Biomechanical Comparison of Hamstring and Patellar Tendon Graft Anterior Cruciate Ligament Reconstruction Techniques: The Impact of Fixation Level and Fixation Method Under Cyclic Loading

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Purpose: To mechanically test different reconstruction techniques of the anterior cruciate ligament (ACL) under incremental cyclic loading and to evaluate the impact of the level and method of graft fixation on tensile properties of each technique. **Type of Study:** In vitro biomechanical study. **Methods:** Four hamstring and 1 patellar tendon reconstruction techniques were performed on 40 young to middle-aged human cadaveric knees (average age, 39 years). An anterior drawer with increasing loads of 20 N increments was applied at 30° of knee flexion. Anatomic, direct interference screw fixation was tested in 2 hamstring and in the patellar tendon groups. Nonanatomic (extracortical) graft anchorage was tested in the remaining 2 hamstring groups with indirect graft fixations on both sides and the combination of indirect tibial and direct femoral fixation. Structural properties were determined throughout the cyclic loading test. **Results:** The more anatomic reconstruction techniques provided significantly higher structural properties and smaller loss of fixation compared with nonanatomic, extracortical fixation, with indirect repair on both fixation sites resulting in the lowest structural properties. The tibial fixation site was the weakest link in all of the anatomic reconstructions. Patellar tendon fixation with attached bone blocks in both bone tunnels significantly improved construct stiffness and decreased graft slippage. **Conclusions:** The results of this study suggest that anatomic fixation should be preferred for anchorage of hamstring tendons and linkage materials should be avoided. Direct soft-tissue fixation with interference screws still allows considerable graft slippage, which can be limited by using a bone block or application of a backup or hybrid fixation, especially on the tibial fixation site. **Key Words:** Anterior cruciate ligament—Graft fixation techniques—Hamstring tendons—Patellar tendon—Cyclic incremental loading—Tensile properties.

The rupture of the anterior cruciate ligament (ACL) has the highest incidence among ligamentous injuries[1] in the human knee. With high activity levels extending into older age groups, the number of isolated and combined ACL ruptures has steadily increased. A rupture of the ACL compromises stability of the knee joint and requires surgical intervention in the majority of cases. With recent advances in the understanding of the biomechanical and biologic properties of the intact ACL, a large number of surgical reconstruction techniques with various graft choices have evolved. The patellar and hamstring tendons have become the most frequently used replacement grafts for the ruptured ACL. While there is little controversy on the fixation technique for patellar tendon grafts, no consensus has been found on the fixation of hamstring tendon grafts. Hamstring tendons have become increasingly popular as the graft of

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choice because their harvest causes less graft-site morbidity[2-4] and functional deficit.[3,5-7] They provide higher structural properties when folded to a tripled or quadrupled construct[8,9] and replicate the nonisometric behavior of the intact ACL (with its anteromedial and posterolateral bundles) more closely than a single-stranded graft.[10,11] However, these tendon grafts usually do not have attached bone blocks, requiring tendon-to-bone healing, which may necessitate an extended time for graft incorporation.[12-15] Therefore, sufficient fixation of these grafts is crucial especially during the early postoperative time, when osseous graft incorporation has not been completed.

Various hamstring reconstruction techniques not only differ by their fixation devices but have considerable differences with respect to fixation level, fixation method (direct *v* indirect), and graft configuration. It is important to evaluate the impact of these factors on the biomechanical properties of common reconstruction techniques under simulation of postoperative loading conditions. Existing data on the biomechanical properties of ACL reconstruction techniques have been predominantly derived from single load-to-failure tests.[16-22] However, during the early postoperative time, the ACL replacement graft will more likely experience cyclic submaximal than single maximum loading.

Therefore, the objective of this study was to evaluate the biomechanical properties of 4 different ACL reconstruction techniques using hamstring tendon grafts that are currently used in clinical practice and compare them with a standard patellar tendon reconstruction technique under incremental cyclic loading conditions. We hypothesized that a more anatomic fixation would be favorable compared with a fixation far away from the joint line, and that a direct tendon fixation would be favorable compared with a technique using linkage materials (e.g., sutures, tape) for indirect graft fixation.

METHODS

In this study, 40 human cadaveric knees were used that were an average age of 39 years (range, 18 to 56 years). Human semitendinosus, gracilis, and patellar tendons were harvested and immediately stored at −20°C. All knees and ligaments were thawed at room temperature 24 hours before use and kept moist with saline irrigation during preparation and mechanical testing. Knees with severe degenerative changes or trauma were excluded from the experiments. All soft-tissue structures except the ACL were dissected leaving a femur-ACL-tibia complex.

The ACL was left intact in 8 specimens to obtain tensile properties of the intact ACL. Four reconstruction techniques were performed with hamstring tendon grafts. Each reconstruction group consisted of 8 specimens. In 2 techniques, graft fixation was achieved in femoral and tibial bone tunnels close to the joint line (anatomic), whereas in the other 2 techniques graft fixation was accomplished away from the joint line on the femoral and tibial cortex (extracortical). For comparison, a standard reconstruction technique with a patellar tendon graft was conducted on another 8 specimens.

