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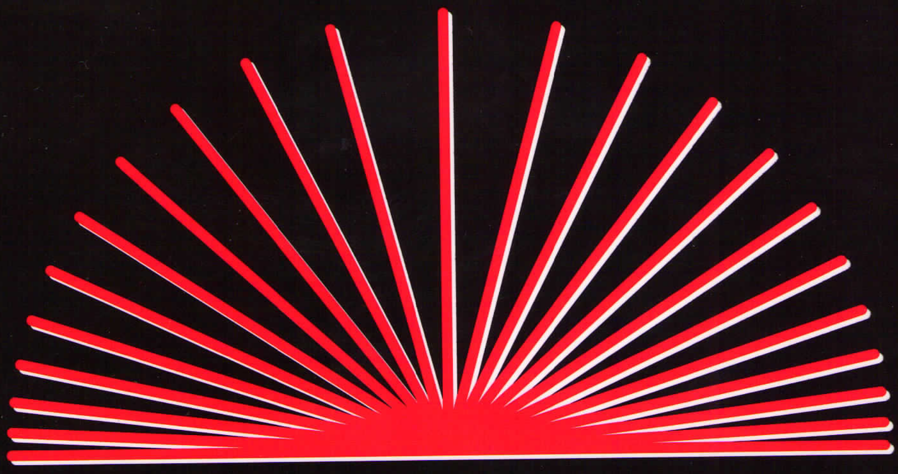

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A Modified Cryo-Jaw for In Vitro Biomechanical Testing of Tendons

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The purpose of this study was to develop a new device, which represents a modification of the Cryo-Jaw described by Riemersa and Schamhardt and modified by Hamner et al., for in vitro biomechanical testing of tendons which allows the lower clamp to move in every direction and thus simulate a pathological dislocation of the knee. Tendons are fixed to the device by freezing the clamped part with dry ice. After fixation of their free ends, the lower clamp was rotated 45°, translated 1 cm, and angled 40° to simulate a knee sprain. Various configurations of bundles were tested: parallel, twisted, and braided. Tests were performed on 10 paired bovine bifurcated digital extensor tendons and 6 paired human hamstring tendons. Grafts were then tested to failure subjected to impulsive load, using a servohydraulic machine. The highest ultimate load recorded for parallel bundles was 4662 ± 565.71 N for bovine bifurcated digital extensor tendons, and 3057 ± 475.44 N for human hamstring tendons. In any case, the tendons ruptured midway, well clear of the frozen part; in no case was slippage of the tendons observed. Thus the device proposed allows one to test what happens to the graft of an ACL reconstructed knee during physiological and pathological movements because it can be easily displaced in every direction.

Key Words: ACL, hamstrings, clamp, dry ice

Introduction

Anterior cruciate ligament (ACL) reconstruction with autologous grafts is a common procedure in orthopaedic surgery. Bone-patellar tendon-bone (BPTB) and doubled gracilis and semitendinosus tendons (DGST) are usually used. In the last

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Hecker, & Hayes (1999) and by
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loads with disruption of the tendons
from the clamps. All devices used
describes a new device for in vitro
the lower clamp to move in every
tion of the knee.

The two clamps are made of steel
that can be tightened together, between
tions are 1 mm deep and have a
rear portion of these clamps is a
clamp can be displaced laterally
be connected to a servohydraulic
placed at the top and bottom of the

After definitive revision of the
10 paired bovine bifurcated digital
string tendons. The tendons were
of the jaws: the four screws of the
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were frozen. Various configurations
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cm, and the testing machine was
inertial effects of the clamps.
ferent tests were performed at
tested to failure using a servohydraulic
every 50 ms).

decade, biomechanical properties of these tendons have been widely studied to optimize the result of ACL reconstruction. Knowing the stiffness, pullout strength, and force/elongation curve of the graft is essential to understanding its behavior in physiological and pathological knee movements. Bony ends of tendons, as in BPTB, can be easily fixed to the testing machine in several ways without damaging the collagenous structure of the tendons. If the bony ends are missing on one or both sides, as with DGST, there could be problems when testing the biomechanical properties. Soft tissue may be markedly deformed and rapidly damaged by excessive compression. Moreover, there is very low friction between the material of the device and wet, soft collagenous tissues.

