

# Femoral Press-Fit Fixation of the Hamstring Tendons for Anterior Cruciate Ligament Reconstruction

Michael Jagodzinski,<sup>\*†</sup> MD, Vahid Behfar,<sup>†</sup> Christof Hurschler,<sup>‡</sup> PhD, Knut Albrecht,<sup>§</sup> PhD, Christian Krettek,<sup>§</sup> PhD, and Ulrich Bosch,<sup>||</sup> PhD

From the <sup>†</sup>Department of Trauma Surgery, Hanover Medical School, the <sup>‡</sup>Laboratory for Biomechanics and Experimental Orthopedics, Department of Orthopedics, Hanover Medical School, the <sup>§</sup>Department of Forensic Medicine, Hanover Medical School, and the <sup>||</sup>Center of Orthopedics and Sports Traumatology of the INI, Hanover, Germany

**Background:** Press-fit fixation of patellar tendon–bone anterior cruciate ligament autografts is an interesting technique because no hardware is necessary. For hamstring tendon grafts, no biomechanical data exist of a press-fit procedure.

**Hypothesis:** Press-fit femoral fixation of hamstring tendons is mechanically equivalent to press-fit patellar tendon–bone fixation.

**Study Design:** Controlled laboratory study.

**Methods:** Patellar and hamstring tendons of 30 human cadavers (age,  $53.8 \pm 18.0$  years) were used. An outside-in press-fit fixation with a knot in the semitendinosus and gracilis tendons and an inside-out and outside-in fixation with the tendons wrapped around a bone block were compared with patellar tendon–bone press-fit fixation in 30 ovine femora. Constructs were cyclically strained and then loaded until failure. Maximum load to failure, stiffness, and elongation during failure testing and cyclical loading were investigated.

**Results:** The maximum load to failure was  $561 \pm 309$  N for the patellar tendon,  $599 \pm 234$  N for the semitendinosus/gracilis tendons knot construct,  $678 \pm 231$  for the semitendinosus/gracilis tendons bone construct inserted outside in, and  $339 \pm 236$  for the semitendinosus/gracilis tendons bone construct inserted inside out (inferior to the others; analysis of variance, Dunn test,  $P < .01$ ). Stiffness of the constructs averaged  $134 \pm 32$  N/mm for the patellar tendon,  $124 \pm 21$  N/mm for the knot construct,  $118 \pm 27$  N/mm for the outside-in fixation, and  $117 \pm 23$  N/mm for inside-out fixation. Elongation during initial cyclical loading was  $0.7 \pm 0.6$  mm for the patellar tendon,  $1.6 \pm 0.5$  mm for the knot construct,  $1.9 \pm 1.2$  mm for the outside-in fixation, and  $1.9 \pm 0.9$  mm for the inside-out fixation (significantly larger for all semitendinosus/gracilis tendon techniques,  $P < .05$ ).

**Conclusions:** Failure loads for the semitendinosus/gracilis tendons bone construct inserted outside in and the semitendinosus/gracilis tendons knot construct were within the confidence interval of the patellar tendon press-fit fixation. All semitendinosus/gracilis tendon graft techniques exhibited larger elongation during initial cyclical loading than the patellar tendon graft. There was no difference in stiffness between all techniques.

**Clinical Relevance:** Two of the 3 hamstring press-fit fixation techniques showed loads to failure similar to the patellar tendon fixation. Preconditioning of the constructs is critical. These results must be interpreted with care because of high standard deviations.

**Keywords:** press-fit fixation; anterior cruciate ligament (ACL); patella; hamstring

\*Address correspondence to Michael Jagodzinski, MD, Department of Trauma Surgery, Hanover Medical School, Carl-Neuberg-Str. 1, 30625 Hanover, Germany (e-mail: Michael@Jagodzinski.com).

No author or related institution has received financial benefit from research in this study.

The American Journal of Sports Medicine, Vol. 32, No. X  
DOI: 10.1177/0363546503262692

© 2004 American Orthopaedic Society for Sports Medicine

The hamstring tendon graft and the bone–patellar tendon–bone (BPTB) graft are the 2 most popular replacement grafts used for anterior cruciate ligament (ACL) reconstruction. Most surgeons today use hardware for fixation of the graft outside (EndoButton [Acufex Microsurgical Inc, Mansfield, Mass], suture postscrew, staple) or inside (non-resorbable and resorbable interference screws, cross pin) the drill holes.<sup>25</sup> This approach is compromised by artifacts

on postoperative magnetic resonance imaging and the necessity of implant removal in case of ACL revision surgery.<sup>16,21</sup> Hardware-free press-fit fixation is a potential solution to these drawbacks.<sup>25</sup> Good mechanical and functional outcome analyses after 5 and 10 years have been published following the BPTB press-fit technique.<sup>5,11</sup>

Hamstring tendon reconstruction of the ACL is a method that is used more and more frequently. The technique is associated with less donor site morbidity.<sup>15,29</sup> Five-year results appear to be equally as good as those reported for patellar tendon (PT) reconstructions.<sup>7,27</sup>

A number of different fixation techniques have been recommended for securing the hamstring graft in the bone tunnels. EndoButton fixation has been associated with migration of the graft in the bone tunnels.<sup>13</sup> Both titanium and bioresorbable screws have shown adequate fixation strength.<sup>31</sup> This close-to-the-joint fixation is critical to achieve graft healing with the formation of Sharpey-like fibers.<sup>30</sup> Despite proper fixation, bone tunnel widening has been observed following reconstruction of the ACL, especially when using tendon grafts.<sup>29</sup> Although there is disagreement about whether biological or mechanical factors predominantly cause this problem,<sup>4,29</sup> it is evident that bone plugs heal faster and show less tunnel enlargement after surgery.<sup>8,14</sup> Moreover, it has been observed that interference screw fixation significantly widens the bone tunnels.<sup>6</sup>

Therefore, press-fit fixation of the hamstring tendons would be a desirable technique, especially if the press-fit procedure would include a bone block that induces more rapid tendon-bone consolidation. Paessler et al<sup>24-26</sup> have described a technique that uses a bottleneck-shaped femoral tunnel and a knot in the hamstring grafts to achieve implant-free press-fit fixation of the tendons. The pullout strength of this technically challenging procedure is reported to be equivalent to interference screw fixation. As of yet, the technique has not been directly compared with press-fit PT fixation.