Hamstring Anatomic Fixation Techniques

Hamstring Tendon Fixation With Biodegradable Interference Screws (HST_{Bio}): In the first technique, a semitendinosus tendon was harvested with an attached bone block (10 mm wide, 15 mm long) from the pes anserine with an overall length of 22 to 24 cm according to the technique by Stähelin and Weiler.[23] The tendon was folded into a tripled construct with the bone block resting in the tendinous loop (Fig 1A) and 2.5 cm on each end of the tendon strands were sewn to each other with 3-0 resorbable sutures. Femoral and tibial bone tunnels were created using an inside-out technique by serial dilation. The diameter of the femoral tunnel matched the cross-section of the graft (7 to 9 mm), whereas the diameter of the tibial tunnel was kept constant at 10 mm to facilitate passage of the attached bone block. Both bone tunnels had a depth of 2.5 cm. The graft was oriented in such a fashion that the tendinous loop with the bone block was placed into the tibial tunnel. The graft was then first secured in the tibial tunnel with a biodegradable poly-(D,L-lactide) interference screw (8 × 23 mm Sysorb; Sulzer Orthopedics, Baar, Switzerland) with the knee positioned in 90° of flexion. The opposing end was pulled into the femoral tunnel, the knee was brought into 30° of flexion and a pretension of 60 N was applied to the tendon for 2 minutes. Then the knee was returned to a flexion angle of approximately 120° to 130° and final femoral graft fixation was achieved with another biodegradable interference screw.

Hamstring Tendon Fixation With Round-Headed Cannulated Interference (RCI) Screws (HST_{RCI}): The second anatomic reconstruction technique (HST_{RCI}) consisted of a 9-cm quadrupled graft (doubled semitendinosus and gracilis tendon) (Fig 1A) with 3 cm of free tendon ends on both sides of the graft sutured together using 3-0 resorbable sutures,