Many researchers have studied different devices so as to avoid these difficulties (Abrahams, 1967; Benedict, Walker, & Harris, 1968; Cohen, Hooley, & McCrum, 1976; Viidik, 1967). A clamp, as described by Riemersa and Schamhardt (1982), is commonly used. This allows excellent grip without major deformation and damage of the tendons within and exterior to the frozen region of the clamp (Cryo-Jaw). Recently this device has been modified by Hamner, Brown, Steiner, Hecker, & Hayes (1999) and by MacWilliams, Wilson, DesJardins, and Chao (1999) in their dynamic knee simulator. Freezing the clamps allows for testing to high loads with disruption of the tendons in the midsubstance without their slipping from the clamps. All devices used today can test tendons only axially. This paper describes a new device for in vitro biomechanical testing of tendons which allows the lower clamp to move in every direction, thus simulating a pathological dislocation of the knee.

Methods

The two clamps are made of steel and aluminium. Both have two indented plates that can be tightened together, between which the tendons are placed. The indentations are 1 mm deep and have a rounded top to avoid damage to the tendons. In the rear portion of these clamps is a container in which dry ice is placed. The lower clamp can be displaced laterally and can be rotated and angled. Both clamps can be connected to a servohydraulic testing machine (Instron 5584) by a steel pin placed at the top and bottom of the clamps (Figures 1 and 2).

After definitive revision of the device, preliminary tests were performed on 10 paired bovine bifurcated digital extensor tendons and 6 paired human hamstring tendons. The tendons were secured to the clamp with moderate compression of the jaws: the four screws of the jaws were tightened with a dynamometric screwdriver up to 5 Nm diagonally. Then the jaws and the clamped part of the tendons were frozen. Various configurations of bundles were tested: parallel, twisted, and braided. The upper grip received the axilla of the looped tendons; the lower grip, after fixation of the free ends of them, was rotated 45°, translated 1 cm, and angled 40° to simulate a knee sprain (Figure 3). The two jaws were set at a distance of 9 cm, and the testing machine was adjusted every time to avoid any influence of inertial effects of the clamps. The graft was then subjected to impulsive load (different tests were performed at various speeds: 180, 360, and 540 mm/min) and tested to failure using a servohydraulic machine. Data were sampled at 20 Hz (one every 50 ms).

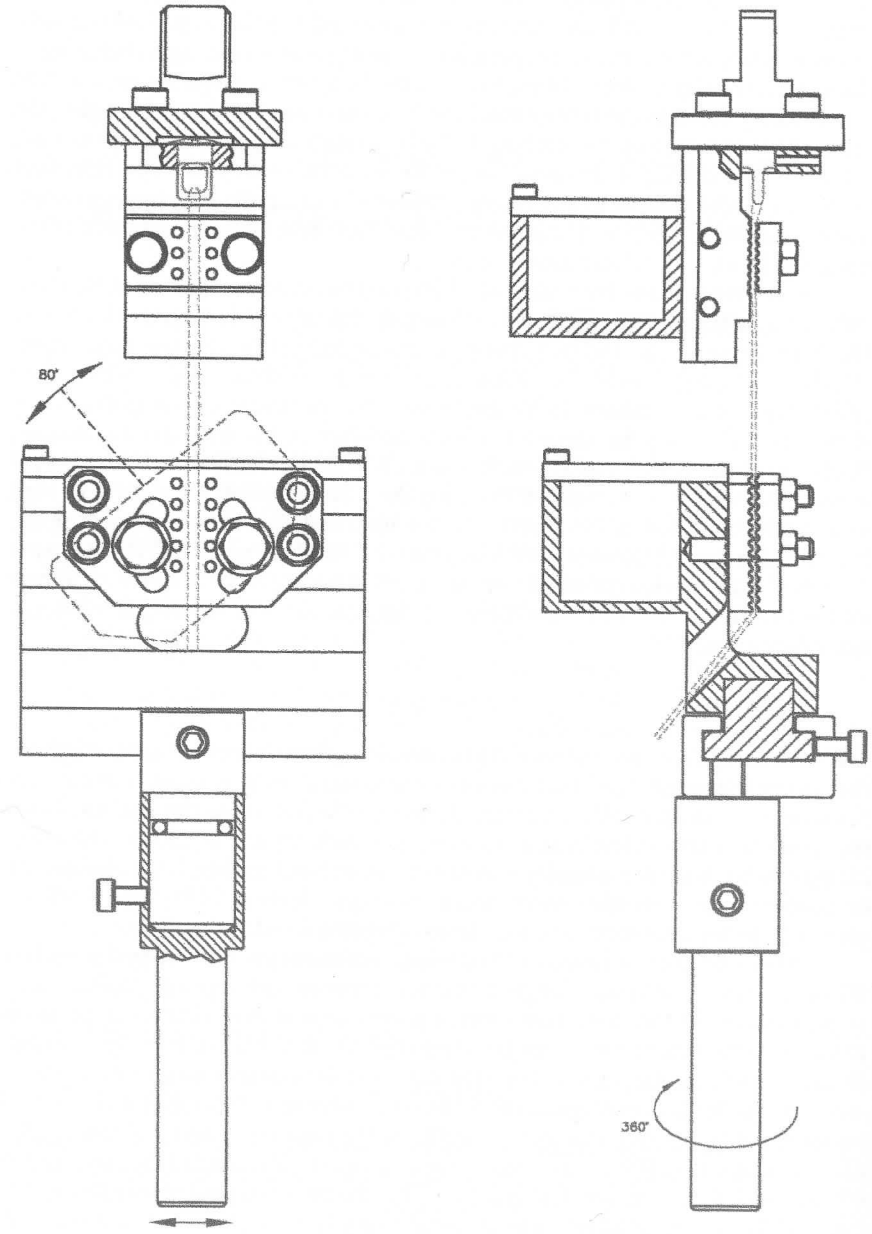
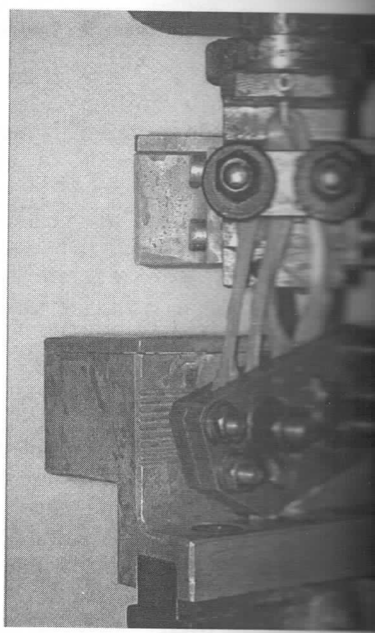