The purpose of this study was to develop a press-fit technique of the hamstring tendons that is free of artificial implants and uses a bone block. Fixation strength of this procedure was compared with the press-fit fixation described by Paessler et al<sup>24-26</sup> and with the well-established press-fit fixation of the PT-bone graft.

## MATERIALS AND METHODS

The knees of 30 human cadavers (60 knees) were used for explantation of the PT/hamstring-bone grafts for this study. The age of the knees was  $53.8 \pm 18.0$  years (range, 18-79 years). Explantation was performed a mean of  $2.1 \pm 1.2$  days (range, 0-3 days) postmortem. We used the tendons of 16 men and 14 women with a height of  $166.8 \pm 7.7$  cm (range, 154-183 cm) and a weight of  $70.8 \pm 19.1$  kg (range, 45-129 kg) for this investigation. There were no signs of ligament degeneration or tibial tuberosity disorders. The bone block of the PT was harvested from the tibial tuberosity and was 30 mm in length. It was trimmed to fit into a 9- to 11-mm drill hole. The PT was 9 mm wide and

detached at the insertion of the patella. An additional bone block was harvested from the tibia medial to the tibial tuberosity in a region where positioning of the tibial tunnel for ACL reconstruction has been recommended.<sup>5,22</sup> Parts of the block were cortical bone. The hamstring tendons had a mean diameter of  $4.5 \pm 0.6$  mm for the gracilis graft and  $7.6 \pm 1.6$  mm for the semitendinosus graft. For the femoral drill holes, we used the femurs of 30 German landrace pigs. The pigs were 1 year old, fully grown, and had weights between 100 and 120 lbs. The femoral neck was cut off and the shaft of the femur cemented into an aluminum holder using cold-curing methylmethacrylate resin (Technovit 4071, Heraeus Kulzer, GmbH, Wehrheim, Germany).

## Graft Preparation and Fixation

There were 15 constructs used in each group. Grafts and bone blocks were kept moist using saline spray during preparation and testing and refrigerated at  $-20^{\circ}\text{C}$  before and after preparation.

All bone tunnels were drilled with an external (lateral condyle) or internal (medial condyle) axial rotation of  $30^{\circ}$  and a femoral shaft flexion of  $60^{\circ}$  in the 11-o'clock or 1-o'clock position, simulating tunnels that are drilled with the knee flexed  $120^{\circ}$ .<sup>23</sup>