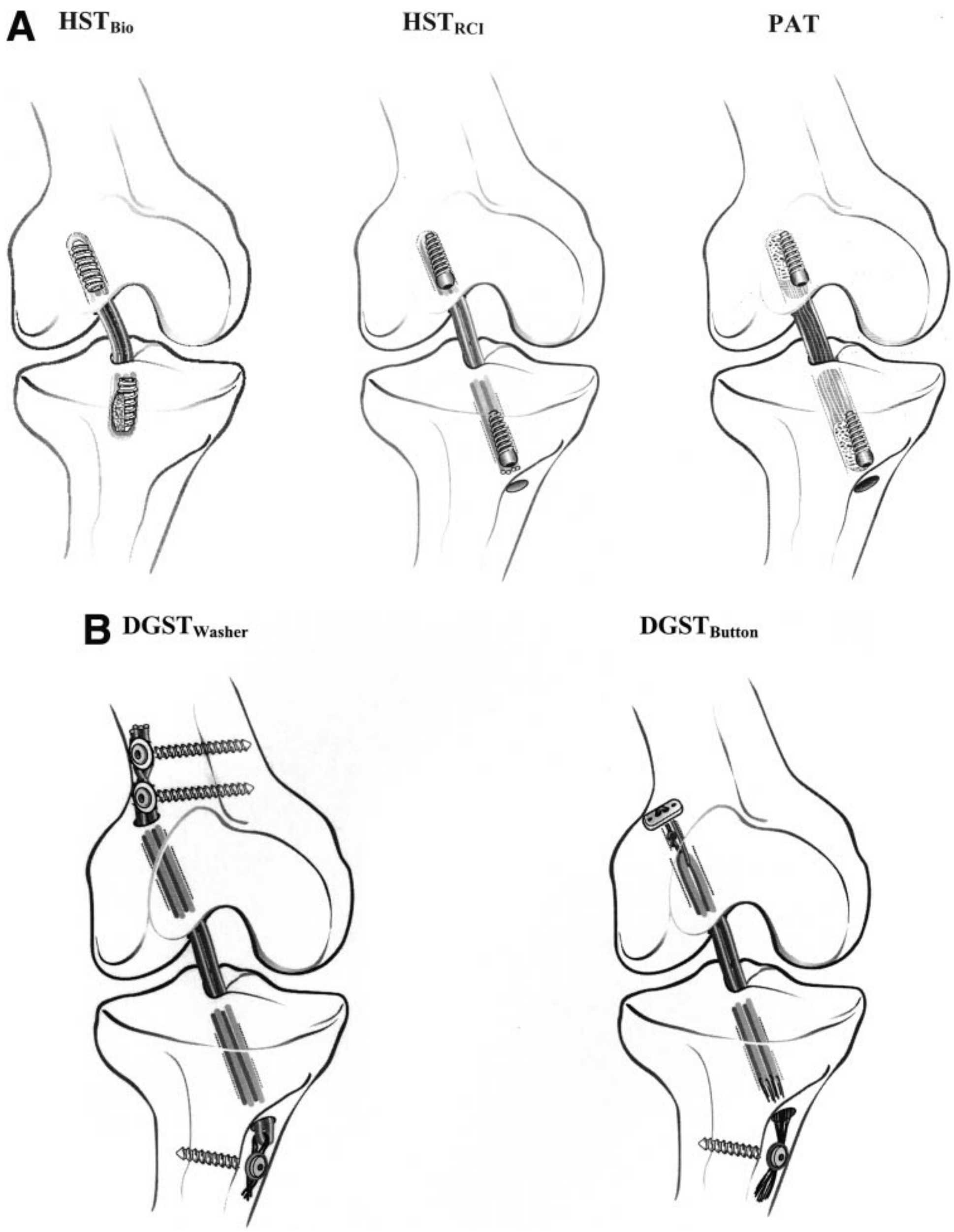

FIGURE 1. (A) Drawings of the anatomic reconstruction techniques. HST$_{Bio}$, tripled semitendinosus with distally attached bone-block and biodegradable interference fit fixation. HST$_{RCI}$, doubled semitendinosus and gracilis tendons with RCI titanium interference fit fixation. PAT, middle-third patellar tendon with attached bone blocks and metal interference fit fixation. (B) The extracortical reconstruction techniques. HST$_{Washer}$, doubled semitendinosus and gracilis tendon with soft-tissue washer and suture/post fixation. HST$_{Button}$, doubled semitendinosus and gracilis tendon with tape/button and suture/post fixation.

leaving an intra-articular distance of 2.5 cm. According to the technique initially described by Pinczewski and published by Corry et al.,[6] a tibial tunnel was drilled in an outside-in direction and a 3-cm deep femoral tunnel was created transtibially. Both tunnel diameters matched the previously measured cross-section of the graft (8 to 9 mm). The quadrupled graft was pulled transtibially into the femoral bone tunnel and directly fixed with a round-headed, soft-threaded titanium interference screw (RCI, Smith & Nephew Donjoy, Andover, MA; 7 $\times$ 25 mm with an 8 mm head) close to the joint line. The graft was then pretensioned with 60 N for 2 minutes at 30° of flexion. For final graft fixation at the same flexion angle, a second soft-threaded titanium screw was inserted into the tibial tunnel in an outside-in fashion until the screw head could be located just proximal to the tunnel exit (Fig 1A).

Hamstring Extracortical Fixation Techniques

Hamstring Tendon Fixation With Titanium Button (HST_{Button}): The first technique was originally described by Rosenberg in 1994 and has been described by Barrett et al.[24] Semitendinosus and gracilis tendons were folded once, providing a 10-cm long quadrupled construct. For indirect femoral fixation, mersilene tape (femoral tunnel length minus 2.5 cm) was placed through the tendon loops and fixed with knots to a titanium button (EndoButton; Smith & Nephew Endoscopy, Andover, MA). Each of the 4 free tendon ends was augmented with a No. 5 Ethibond suture (Ethicon, Somerville, NJ) using a Krackow stitch. Femoral and tibial bone tunnels were drilled to match the previously determined graft diameter. The titanium button and the mersilene tape with the attached tendon graft were pulled through the femoral tunnel and provided fixation by locking the titanium button on the femoral cortex. Indirect fixation on the tibial cortex was accomplished by tightening the Ethibond sutures of the free tendon ends around a bicortical screw (4.5 mm; Synthes, Paoli, PA) and compacting them under a metal washer (6.5 mm; Synthes) (suture/post fixation) (Fig 1B).

Hamstring Tendon Fixation With Soft-Tissue Washer (HST_{Washer}): In the second technique, the free ends of a doubled semitendinosus and gracilis tendon were pulled though a femoral bone tunnel and directly fixed to the femoral cortex in a figure 8 with 2 soft-tissue washers (6.0 mm, Synthes).[25] Two bicortical screws (4.5 mm Synthes) fixed these soft-tissue washers onto the tendons. On the tibial side, indirect graft fixation was achieved with 4 No. 5 Ethibond sutures that were pulled through the tendon loops of the graft and were manually tightened around a bicortical screw under a metal post-washer (6.5 mm Synthes) (Fig 1B).[16] The tunnel diameter matched the cross-sectional area of the graft (7 to 9 mm). Both graft constructs (HST_{Button} and HST_{Washer}) were pretensioned at 30° of flexion with 60 N for 2 minutes before final fixation at the same flexion angle.

Patellar Tendon Reconstruction Technique (PAT)

A 10-mm wide patellar tendon with two attached semicircular bone blocks (10 mm diameter) was placed transtibially into femoral and tibial bone tunnels of matching diameter in a standard fashion. Graft fixation was achieved in each bone tunnel using standard metal interference screws (8 × 25 mm; Arthrex, Naples, FL) (Fig 1A). The graft was pretensioned with 60 N for 2 minutes prior to final fixation. Pretensioning and final fixation of the graft were performed at a flexion angle of 30°.

Test Setup

A materials testing system (model 1455; Zwick, Ulm, Germany) was used for the biomechanical experiments. Each knee was placed onto customized stainless steel clamps at a flexion angle of 30°. The femoral part of the clamp was rigidly fixed to the testing apparatus, while the tibia was mounted to a displaceable worktable that allowed for the simulation of an anterior translation of the tibia with all other motions constrained (Fig 2).