Figure 1 — The modified Cryo-Jaw for biomechanical testing of tendons.

Figure 2 — The posterior container



The highest ultimate load recorded
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and 3057 N (range: 1804–3057; mean
tendons. The highest stiffness record

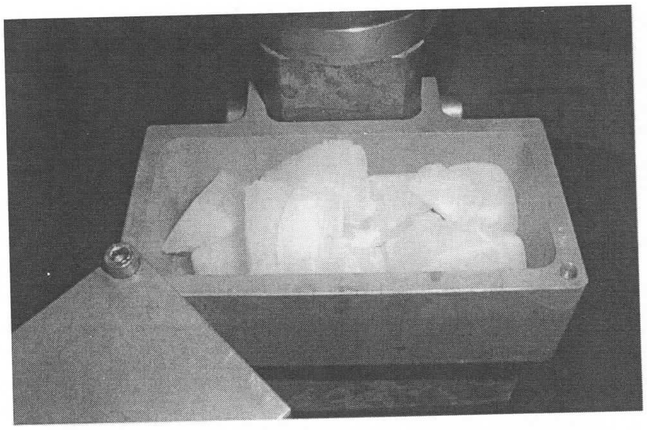


Figure 2 — The posterior container for dry ice on both clamps.

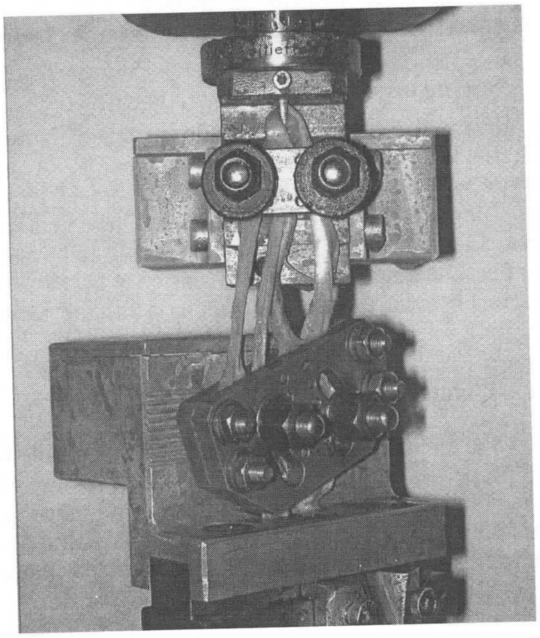
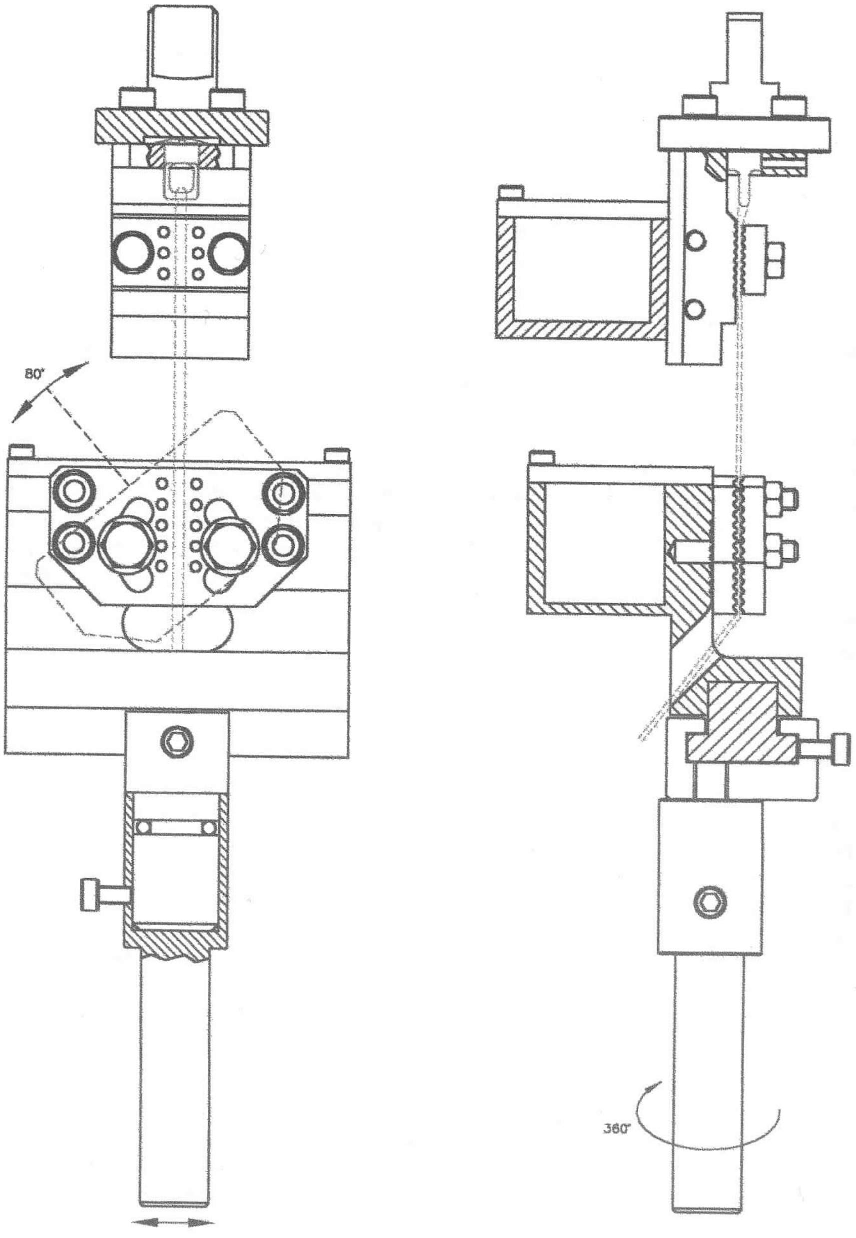