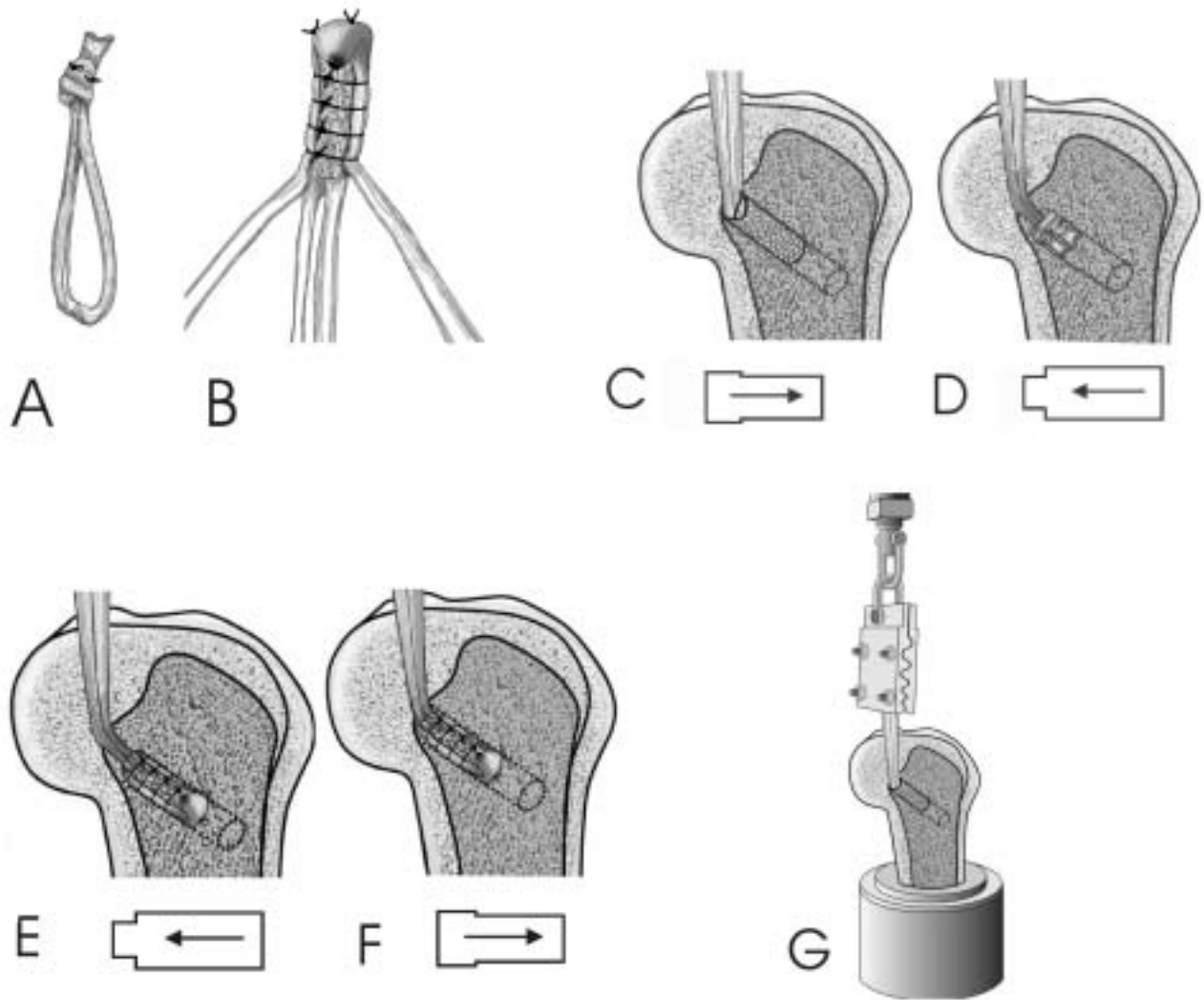
## Bone Block-PT Graft

The bone block of the PT grafts was trimmed to fit into a 9- to 11-mm drill hole and to create a cone. The femoral bone tunnel was drilled with a drill bit that was 1 mm smaller in diameter. The tunnel entrance was overdrilled to match the maximum size of the bone block. The bone plug was inserted from the inside out with the insertion of the PT angulated  $20^{\circ}$  with respect to the femoral shaft in the sagittal plane (Figure 1C).<sup>10</sup>

## Semitendinosus/Gracilis Tendon Knot Graft

For the hamstring technique described by Paessler et al,<sup>24,26</sup> a knot was tied in the semitendinosus and gracilis tendons, leaving a 10-mm tendon behind the knot (Figure 1A); knots were secured by 4 sutures (Mersilene No. 0, Ethicon Inc, Somerville, NJ). The knots were tightened until their diameter fit into a drill hole that exceeded the diameter of the tendon, with a maximum of 4 mm.

A bottleneck-shaped femoral tunnel was created using a drill bit with the diameter of both tendons. The cortical bone of the extra-articular entrance of the tunnel was overdrilled with a drill bit that matched the diameter of the 2 knots. An impactor (Wolf, Knittlingen, Germany) was used to condense the spongiosa. The semitendinosus tendon was introduced first from the outside to the inside and positioned anterior to the gracilis tendon. Both tendons were advanced until they came to rest at the bottleneck with their knots (Figure 1D). A pretension of 89 N (20 lb) was applied for 5 minutes. For this technique, an additional



**Figure 1.** Fixation techniques that were investigated. S/G grafts were prepared as loops with knots that were secured by sutures (SGK group; A). Alternatively, a cortical bone block from the anterior tibia was harvested and prepared with a hole matching the diameter of the semitendinosus tendon. The S/G tendons were wrapped around this block and secured with sutures (SGBO and SGBI groups; B). Press-fit PT bone was inserted in a tunnel entrance that matched the maximum diameter of the bone block. The width of the interior diameter was 1 mm less (PT group; C). The same procedure was used for the SGBI technique (F). For both SGK and SGBO groups, a bottleneck-shaped tunnel with an internal diameter of the S/G tendons and an external diameter matching the size of the knots or the bone block/tendons was established (D, E). The grafts have to be inserted from the outside (arrow) and come to rest against the cortical wall of the tunnel. For both techniques, an additional incision (approximately 1.5 cm) is necessary. All constructs were mounted on a platform of a biomechanical testing machine. The bone tunnel–force direction angle was 60° (G). S/G, semitendinosus/gracilis; PT, patellar tendon; SGK, semitendinosus/gracilis tendons knot construct; SGBO, semitendinosus/gracilis tendons bone construct inserted outside in; SGBI, semitendinosus/gracilis tendons bone construct inserted inside out.

incision is necessary to insert the knots into the external tunnel entrance.

#### Semitendinosus/Gracilis Tendon Bone Block Graft, Outside-In Fixation

A bone plug from the medial anterior tibia (30 × 9 mm) was modified using a custom-made drilling template. Four grooves

were created on the sides of the plug, and a transverse hole was drilled that matched the diameter of the semitendinosus tendon. The tendons were wrapped around the bone block and fixed with sutures (Mersilene No. 0) (Figure 1B). The thickness of the construct was evaluated using a drill hole sizer (Wolf). The bone tunnel was created as described for the hamstring knot technique (semitendinosus/gracilis tendon knot graft [SGK]). The constructs

were inserted from the outside to the inside using a pusher, until the bone block came to rest at the bottleneck (Figure 1E). This technique needs an additional incision to pull the construct through the fascia lata.

#### Semitendinosus/Gracilis Tendon Bone Block Graft, Inside-Out Fixation

This group consisted of a tendon bone block graft as described earlier. The femoral drill hole was created analogous to the PT preparation. The plug was inserted from the inside to the outside and advanced with a pusher (Figure 1F).

#### Mechanical Testing

The constructs were thawed at 4°C 24 hours before mechanical testing and kept moist using saline spray during the entire procedure.

A mechanical testing machine (Mini Bionix 858, MTS Systems Co, Eden Prairie, Minn) was used for the mechanical evaluation of the constructs. The potted femora were rigidly fixed in a base platform at 0°, setting the bone tunnel–force direction angle to 60°. This represents a simulation of human ACL reconstructs with a knee flexion angle of 30° (Lachman position<sup>28</sup>) (Figure 1G). There was a distance of 30 mm between the grafts and the clamp; the total length of all tendons was trimmed to 50 mm, leaving 20 mm for fixation in a custom-made, S-shaped clamp (Figure 1G).

The constructs were pretensioned with 60 N for 30 seconds before testing. Then, 20 cycles of mechanical loads between 60 and 260 N were applied at a repetition rate of 1 Hz. The increase in construct length was recorded. Length changes are reported between the minimum of the first (15th) and the maximum of the 5th (20th) cycle. After a decreasing ramp (60–10 N), a rest of 30 seconds was allowed. A failure test with a speed of 1 mm/s followed. The maximum failure load, failure mode, and stiffness of the constructs were analyzed.