The testing protocol is shown in Fig 3. First, an anterior preload of 5 N was applied. The tibia was then displaced anteriorly at a rate of 120 mm/min until a load of 100 N was attained and then returned to the

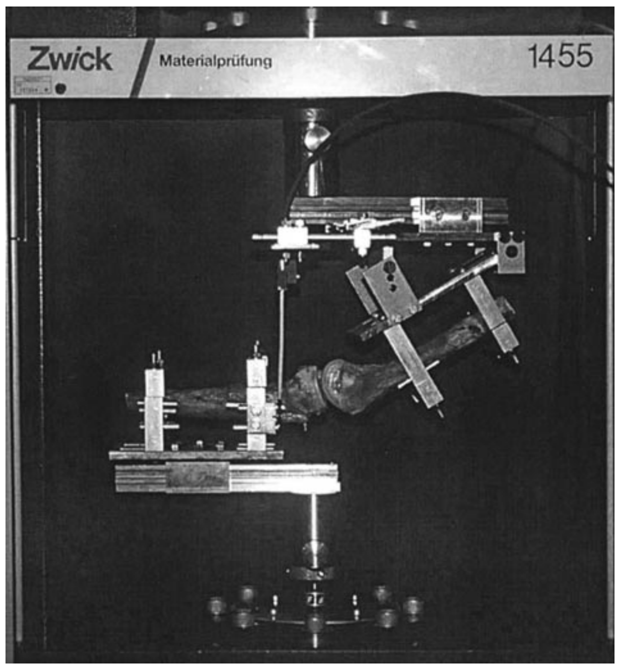

FIGURE 2. Test setup with knee joint at 30° of flexion.

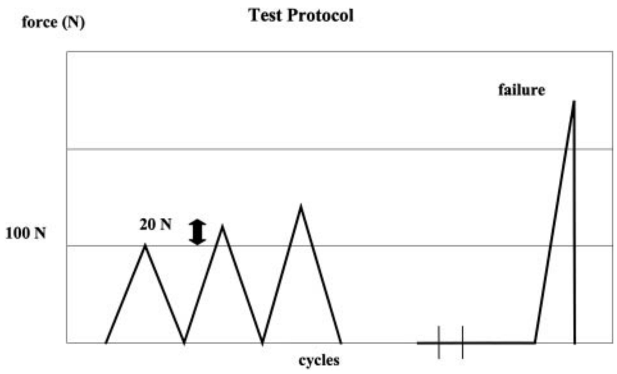

FIGURE 3. Schematic of testing protocol. Cyclic loading with 20 N increments until failure.

starting position, determined at the initial preload of 5 N. This was followed by consecutive loading cycles with an incremental load increase of 20 N per cycle until failure with the tibia always returning to its initially determined starting position. The load-elongation data were digitally recorded from the material testing machine and transferred to in-house software on a personal computer. A customized Visual Basic 5.0 program was developed for final data analysis.

The following parameters were measured during the cyclic loading at the cycles up to 100 N, 200 N, 300 N, and 400 N: stiffness, energy loss (area of the hysteresis curve during loading and unloading), and displacement (Fig 4). Additionally, the parameter "laxity increase" was introduced and defined as the change in displacement of the graft construct from its initial starting position to the position where a load pickup was recorded during the subsequent loading cycles (Fig 4) at 200 N, 300 N, and 400 N. The laxity increase quantified the loss of graft fixation in terms of graft slippage, plastic deformation of the linkage materials, and knot tightening, without including the elongation of the tendon graft itself. Maximum load, stiffness, displacement, and failure mode were also recorded.

Statistical analysis was conducted with the SPSS Version 7.5 software package (SPSS, Chicago, IL). In all groups, nonparametric distribution of the data was found (Kolmogorow-Smirnow test). Parameters of interest were statistically compared between groups using the Mann-Whitney *U* Wilcoxon rank-sum test. The level of significance was set at $P < .05$.

RESULTS

The data for 1 specimen in the HST_{Bio} group were lost due to technical difficulties. Therefore, the number of specimens in this group was reduced to 7 while all the remaining groups consisted of 8 specimens. There was no statistical difference in age distribution between the groups.

The number of specimens in the HST_{Bio} group decreased during the cyclic loading to 4 and 3 at the loading cycles up to 300 N and 400 N, respectively, because of prior failure. The number of specimens in the HST_{RCI} group was reduced to 4 and 1 at 200 N and 300 N, respectively, also due to prior failure. All specimens in this group had failed before the loading cycle up to 400 N. Therefore, no statistical analysis was performed on the HST_{RCI} group for the loading cycles up to 300 N and 400 N. No failure was seen in either of the extracortical fixation techniques before the reported loading cycles. The PAT group was reduced to 5 and 3 for the loading cycles up to 300 N and 400 N, respectively, because of prior failure (Table 1). The cyclic loading of the ACL and its reconstruction techniques showed the following results.

