and Discussions

Figures 3 through 9 show the surface strains of the tendon segments for seven cycles from test no. 1 through 7. It appears, with two exceptions (test no. 4 and 5), that the local surface strains near the gripped ends (seg. 2). The grip (end) effect may cause this nonuniform distribution of strains on the tendon specimen. Figure 10 shows the description of specimens from the same tendon of peroneus longus divided into three sections (muscle end section, mid-portion, bone end section) along the length. Thus, each section has three segments (seg. 1, seg. 2, seg. 3) for comparing the surface deformations of specimens from the same tendon, the surface strains of middle segments of specimens (segment 2) were chosen because the grip (end) effect was thought to be minimal in this segment. Figure 11 shows the surface strains of segment 2 for seven cycles in tests of three specimens from the same tendon. In this figure, the bone end section of a long tendon has the smallest deformation (the stiffest) and the mid-portion of a long tendon has the largest deformation (the softest) during cyclic extension.

Figure 12 presents the surface strains of the tendon segments with a 120 seconds rest period for test no. 1. Its cyclic load relaxation and recovery responses are shown in Fig. 13. Comparing Figs. 12 and 13, the surface strains in segment 2 after the rest periods are reduced (recovered) from those before the rest period. However, recovery phenomena for surface strains corresponding to their load recovery after the rest period were not consistent in all the specimens in this study.

Table 2 presents the cyclic peak loads and peak surface strains in the tendon segments at corresponding cy-
Fig. 4 Surface strains of the tendon segments with cycles for test no. 2 (——: Seg. 1, ++++: Seg. 2, ····: Seg. 3)

Fig. 5 Surface strains of the tendon segments with cycles for test no. 3 (——: Seg. 1, ++++: Seg. 2, ····: Seg. 3)

Fig. 6 Surface strains of the tendon segments with cycles for test no. 4 (——: Seg. 1, ++++: Seg. 2, ····: Seg. 3)

Fig. 7 Surface strains of the tendon segments with cycles for test no. 5 (——: Seg. 1, ++++: Seg. 2, ····: Seg. 3)

Fig. 8 Surface strains of the tendon segments with cycles for test no. 6 (——: Seg. 1, ++++: Seg. 2, ····: Seg. 3)

Fig. 9 Surface strains of the tendon segments with cycles for test no. 7 (——: Seg. 1, ++++: Seg. 2, ····: Seg. 3)
Fig. 10 Illustration of the same tendon, which is divided into three sections (muscle end section, mid-portion, bone end section), and each section has three segments.

Fig. 11 Surface strains in the segment 2 of the each section from the same tendon with cycles (——: test no. 1 [muscle end section], ++++: test no. 2 [mid-portion], □□□□: test no. 3 [bone end section]).

Fig. 12 Surface strains of the tendon segments with a 120 seconds rest period for test no. 1 (——: Seg. 1, ++++: Seg. 2, ---: Seg. 3).

Table 2 Cyclic peak load (N) and surface strain (%) at each tendon segments with one rest period (120 seconds)

| Test No | Cycle No. (Time) | Peak Load (N) | Peak Surface Strain (%) |
|---------|-----------------|---------------|-------------------------|
| 1       | 1(1,5)          | 11.17         | 2.94                    |
|         | 7(19,5)         | 10.11         | 2.94                    |
|         | 8(141,5)        | 10.47         | 2.94                    |
|         | 14(159,5)       | 9.90          | 2.94                    |
| 2       | 1(1,5)          | 10.54         | 3.20                    |
|         | 7(19,5)         | 9.54          | 3.05                    |
|         | 8(141,5)        | 9.89          | 3.05                    |
|         | 14(159,5)       | 9.34          | 3.05                    |
| 3       | 1(1,5)          | 12.85         | 3.48                    |
|         | 7(19,5)         | 11.65         | 3.80                    |
|         | 8(141,5)        | 11.76         | 3.80                    |
|         | 14(159,5)       | 11.43         | 3.80                    |
| 4       | 1(1,5)          | 11.34         | 1.58                    |
|         | 7(19,5)         | 10.32         | 1.26                    |
|         | 8(141,5)        | 10.32         | 1.26                    |
|         | 14(159,5)       | 9.79          | 1.26                    |
| 5       | 1(1,5)          | 14.77         | 1.32                    |
|         | 7(19,5)         | 13.23         | 1.32                    |
|         | 8(141,5)        | 13.54         | 1.32                    |
|         | 14(159,5)       | 12.89         | 1.32                    |
| 6       | 1(1,5)          | 1.58          | 3.97                    |
|         | 7(19,5)         | 1.06          | 3.97                    |
|         | 8(141,5)        | 1.08          | 3.97                    |
|         | 14(159,5)       | 0.98          | 3.97                    |
| 7       | 1(1,5)          | 3.71          | 3.94                    |
|         | 7(19,5)         | 3.05          | 3.94                    |
|         | 8(141,5)        | 3.14          | 3.94                    |
|         | 14(159,5)       | 2.91          | 3.94                    |

Cyclic peak load relaxation and recovery with a 120 seconds rest period for test no. 1.

Table 2 shows the cyclic peak load (N) and surface strain (%) at each tendon segments with one rest period (120 seconds). The surface strains of the gripped ends (segments 1 and 3) were generally greater than those of middle segment (segments 2).
4. Conclusion

The strains varied along the length on the each tendon specimen in this study. However, in general, the surface strains near the gripped ends were greater than the surface strains in the middle segment of the tendon specimens. The recovery for peak load after the rest period was consistent but the changes in patterns of surface strains after the rest period were not consistent. The nonuniform distribution of strains on tendon specimens observed in this study could have been affected by the gripping method (end effect). In two cases (test no. 4 and 5), although the strains of the gripped ends could have been affected by the end effect, the strains of the middle segment (segment 2) were greater than those of the gripped ends. From these results, the deformation patterns of the collagenous tissues might be dependent upon both non-homogeneous material properties (e.g. differences in microstructure and/or biochemical composition) along the specimen and the end effect.

The advantage of a photodiode measurement of surface strains include the following: 1) it is a noncontacting method which eliminates errors and distortions caused by clip gauges or mechanical/electronic transducers; 2) it is more accurate than pervious noncontacting methods, e.g. the VDA and the high speed photographic method; 3) it is a fully automatic, thus reducing labor for replaying video tapes or films and potential errors from human judgement which can occur during digitizing data from photographs. Because the photodiode camera, employs a solid state photodiode array to sense black and white images, scan targets (black image) on the surface of the tendon specimen and back lighting system (white image), and stored automatically image data for surface strains of the tendon specimen on the computer during cyclic extensions.

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