The tests were recorded with a digital video camera. Constructs were photo-optically marked at intervals of 10 mm starting at the ridge of the femoral drill hole. One marker was located in the bone and 3 markers within the tendons, with a distance of 10 mm between each marker. Markers A and B were used to investigate length changes within the tendon and markers C and D to analyze changes between tendon and bone (Figure 2). A digital video of the experiments was recorded (frame rate: 25 pictures per second).

An image-analyzing software (ImageJ, National Institutes of Health, Bethesda, Md, [www.nih.gov](http://www.nih.gov)) was used to determine length changes. The measurements are reported in percent of the initial length. We analyzed the length change between tendon-bone and tendon-tendon markers. The procedure was executed from the smallest length observed during the 1st (15th) loading cycle to the maximum length attained during the 5th (20th) loading cycle. Moreover, lengthening between the beginning and end of failure testing was examined. These data were com-

pared with the length changes that were recorded by the mechanical testing machine.

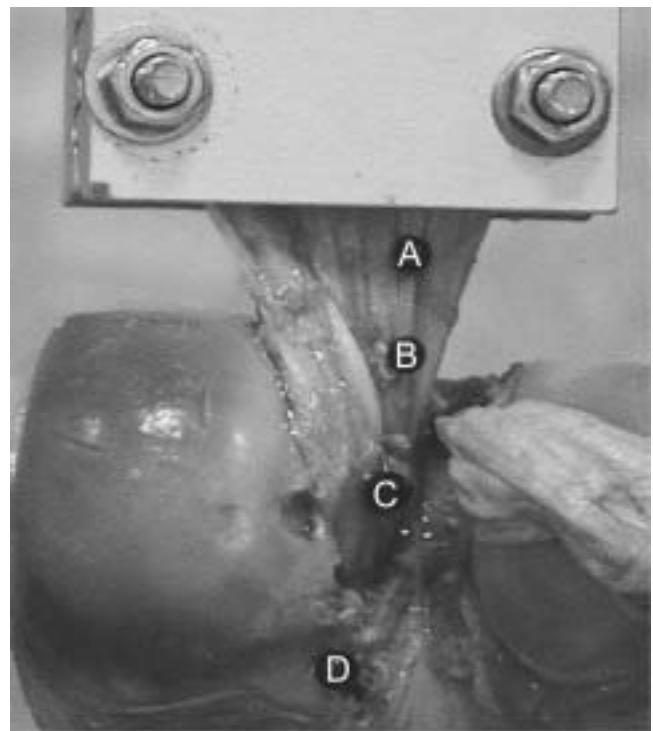
#### Statistical Analysis

All mean values are reported with standard deviations, such as maximum and minimum. The 4 groups were compared using a 1-way analysis of variance (ANOVA). Normality and equal variance tests were conducted. If the normality test failed, a Kruskal-Wallis ANOVA on ranks was executed with a post hoc Dunn test. If normality tests were passed, an equal variance test was conducted. Comparison of 2 groups was conducted using a nonparametric Wilcoxon test. Power tests were applied for non-significant findings. All operations were performed using SigmaStat 3.0 (SPSS Science Inc, Chicago, Ill). A *P* value of .05 was predetermined as statistically significant.

## RESULTS

#### Diameter of Drill Holes

The maximum diameter of the drill hole was  $10.5 \pm 0.7$  mm (range, 9–11 mm) in the PT group,  $10.4 \pm 0.5$  mm (range, 10–11 mm) in the SGK group,  $10.9 \pm 0.3$  mm (range, 10–11 mm) in the SGBO group, and  $10.7 \pm 0.6$  mm (range, 9.5–11.5 mm) in the semitendinosus/gracilis tendon bone block



**Figure 2.** Photo-optical markers were used to analyze length changes of the constructs. The distance between the 2 markers attached to the tendon (A, B) and between the tendon and the entrance of the bone tunnel (C, D) was evaluated.

TABLE 1  
Groups Investigated in this Study<sup>a</sup>

Parameter	PT	SGK	SGBO	SGBI	Significance
Number of specimens	15	15	15	15	
Diameter of tendons/bone blocks	9.5 ± 0.7	7.6 ± 0.5	7.8 ± 0.9	9.8 ± 0.6	PT – SGBI, NS; SGK – SGBO, NS
Maximum diameter of drill hole	10.5 ± 0.7	10.4 ± 0.5	10.9 ± 0.3	10.7 ± 0.6	NS
Age of donors	53.6 ± 17.7	55.5 ± 22.6	46.5 ± 23.2	53.7 ± 18.5	NS
Number of premature pullouts	3	1	0	9	

<sup>a</sup>PT, patellar tendon; SGK, semitendinosus/gracilis tendons knot construct; SGBO, semitendinosus/gracilis tendons bone construct, inserted outside in; SGBI, semitendinosus/gracilis tendons bone construct, inserted inside out; NS, not significant.

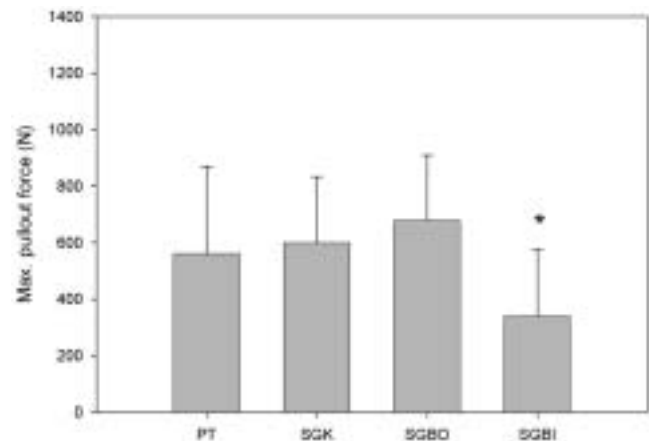
graft, inside-out fixation (SGBI) group. The ANOVA indicated that there was no statistical difference between these groups ( $P = .16$ ). The internal diameter of the inside-out techniques was  $9.5 \pm 0.7$  mm (range, 8-10 mm) in the PT group and  $9.8 \pm 0.6$  mm (range, 8.5-10.5 mm) in the SGBI group ( $P = .27$ ). The internal diameter of the outside-in techniques was  $7.6 \pm 0.5$  mm (range, 7-8 mm) in the SGK group and  $7.8 \pm 0.9$  mm (range, 7-10 mm) in the semitendinosus/gracilis tendon bone block graft, outside-in fixation (SGBO) group ( $P = .68$ ) (Table 1).