Figure 3 — The lower grip, after freezing the tendons, is rotated 45°, translated 1 cm, and angled 40°, simulating a knee sprain.

Results

The highest ultimate load recorded for parallel bundles was 4662 N (range: 3114–4662; mean: 3846.43; *SD*: 565.71) for bovine bifurcated digital extensor tendons, and 3057 N (range: 1804–3057; mean: 2428.33; *SD*: 475.44) for human hamstring tendons. The highest stiffness recorded was 663 N/mm (range: 376–663; mean:



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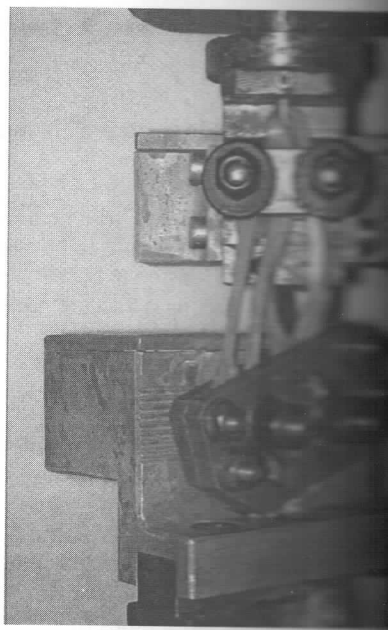