Stiffness

The stiffness of the intact ACL (Table 2) was significantly higher ($P < .05$) than in all tested reconstruction techniques at all reported loading cycles. When comparing the hamstring tendon reconstruction techniques, a significantly higher stiffness was found for anatomic graft fixation (HST_{Bio}) compared with either extracortical fixation techniques HST_{Button} and HST_{Washer} at the cycles up to 200 N, 300 N, and 400 N ($P < .05$) (Table 2). The second anatomic fixation technique HST_{RCI} showed no significant differences in comparison with HST_{Button} and HST_{Washer} at any reported loading cycle. No significant differences were found between both anatomic (HST_{Bio} *v* HST_{RCI}) and extracortical (HST_{Button} *v* HST_{Washer})

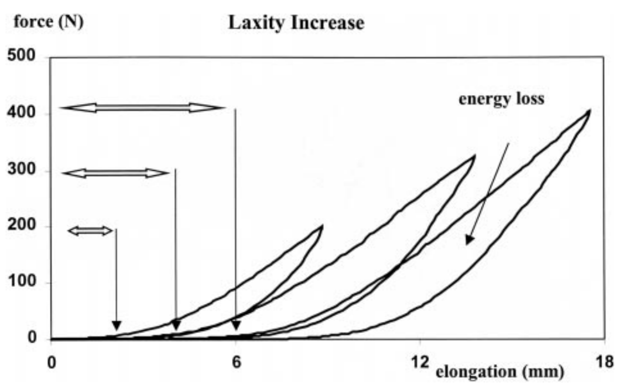

FIGURE 4. Schematic of laxity increase during cyclic loading.

TABLE 1. *Change in Specimen Number During Cyclic Loading*

Cycle	HST_{Bio}	HST_{RCI}	HST_{Button}	HST_{Washer}	PAT	ACL
100 N	7	8	8	8	8	8
200 N	7	4	8	8	7	8
300 N	4	1	8	8	5	8
400 N	3	0	8	8	3	8

reconstruction techniques at their respective loading cycles.

When comparing the hamstring tendon fixation techniques with the patellar tendon reconstruction (PAT), a significantly higher ($P < .05$) stiffness was found for PAT at all loading cycles compared with either anatomic (HST_{Bio}, HST_{RCI}) and extracortical fixation techniques (HST_{Button} and HST_{Washer}) with the exception for the cycle up to 400 N for comparison with HST_{Bio}.

Energy Loss

The energy loss during the cyclic loading of the intact ACL (Table 2) was significantly less than that in all tested reconstruction techniques at all loading cycles ($P < .05$). When comparing the hamstring tendon reconstruction techniques, a significantly smaller energy loss was found in the anatomic reconstruction technique, HST_{Bio}, compared with either extracortical fixation techniques (HST_{Button}, HST_{Washer}) at all loading cycles ($P < .05$) with the exception of the loading cycle up to 100 N for the HST_{Washer} group. No significant differences were found between the second anatomic reconstruction technique HST_{RCI} and both extracortical fixation techniques HST_{Button} and HST_{Washer}. When comparing both anatomic and extracortical reconstruction techniques, the HST_{Bio} group lost significantly less energy than the HST_{RCI} group ($P < .05$), whereas there were no significant differences among the extracortical fixation techniques. The energy loss in the PAT group was significantly lower than that in either anatomic (HST_{Bio}, HST_{RCI}) and extracortical hamstring tendon graft fixation techniques (HST_{Button} and HST_{Washer}) at all reported loading cycles ($P < .05$) with the exception at the loading cycle up to 400 N in the HST_{Bio} group.

Displacement

The displacements of the intact ACL (Table 3) were significantly lower than in all reconstruction techniques at all loading cycles ($P < .05$). Anatomic graft fixation with biodegradable interference screws (HST_{Bio}) significantly decreased anterior displacement compared with all indirect extracortical graft fixation (HST_{Button}) at the loading cycles up to 200 N and 400 N ($P < .05$). No significant differences were

TABLE 2. *Tensile Properties During Incremental Cyclic Loading for Each Reconstruction Technique*

Cycle	HST_{Bio}	HST_{RCI}	HST_{Button}	HST_{Washer}	PAT	ACL
Stiffness (N/mm): mean (SD)						
100 N	19.1 (7.0)^{e}	20.9 (6.6)^{e}	15.1 (4.0)^{e}	20.3 (6.7)^{e}	29.2 (6.7)^{a,b,c,d}	43.8 (14.6)^{f}
200 N	36.0 (5.2)^{c,d,e}	28.5 (13.7)^{e}	23.0 (2.9)^{a,e}	26.9 (7.5)^{a,e}	50.6 (6.5)^{a,b,c,d}	76.3 (17.3)^{f}
300 N	48.0 (7.0)^{c,d,e}	—	30.3 (4.1)^{a,e}	31.7 (6.7)^{a,e}	61.6 (4.9)^{a,c,d}	92.6 (21.3)^{f}
400 N	58.9 (5.1)^{c,d}	—	38.9 (5.5)^{a,e}	36.8 (6.1)^{a,e}	72.7 (3.4)^{c,d}	105.4 (19.8)^{f}
Energy loss (mJ): mean (SD)						
100 N	124 (55)^{b,c,e}	268 (140)^{a,e}	207 (89)^{a,e}	159 (60)^{e}	61 (45)^{a,b,c,d}	20 (12)^{f}
200 N	279 (99)^{b,c,d,e}	910 (660)^{a,e}	581 (136)^{a,e}	484 (164)^{a,e}	83 (39)^{a,b,c,d}	34 (10)^{f}
300 N	480 (193)^{c,d,e}	—	950 (184)^{a,e}	832 (177)^{a,e}	197 (99)^{a,c,d}	27 (10)^{f}
400 N	723 (42)^{c,d}	—	1,318 (283)^{a,e}	1,234 (335)^{a,e}	245 (86)^{c,d}	44 (14)^{f}