#### Load to Failure

Maximum pullout forces were  $561 \pm 309$  N (range, 160-1203 N) for the PT fixation,  $599 \pm 234$  N (range, 160-956 N) for the SGK group,  $678 \pm 231$  N (range, 238-1175 N) for the SGBO technique, and  $339 \pm 236$  N (range, 160-884 N) for SGBI constructs. The loads of this group were significantly lower than the ones of all other fixation techniques (ANOVA on ranks,  $P < .01$ ) (Figure 3). There was no significant difference observed in the maximum load to failure between the PT, SGK, and SGBO groups. The power of this test was 0.49. Power analyses indicated that a sample size of 350 would have been necessary with the obtained standard deviations and means to obtain a power greater than 0.80.

#### Failure Mode

There were 3 (20%) premature pullouts of a graft in the PT group, 1 (7%) in the SGK group, 0 in the SGBO group, and 9 (60%) in the SGBI group. The failure mode in the PT group was a bone plug pullout failure in 9 of 15 (66%), a rupture of the tendon at the insertion to the bone block in 4 (27%), and a fracture of the femoral condyle in 2 (13%) of the trials. The SGK fixations failed as a result of pullout of the knots in 10 (67%), rupture of the tendons in 2 (13%), and fracture of the condyle in 3 (20%) of the cases. The SBGO constructs were pulled out of the bone 7 (47%) times. There was a rupture of the tendon in 5 (33%) and a fracture of the condyle in 1 (7%) of the examinations. The bone block was fractured in 1 (7%) instance. The SGBI fixations were loaded until they failed because of pullout of the bone plug in all 15 (100%) cases.

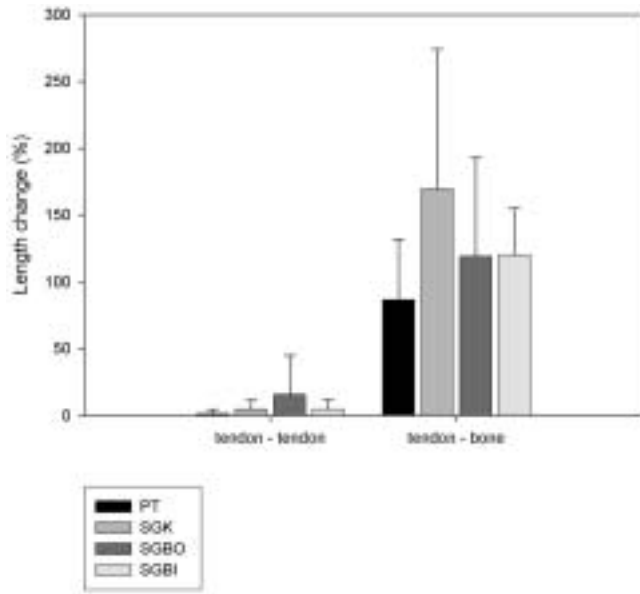


**Figure 3.** Maximum load to failure of the 4 techniques investigated in this study: SGBI fixation was significantly inferior to all other techniques. PT, patellar tendon; SGK, semitendinosus/gracilis tendons knot construct; SGBO, semitendinosus/gracilis tendons bone construct, inserted outside in; SGBI, semitendinosus/gracilis tendons bone construct, inserted inside out; \*, analysis of variance on ranks,  $P < .01$ .

These results are mirrored in the data obtained from video analysis of the load-to-failure experiments. Distance between photo-optical markers attached to bone and tendon at the moment of failure increased  $86.4\% \pm 45.5\%$  in the PT group,  $169.7\% \pm 104.5\%$  in the SGK group,  $119.1\% \pm 73.8\%$  in the SGBO group, and  $120\% \pm 35.0\%$  in the SGBI group (Kruskal-Wallis 1 way ANOVA on ranks:  $P = .22$ ). In contrast, the markers on the tendons were stretched  $1.3\% \pm 3.1\%$  in the PT group,  $4.6\% \pm 6.9\%$  in the SGK group,  $15.8\% \pm 29.2\%$  in the SGBO group, and  $4.7\% \pm 6.9\%$  in the SGBI group ( $P = .42$ ). The elongation during failure testing between tendon and bone was larger for all fixations than between markers placed on the tendons ( $P < .01$ ) (Figure 4).

#### Graft/Fixation Stiffness

The stiffness of the PT grafts was higher ( $134 \pm 32$  N/mm; range, 54-170 N/mm) than in the SGK ( $121 \pm 18$  N/mm; range, 101-149 N/mm), SGBO ( $120 \pm 24$  N/mm; range, 86-