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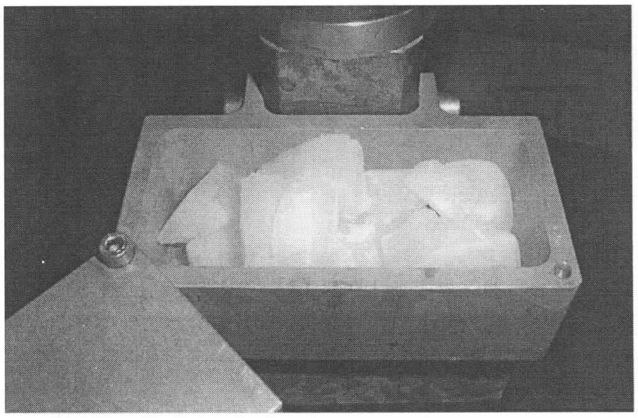

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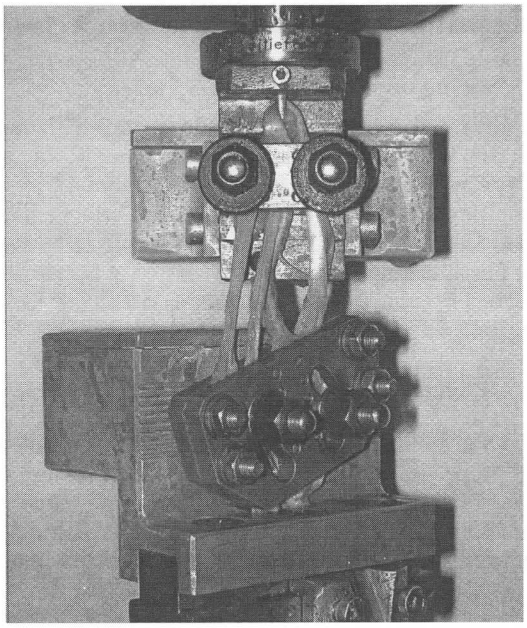

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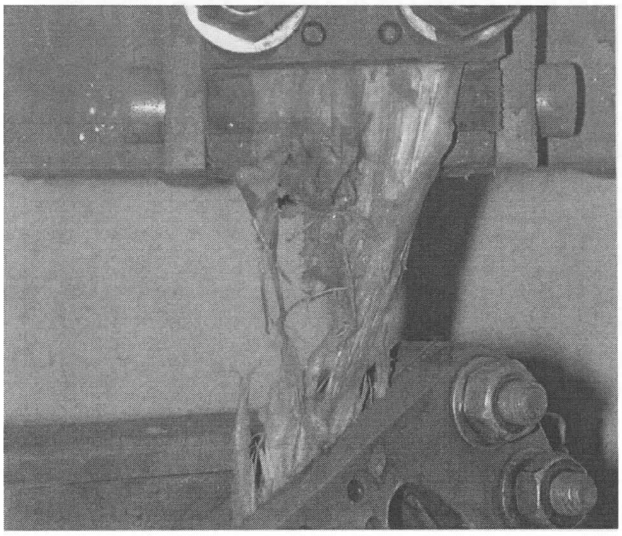

Figure 4 — The rupture of the tendons is in their midsubstance, far from the frozen part.

471.08; *SD*: 113.87) for bovine bifurcated digital extensor tendons, and 480 N/mm (range: 192–480; mean: 310.33; *SD*: 97.39) for human hamstring tendons. In any case, the tendons ruptured midway, well clear of the frozen part (Figure 4). In no case was slippage of the tendons observed. The Cryo-Jaw system has been demonstrated to reach ultimate load up to 13,800 N (with digital flexor tendons of horses) with no slippage. It would not be possible for this tremendous tension to be reached with human grafts, demonstrating that freezing free ends of tendons is a secure, satisfactory, and reproducible manner for fixing wet, soft tissue to testing machines.

Discussion

The wet interface between soft tissue and the camping device is a major problem when testing the biomechanical properties of the tendons. Excessive pressure of jaws can lead to deformation and/or lesion of the clamped part of the tendons. Moreover, friction between inner collagenous fibers is lower than the friction between outer fibers and the clamp, resulting in undetected slipping of the inner fibers.