NOTE. a-f represent significantly different corresponding data pairs.
a: Significantly different from HST_{Bio}.
b: Significantly different from HST_{RCI}.
c: Significantly different from HST_{Button}.
d: Significantly different from HST_{Washer}.
e: Significantly different from PAT.
f: Significantly higher than all reconstruction techniques.

TABLE 3. *Tensile Properties During Incremental Cyclic Loading for Each Reconstruction Technique*

Cycle	HST_{Bio}	HST_{RCI}	HST_{Button}	HST_{Washer}	PAT	ACL
Displacement (mm): mean (SD)						
100 N	8.9 (1.8)	6.9 (2.3)^{c}	10.7 (3.1)^{b,e}	8.5 (3.6)	7.3 (2.1)^{c}	3.8 (0.7)^{f}
200 N	12.4 (2.1)^{c,e}	15.2 (4.0)^{e}	18.2 (5.5)^{a,e}	13.8 (5.9)^{e}	9.4 (1.6)^{a,b,c,d}	4.5 (1.3)^{f}
300 N	18.8 (6.1)^{e}	—	25.0 (7.2)^{d,e}	19.5 (7.8)^{c,e}	11.9 (1.8)^{a,c,d}	5.6 (1.6)^{f}
400 N	20.1 (1.4)^{c,e}	—	31.5 (8.1)^{a,d,e}	25.5 (9.2)^{c,e}	13.1 (1.6)^{a,c,d}	6.3 (1.6)^{f}
Laxity increase (mm): mean (SD)						
200 N	2.6 (2.1)	3.0 (3.8)	4.5 (3.6)^{e}	2.0 (2.9)	1.3 (0.7)^{c}	—
300 N	6.2 (4.8)^{c}	—	9.8 (5.3)^{a,d,e}	5.0 (5.6)^{c}	2.6 (0.6)^{c}	—
400 N	8.0 (0.2)^{c}	—	12.4 (3.4)^{a,e}	8.2 (4.5)^{e}	3.4 (1.4)^{c,d}	—

NOTE. a-f represent significantly different corresponding data pairs.
a: Significantly different from HST_{Bio}.
b: Significantly different from HST_{RCI}.
c: Significantly different from HST_{Button}.
d: Significantly different from HST_{Washer}.
e: Significantly different from PAT.
f: Significantly higher than all reconstruction techniques.

found compared with the second extracortical fixation technique (HST_{Washer}) with direct femoral and indirect tibial fixation. The displacement of the second anatomic reconstruction technique, HST_{RCI}, was also lower than that in the extracortical HST_{Button} group throughout the cyclic testing with significant differences found at the loading cycle up to 100 N ($P < .05$). No significant differences were found in comparison with the HST_{Washer} group at all loading cycles. When comparing anatomic and extracortical reconstruction techniques, no significant differences were found between HST_{Bio} and HST_{RCI}, whereas the displacements in the HST_{Washer} group with combined direct and indirect tendon graft fixation were found to be significantly lower than in the HST_{Button} group with all indirect tendon graft anchorage at the loading cycles up to 300 N and 400 N ($P < .05$).

Laxity Increase

When evaluating the loss of fixation in the hamstring tendon graft reconstruction techniques (Table 3), the laxity increase for anatomic biodegradable interference screw fixation (HST_{Bio}) was significantly less than that of the all indirect extracortical reconstruction technique HST_{Button} at the cycles up to 300 N and 400 N ($P < .05$). There was no significant difference compared with the HST_{Washer} group. The laxity increase of the second anatomic reconstruction technique HST_{RCI} was not significantly different from either extracortical fixation techniques HST_{Button} or HST_{Washer}. No significant differences were found between HST_{Bio} and HST_{RCI}, whereas all indirect extracortical hamstring tendon fixation (HST_{Button}) showed a significantly larger laxity increase than combined direct and indirect fixation (HST_{Washer}) at the loading cycle up to 300 N ($P < .05$).

The laxity increase of the PAT group was significantly lower than that in all indirect extracortical fixation of hamstring tendons (HST_{Button}) at all loading cycles except at 100 N ($P < .05$). When compared to the HST_{Washer} group, significant differences were found at the loading cycle up to 300 N ($P < .05$). Even though values for laxity increase were lower in the PAT group at all loading cycles compared with the anatomic interference screw fixation groups (HST_{Bio}, HST_{RCI}), no significant differences could be detected.