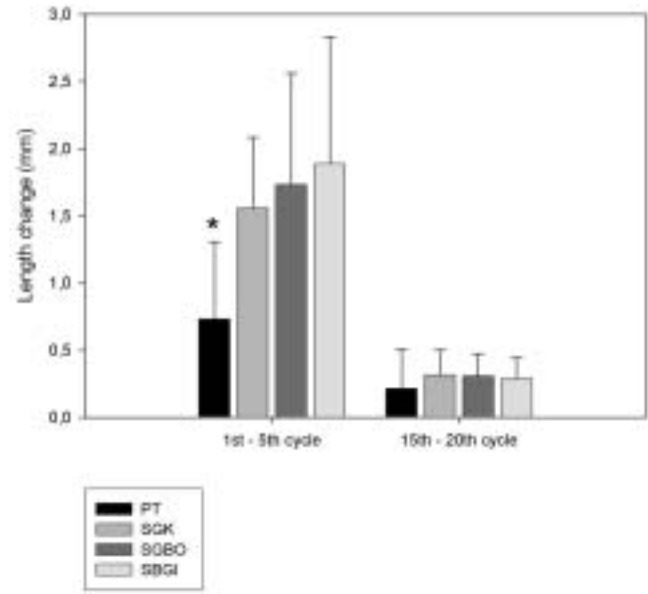


**Figure 4.** Stretching of optical markers (compare Figure 2) located on the tendon and bone of the constructs during failure testing. The amount of cyclical loading elongation was significantly larger between tendon and bone than between tendon-tendon markers (Wilcoxon test,  $P < .04$ ). PT, patellar tendon; SGK, semitendinosus/gracilis tendons knot construct; SGBO, semitendinosus/gracilis tendons bone construct, inserted outside in; SGBI, semitendinosus/gracilis tendons bone construct, inserted inside out.

149 N/mm), and SGBI groups ( $117 \pm 23$  N/mm; range, 92-150 N/mm). These differences were not significant ( $P = .43$ ;  $\alpha = .49$ ).

#### Length Increase During Cyclic Loading

The cyclical loading elongation determined by optical markers on the tendons between the 1st and 5th cycle was  $1.8\% \pm 2.4\%$  (range, 0%-8%) for the PT,  $3.9\% \pm 2.5\%$  (range, 0%-8%) for the SGK,  $2.7\% \pm 2.5\%$  (range, 0%-6%) for the SGBO, and  $2.0\% \pm 1.6\%$  (range, 0%-4%) for the SGBI constructs. In between tendon and bone, elongation was  $6.3\% \pm 1.7\%$  (range, 3%-9%) for the PT,  $8.6\% \pm 3.6\%$  (range, 2%-15%) for the SGK,  $9.9\% \pm 3.1\%$  (range, 6%-17%) for the SGBO, and  $12.8\% \pm 4.3\%$  (range, 8%-18%) for the SGBI constructs. Elongation of PT fixation in between tendon and bone during these initial cycles was significantly smaller than for all other observed techniques ( $P < .01$ ). Differences between all other groups were not significant. From the 15th to the 20th loading cycle, length changes were significantly shortened in between tendon-bone markers to  $4.1\% \pm 1.8\%$  (range, 2%-7%) for the PT,  $5.6\% \pm 1.8\%$  (range, 3%-103%) for the SGK,  $5.0\% \pm 1.4\%$  (range, 3%-7%) for the SGBO, and  $6.2\% \pm 2.8\%$  (range, 4%-11%) for the SGBI constructs. There was no significant difference between these groups ( $\alpha = .35$ ). In between tendon-tendon markers, elongation between the 15th and 20th loading



**Figure 5.** The cyclical loading elongation of the PT construct during the first 5 cycles of loading was significantly smaller than that of all other fixation techniques. From the 15th to 20th cycle, no significant differences between the groups were detected. PT, patellar tendon; SGK, semitendinosus/gracilis tendons knot construct; SGBO, semitendinosus/gracilis tendons bone construct, inserted outside in; SGBI, semitendinosus/gracilis tendons bone construct, inserted inside out; \*, analysis of variance on ranks,  $P < .03$ .

cycle was  $2.3\% \pm 1.6\%$  (range, 0%-5%) for the PT,  $2.3\% \pm 2.1\%$  (range, 0%-7%) for the SGK,  $1.1\% \pm 1.3\%$  (range, 0%-5%) for the SGBO, and  $1.0\% \pm 1.2\%$  (range, 0%-2%) for the SGBI constructs. There was no significant difference between these groups ( $\alpha = .36$ ). Measurements of elongation between the maximum of the 15th and 20th cycles resulted in elongation of the constructs smaller than 1% for all groups. There were no significant differences between the 4 fixation techniques ( $\alpha = .78$ ). The overall length change was  $10.3\% \pm 3.1\%$  (range, 5%-15%) for the PT,  $14.2\% \pm 5.1\%$  (range, 7%-22%) for the SGK,  $15.0\% \pm 3.6\%$  (range, 10%-22%) for the SGBO, and  $19.0\% \pm 6.2\%$  (range, 12%-27%) for the SGBI groups. Lengthening of the SGBI group was significantly larger than for the PT group ( $P = .01$ ).

The cyclical loading elongation determined by the mechanical testing between the 1st and 5th loading cycle was  $0.73 \pm 0.58$  mm (range, 0.09-2.08 mm) for the PT,  $1.56 \pm 0.53$  mm (range, 1.00-2.95 mm) for the SGK,  $1.73 \pm 0.83$  mm (range, 0.27-3.50 mm) for the SGBO, and  $1.89 \pm 0.94$  mm (range, 1.10-3.56 mm) for the SGBI constructs. Cyclical loading elongation of PT fixation was significantly smaller than all other observed techniques ( $P < .001$ ). From the 15th to the 20th loading cycle, length changes were significantly shortened to  $0.21 \pm 0.29$  mm (range, 0.04-1.06 mm) for the PT,  $0.31 \pm 0.19$  mm (range, 0.14-0.91 mm) for the SGK,  $0.30 \pm 0.17$  mm (range, 0.08-0.66 mm) for

the SGBO, and  $0.29 \pm 0.15$  mm (range, 0.18-0.59 mm) for the SGBI constructs. There was no significant difference between these groups ( $\alpha = .49$ ). The graph for these parameters is shown in Figure 5.

## DISCUSSION

Hamstring tendon autograft reconstruction of the ACL is commonly used. Follow-up has shown similar long-term results as for BPTB reconstructions.<sup>9</sup> Up to the present point, tendon–bone tunnel healing is inferior to the osseous integration of the BPTB grafts.<sup>8,14</sup> Mechanical studies of press-fit femoral fixation for hamstring grafts have not been published to date. The purpose of this study was to investigate the mechanical properties of press-fit femoral fixation of the hamstring tendons in comparison with BPTB fixation.