Freezing the jaws to the clamped part of the tendons overcomes this problem. Only reduced pressure is applied to the jaws so that the clamped parts of the tendons are only deformed by the indentations of the jaws but are not disrupted by them. Dry ice is applied since the tendons are frozen up to the undeformed zone a few millimeters away from the clamp. Then compression is increased without increasing the deformation of the tendons because they are frozen. At this stage the frozen profiles of the tendons are gripped tightly in the jaws of the clamps. The temperature of the tendon must be carefully monitored, taking care not to freeze the midsubstance. Hamner et al. (1999) could not find any significant difference in

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strength of unembalmed
Cohen, R.E., Hooley, C.J., &
tissue. *Journal of Bio*
Hamner, D.L., Brown, C.H.,
tendon grafts for
evaluation of the use of
and Joint Surgery
MacWilliams, B.A., Wilson,
cocontraction reduces
ment load in weight-bearing
Nicklin, S., Waller, C.,
properties of braided
793.
Riemersa, D.J., & Schamhardt,
rheology studies of horse
620.
Viidik, A. (1967). Experimental
Biomedical Engineering
Wallace, M.P., Howell, S.M.,
hamstring graft as a
paedic Research, **15**,

the biomechanical behavior between tendons tested at 13 °C and those tested at room temperature.

In the last decade many researchers have studied the biomechanical properties of hamstrings tendons either at impulsive or cyclic loading. But all tests were performed axially. Hamner et al. (1999) demonstrated that the four parallel bundles of a gracilis and semitendinosus graft are much stronger and stiffer than ACL and BPTB graft when tested axially. Moreover, ultimate load and stiffness increases if the four bundles are under equal tension. Unfortunately, this situation is very different from what happens during physiological and pathological knee movements. In fact, Wallace, Howell, and Hull (1997) have demonstrated that the peak tensions of the four bundles are not equal during passive motion.

The improvement using our device is that, unlike all other similar devices that have been presented for biomechanical testing of tendons, it can be easily displaced in every direction to simulate traumatic dislocations of the knee. Cyclic loading and ultimate loads can be measured. The device can be easily secured to a servohydraulic materials testing machine. This new device allows two doubled tendons to be tested at the same time. Almost every configuration of the bundles is possible: parallel, twisted, and braided. We believe the device proposed allows one to test, in a reproducible manner, what happens in an ACL-reconstructed knee during physiological and pathological movements.

References

Abrahams, M. (1967). Mechanical behaviour of tendon in vitro. *Medical & Biological Engineering*, **5**, 433-443.

Benedict, J.V., Walker, L.B., & Harris, E.H. (1968). Stress-strain characteristics and tensile strength of unembalmed human tendon. *Journal of Biomechanics*, **1**, 53-63.

Cohen, R.E., Hooley, C.J., & McCrum N.G. (1976). Visco-elastic creep of collagenous tissue. *Journal of Biomechanics*, **9**, 175-184.

Hamner, D.L., Brown, C.H., Steiner, M.E., Hecker, A.T., & Hayes W.C. (1999). Hamstring tendon grafts for reconstruction of the anterior cruciate ligament: Biomechanical evaluation of the use of multiple strands and tensioning technique. *Journal of Bone and Joint Surgery [Am.]*, **81A**, 549-557.

MacWilliams, B.A., Wilson, D.R., DesJardins, D.J., & Chao, Y.S. (1999). Hamstrings cocontraction reduces internal rotation, anterior translation, and anterior cruciate ligament load in weight-bearing flexion. *Journal of Orthopaedic Research*, **17**, 817-822.

Nicklin, S., Waller, C., Walker, P., Chung, W.K., & Walsh, W.R. (2000). In vitro structural properties of braided tendon grafts. *American Journal of Sports Medicine*, **28**, 790-793.

Riemersa, D.J., & Schamhardt, H.C. (1982). The Cryo-Jaw, a clamp designed for in vitro rheology studies of horse digital flexor tendons. *Journal of Biomechanics*, **15**, 619-620.

Viidik, A. (1967). Experimental evaluation of the tensile strength of isolated rabbit tendons. *Biomedical Engineering*, **2**, 64-67.

Wallace, M.P., Howell, S.M., & Hull, M.L. (1997). In vivo tensile behavior of a four-bundle hamstring graft as a replacement for the anterior cruciate ligament. *Journal of Orthopaedic Research*, **15**, 539-545.