Maximum Values

The maximum load of the intact ACL (Table 4) was significantly higher than in all its reconstruction techniques ($P < .05$). The maximum loads of the anatomic hamstring tendon reconstruction techniques HST_{Bio} (375 $\pm$ 144 N) and HST_{RCI} (207 $\pm$ 50 N) were significantly lower than that of the extracortical fixation technique HST_{Washer} (554 $\pm$ 170 N) ($P < .05$). No significant difference was found between HST_{Bio} and HST_{Button} (505 $\pm$ 43 N), while the maximum load of the HST_{RCI} group was significantly lower than in the HST_{Button} group ($P < .05$). When comparing maximum loads of anatomic and extracortical reconstruction techniques, significant differences were found between HST_{Bio} and HST_{RCI}, while no significant differences were detected between HST_{Button} and HST_{Washer}. The maximum load of the patellar tendon reconstruction technique (PAT) was significantly lower (384 $\pm$ 170 N) than that in either

TABLE 4. *Maximum Tensile Properties for Each Reconstruction Technique*

Max	HST_{Bio}	HST_{RCI}	HST_{Button}	HST_{Washer}	PAT	ACL
Load (N)	375 (144)^{b,d}	207 (50)^{a,c,d,e}	505 (43)^{b,e}	554 (91)^{a,b,e}	384 (170)^{b,c,d}	1994 (206)^{f}
Stiffness (N/mm)	52 (15)^{b}	35 (10)^{a,e}	42 (10)^{e}	43 (10)^{e}	66 (22)^{b,c,d}	189 (21)^{f}
Displacement (mm)	24 (9)^{c}	19 (9)^{c,d}	41 (11)^{a,b,e}	34 (8)^{b,e}	19 (13)^{c,d}	19 (4)^{c,d}

NOTE. a-f represent significantly different corresponding data pairs.
a: Significantly different from HST_{Bio}.
b: Significantly different from HST_{RCI}.
c: Significantly different from HST_{Button}.
d: Significantly different from HST_{Washer}.
e: Significantly different from PAT.
f: Significantly higher than all reconstruction techniques.

extracortical hamstring tendon fixation techniques (HST_{Button}, HST_{Washer}) ($P < .05$). No significant difference was found between PAT and the anatomic hamstring reconstruction group HST_{Bio}. However, maximum load was significantly greater in the PAT group than that in the HST_{RCI} group ($P < .05$).

The maximum stiffness of the intact ACL (189 ± 21 N/mm) was significantly higher than in all reconstruction techniques ($P < .05$). The maximum stiffness of either anatomic hamstring tendon reconstruction techniques HST_{Bio} (52 ± 15 N/mm) and HST_{RCI} (35 ± 10 N/mm) was not significantly different from either extracortical fixation technique, HST_{Button} (42 ± 10 N/mm) or HST_{Washer} (43 ± 10 N/mm). The maximum stiffness in the HST_{Bio} group was significantly higher than that in the HST_{RCI} group ($P < .05$). There were no significant differences between both extracortical reconstruction techniques. The maximum stiffness of PAT (66 ± 22 N/mm) was significantly higher than that in either extracortical reconstruction technique ($HST_{Button,}$ HST_{Washer}) and in the HST_{RCI} group ($P < .05$). There was no significant difference between PAT and HST_{Bio}.

The maximum displacements found in the HST_{Bio} (24 ± 9 mm) and HST_{RCI} (19 ± 9 mm) groups were significantly lower than that in the HST_{Button} group (41 ± 11 mm) ($P < .05$). There was no significant difference when comparing these groups with HST_{Washer} (34 ± 8 mm). The maximum displacement of PAT (19 ± 13 mm) was significantly lower than in either extracortical hamstring reconstruction technique ($HST_{Button,}$ HST_{Washer}) ($P < .05$). There was no significant difference between PAT and either anatomic fixation technique.

Failure Mode

The failure modes of the intact ACLs were intraligamentous rupture (n = 4), rupture of the ligament from its tibial insertion with bony avulsion (n = 3), and ligamentous rupture from its femoral insertion (n = 1). All ACL reconstructions in the HST_{Bio} group failed on the tibial side by either slippage (n = 6) or tear (n = 2) of the tendon graft from the screw fixation site. In the HST_{RCI} group, all reconstructions failed by slippage of the graft out of the tibial tunnel with the RCI titanium screw left in place. In the HST_{Button} group, all specimens failed by either rupture of the knots/sutures on the tibial side (n = 6) or tear of the mersilene tape (n = 2). Rupture of the sutures in graft fixation on the tibial side was the predominant mode of failure in the HST_{Washer} group (n = 6) while slippage and tear of the tendon ends from the soft-tissue washers were observed in the remaining 2 specimens. In the PAT group, failure occurred on the tibial fixation site in all cases. Graft pullout was observed with (n = 3) and without (n = 5) bone-block fracture.

DISCUSSION

Hamstring and patellar tendons have become the most popular replacement grafts for ACL reconstructions. However, the ideal technique for graft fixation remains controversial, especially with hamstring tendons. This study was conducted to determine the impact of level and method of fixation on the mechanical properties of 4 hamstring reconstruction techniques and compare them with a standard patellar-tendon graft reconstruction at the time of implantation. The biomechanical properties of ACL repairs have been frequently reported from experiments using either older human cadaveric[16,22] knees or animal specimens.[26-30] However, several studies showed that the structural properties of an ACL reconstructed knee were significantly affected by age and origin of the cadaveric bone (human *v* animal).[10,16,22,31] In this study, only young to middle-aged human cadaveric knees were used for biomechanical testing.