This study was conducted using human cadavers and young ovine femora. Care was taken to explant the tendons shortly after autopsy ( $2.1 \pm 1.2$  days). The mechanical properties of the tendons of this collective were different from young human tendons; however, most failures were observed as a result of fixation failure rather than from tendon rupture. Ovine femora are smaller in size than human femora. Creation of a 10-mm bone tunnel creates a greater stress riser than it does in human bone. This may explain the incidence of bone fracture (8%) that was seen in this study.

In contrast to other investigators, we used a single graft–bone tunnel angle for mechanical testing ( $60^\circ$ ). This represents a simulation of human ACL reconstructs at a knee flexion angle of  $30^\circ$  (Lachman position<sup>28</sup>). In vivo, tunnel angles vary according to surgical technique and knee flexion angle. Increasing knee extension may lead to more tension of the graft<sup>19</sup>; however, the graft–femoral bone tunnel angle increases at the same time, which has been demonstrated to increase pullout forces.<sup>28</sup> Thus, it can be assumed that the results for mechanical tests such as failure loads would have been exceeded if further tests were performed with increased graft–bone tunnel angles.

Other authors who have investigated press-fit fixations have used an angulation of the femoral tunnel and the graft.<sup>20</sup> Higher strain rates have been investigated by other authors (30 mm/s).<sup>2,18</sup> The strain rate used in this study (1 mm/s) has been used in most recent investigations.<sup>12,17,28,31</sup>

Various different numbers of cycles, recovery periods, and strain magnitudes have been used to determine the biomechanical properties of graft fixations.<sup>12,17,20,28,31</sup> In our view, several hundred cycles would have biased the measurements obtained for SGK group because tendon knots are affected more by dehydration than bone blocks. In vivo, dehydration is less likely to occur.

The maximum load-to-failure forces found in this study ( $561 \pm 309$  N for PT at  $60^\circ$ ) are very consistent with findings for PT-bone press-fit fixation that have been previously reported: Seil et al<sup>28</sup> found a maximum pullout force of  $455 \pm 131$  N for a graft-force angle of  $45^\circ$  and of  $708 \pm 211$  N for an angle of  $80^\circ$ . Higher pullout forces have been

reported for interference screw fixation,<sup>31</sup> even with a bone tunnel–force angle of  $0^\circ$ . Good long-term results have been achieved with the PT-bone press-fit technique followed by an aggressive rehabilitation program.<sup>5</sup> The SGK and SGBO techniques have promise for a similar approach.

The wide standard deviations, especially for the maximum load to failure, are a significant limitation on the interpretation of the results. This applies in particular to the SGBI group (70%). This variation is a result of the high percentage of premature graft pullouts that were observed in this group. Standard deviations for elongation were also high for measurements with little length change. These results must be interpreted with care.

Several investigators found a difference in fixation creep between PT and hamstring grafts.<sup>1</sup> These differences were also evident in this investigation. As for other semitendinosus and gracilis tendon procedures, cyclic preconditioning before final fixation is crucial for reproducible results. Fifteen cycles of loading between 60 and 260 N were found to be sufficient to achieve similar preconditioning in all groups of this study. The results for cyclical loading elongation obtained from video analyses were consistent with the lengthening recorded by the mechanical testing machine. This proves that the clamp and femoral fixation used in this study were sufficient and did not have an impact on the results.

Both SGK and SGBO techniques, like other techniques (cross pins, Bone Mulch Screw<sup>17</sup>) require an additional incision to insert the graft from the outside to the inside of the joint. The technique that requires a single incision (SGBI) was found to be not an adequate fixation. Interference screw fixation can be performed using a single incision. However, if resorbable screws are used, replacing the screw is either fibrous or fatty and fibrous but never bone.<sup>3</sup>

To our knowledge, this study is the only investigation that reports data for a press-fit hamstring fixation with a bone block. Other authors have analyzed interference screw fixation of hamstring grafts wrapped around a bone block.<sup>31</sup> They have found this technique to be of equal quality in terms of mechanical properties compared with a pure tendon fixation. We conclude the same for the SGBO group of this investigation. However, the potential advantages of this approach are obvious. Because bone tunnel widening and insufficient tendon incorporation have been associated with hamstring but not with BPTB grafts, a bone block that is rigidly included in the fixation may help to avoid these adverse effects.

Further clinical studies are necessary to follow up on the healing process of a femoral press-fit fixation. These should include careful analysis of bone tunnel enlargement.

## ACKNOWLEDGMENT

We express special thanks to Mr Krentscher from the Department of Forensic Medicine for supporting this investigation. We also thank L Hoy from the Institute for Biometrics, Hanover Medical School, for the assistance in the statistical analysis of data.

## REFERENCES

- Adam F, Pape D, Steimer O. Biomechanical properties of interference screw implantation in replacement of the anterior cruciate ligament with patellar and hamstring transplants: an experimental study using roentgen stereometry analysis (RSA). *Orthopade*. 2001;30:649-657.
- Aune AK, Ekland A, Cawley PW. Interference screw fixation of hamstring vs patellar tendon grafts for anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 1998;6:99-102.
- Bach FD, Carlier RY, Elis JB. Anterior cruciate ligament reconstruction with bioabsorbable polyglycolic acid interference screws: MR imaging follow-up. *Radiology*. 2002;225:541-550.
- Berg EE, Pollard ME, Kang Q. Interarticular bone tunnel healing. *Arthroscopy*. 2001;17:189-195.
- Boszotta H. Arthroscopic anterior cruciate ligament reconstruction using a patellar tendon graft in press-fit technique: surgical technique and follow-up. *Arthroscopy*. 1997;13:332-339.
- Clatworthy MG, Annear P, Bulow JU. Tunnel widening in anterior cruciate ligament reconstruction: a prospective evaluation of hamstring and patella tendon grafts. *Knee Surg Sports Traumatol Arthrosc*. 1999;7:138-145.
- Cooley VJ, Deffner KT, Rosenberg TD. Quadrupled semitendinosus anterior cruciate ligament reconstruction: 5-year results in patients without meniscus loss. *Arthroscopy*. 2001;17:795-800.
- Fink C, Zapp M, Benedetto KP. Tibial tunnel enlargement following anterior cruciate ligament reconstruction with patellar tendon autograft. *Arthroscopy*. 2001;17:138-143.
- Freedman KB, D'Amato MJ, Nedeff DD. Arthroscopic anterior cruciate ligament reconstruction: a metaanalysis comparing patellar tendon and hamstring tendon autografts. *Am J Sports Med*. 2003;31:2-11.
- Hefzy MS, Grood ES, Noyes FR. Factors affecting the region of most isometric femoral attachments, part II: the anterior cruciate ligament. *Am J Sports Med*. 1989;17:208-216.
- Hertel P, Widjaja G, Cierpinski T. 10-year results of a bone patellar tendon bone press fit technique. Presented at: 63rd Annual Meeting of the Deutsche Gesellschaft fuer Unfallchirurgie (German Trauma Society), 1999, Berlin.
- Hoffmann RF, Peine R, Bail HJ. Initial fixation strength of modified patellar tendon grafts for anatomic fixation in anterior cruciate ligament reconstruction. *Arthroscopy*. 1999;15:392-399.
- Hoher J, Moller HD, Fu FH. Bone tunnel enlargement after anterior cruciate ligament reconstruction: fact or fiction? *Knee Surg Sports Traumatol Arthrosc*. 1998;6:231-240.
- Jansson KA, Harilainen A, Sandelin J. Bone tunnel enlargement after anterior cruciate ligament reconstruction with the hamstring autograft and endobutton fixation technique: a clinical, radiographic and magnetic resonance imaging study with 2 years follow-up. *Knee Surg Sports Traumatol Arthrosc*. 1999;7:290-295.
- Kartus J, Movin T, Karlsson J. Donor-site morbidity and anterior knee problems after anterior cruciate ligament reconstruction using autografts. *Arthroscopy*. 2001;17:971-980.
- Kohn D, Busche T, Carls J. Drill hole position in endoscopic anterior cruciate ligament reconstruction: results of an advanced arthroscopy course. *Knee Surg Sports Traumatol Arthrosc*. 1998;6(suppl 1):S13-S15.
- Kousa P, Jarvinen TL, Vihavainen M. The fixation strength of six hamstring tendon graft fixation devices in anterior cruciate ligament reconstruction, part I: femoral site. *Am J Sports Med*. 2003;31:174-181.
- Kurosaka M, Yoshiya S, Andrish JT. A biomechanical comparison of different surgical techniques of graft fixation in anterior cruciate ligament reconstruction. *Am J Sports Med*. 1987;15:225-229.
- Markolf KL, Gorek JF, Kabo JM. Direct measurement of resultant forces in the anterior cruciate ligament: an in vitro study performed with a new experimental technique. *J Bone Joint Surg Am*. 1990;72:557-567.
- Musahl V, Abramowitch SD, Gabriel MT. Tensile properties of an anterior cruciate ligament graft after bone-patellar tendon-bone press-fit fixation. *Knee Surg Sports Traumatol Arthrosc*. 2003;11:68-74.
- Noyes FR, Barber-Westin SD. Revision anterior cruciate surgery with use of bone-patellar tendon-bone autogenous grafts. *J Bone Joint Surg Am*. 2001;83:1131-1143.
- Odensten M, Gillquist J. A modified technique for anterior cruciate ligament (ACL) surgery using a new drill guide for isometric positioning of the ACL. *Clin Orthop*. 1986;213:154-158.
- Paessler HH. Anatomical reconstruction of the anterior cruciate ligament with a patellar tendon autograft using a miniarthrotomy technique. In: Szabo Z, Kerstein MD, Lewis EL, eds. *Surgical Technology International III*. San Francisco, Calif: Universal Medical Press; 1996:563-570.
- Paessler HH. *Neue Techniken in der Kniechirurgie*. Darmstadt, Germany: Steinkopff Verlag; 2002.
- Paessler HH, Mastrokalos DS. Anterior cruciate ligament reconstruction using semitendinosus and gracilis tendons, bone patellar tendon, or quadriceps tendon-graft with press-fit fixation without hardware: a new and innovative procedure. *Orthop Clin North Am*. 2003;34:49-64.
- Paessler HH, Thermann H. *The Anterior Cruciate Ligament: State of the Art 2000*. Heidelberg, Germany: Barth Verlag; 2002.
- Rosenberg TD, Deffner KT. ACL reconstruction: semitendinosus tendon is the graft of choice. *Orthopedics*. 1997;20:396, 398.
- Seil R, Rupp S, Krauss PW. Comparison of initial fixation strength between biodegradable and metallic interference screws and a press-fit fixation technique in a porcine model. *Am J Sports Med*. 1998;26:815-819.
- Webster KE, Feller JA, Hameister KA. Bone tunnel enlargement following anterior cruciate ligament reconstruction: a randomised comparison of hamstring and patellar tendon grafts with 2-year follow-up. *Knee Surg Sports Traumatol Arthrosc*. 2001;9:86-91.
- Weiler A, Hoffmann RF, Bail HJ. Tendon healing in a bone tunnel, part II: histologic analysis after biodegradable interference fit fixation in a model of anterior cruciate ligament reconstruction in sheep. *Arthroscopy*. 2002;18:124-135.
- Weiler A, Hoffmann RF, Stahelin AC. Hamstring tendon fixation using interference screws: a biomechanical study in calf tibial bone. *Arthroscopy*. 1998;14:29-37.