We also simulated the immediate postoperative loading condition when graft incorporation has yet to take place and knee stability primarily depends on initial graft fixation. A tibial anterior drawer was simulated because this motion is restricted by the primary function of the ACL. The anterior drawer test was conducted at 30° of flexion, based on the findings of Livesay et al.[11] who showed that the intact ACL was tensioned most uniformly at this flexion angle. For simulation of the postoperative loading situation the reconstructed knees underwent cyclic loading rather than single load-to-failure testing, which had been favored for biomechanical evaluation of ACL reconstruction techniques in recent years.[16-19] An incremental load increase per cycle was performed to determine the possible effect of even small load changes on anterior knee stability, especially toward higher loading levels as might be expected during early aggressive rehabilitation.

According to the hypothesis of this study, we examined whether direct tendon graft fixation of hamstring tendons closer to the joint line would improve the mechanical properties of the knee after ACL reconstruction. Our results clearly showed that direct anatomic tendon graft fixation significantly improved anterior stiffness of the reconstructed knee joints during cyclic loading. This can be seen by the significantly higher stiffness found in the HST_{Bio} and PAT groups with direct interference fit fixation. These findings are in agreement with the study of Ishibashi et al.[32] who found an increase in anterior stability when moving the fixation site of a patellar tendon closer to the joint line.

However, a crucial factor for direct tendon graft fixation with interference screws was the tibial fixation site. When direct graft fixation was achieved without a bone block (HST_{RCI}), the sustained loads during cyclic loading significantly decreased with consistent failure of the reconstruction by graft pullout from the tibial tunnel. These findings are in agreement with other studies that found similar failure modes at comparable load magnitudes.[16,19,33] The use of a bone block in the tibial tunnel significantly improved the anterior stiffness as seen in the HST_{Bio} and PAT groups. A second bone block in the femoral tunnel (PAT) provided an additional increase in anterior stiffness compared with single or no bone-block constructs.

In all its respective groups (HST_{Bio}, HST_{RCI}, PAT), the dominant failure site remained at the tibial tunnel. These findings imply that either a completely reconstructed knee joint or at least the tibial fixation site should be mechanically tested when evaluating the tensile properties of ACL reconstruction techniques with interference fit fixation. Caution should be used when testing the femoral fixation site only as it possibly overestimates the tensile properties of the knee after complete reconstruction.[18,19,26,33]

One explanation for the low fixation strength in the tibial tunnel might be the lower bone density normally found in tibial bone compared to the femur.[34] In the HST_{RCI} group, slippage of the tendon out of the tibial tunnel occurred with the interference screw left in place and with no apparent tendon lacerations at loads around 200 N, and 7 of 8 specimens failed at loads of 300 N. These observations suggest that the use only of a metal interference screw with its round-headed soft-threaded design did not provide sufficient direct soft-tissue fixation in the tibial bone to withstand loads that might be experienced during postoperative rehabilitation. The significantly lower stiffness of the extracortical reconstruction techniques HST_{Button} and HST_{Washer} are in agreement with the reported mechanical properties of such indirect fixation techniques with linkage materials as suture knots or tape.[16,29,35,36] In a study by Höher et al.,[35] it was shown that the lower stiffness and increased elongation of these tendon graft fixation constructs primarily resulted from the mechanical behavior of the suture and tape material, when cycled even at submaximal load levels. In another report by Phillips et al.[37] it was also shown that knot tightening of the suture/tape materials was the primary cause of elongation. The failure modes in both extracortical reconstruction techniques confirm these findings as rupture of the knots and the suture/tape material were always the failure site in the HST_{Button} and the predominant site of failure in the HST_{Washer} group.

The loading-unloading behavior of the tested reconstruction techniques, reflected by the parameter "energy loss" during cyclic loading, supports the hypothesis that direct tendon graft fixation close to the joint line mimics the mechanical behavior of the intact ACL more accurately than indirect extracortical fixation. In the intact ACL, the loading and unloading patterns are almost identical. In both direct anatomic reconstruction techniques with either 1 (HST_{Bio}) or 2 (PAT) bone blocks, the loading-unloading patterns of the intact ACL were replicated more closely than in either extracortical fixation techniques, which showed a significantly larger immediate force drop during unloading. A different unloading path might be an indicator of the continuous loss of graft fixation, resulting in failure of the ACL reconstruction. In the extracortical reconstruction techniques, this might be caused by the plastic load response or so-called "stretch-out" of the suture/tape materials, which was reported to occur at much lower loads than in ligamentous soft tissue[35,37,38] and its loss of fixation strength under cyclic loading.[36,39] In the anatomic reconstruction techniques, the different unloading behavior can be mainly attributed to tendon graft slippage from interference fit fixation. Direct bone-tendon-bone (PAT) fixation significantly reduced the difference between the loading and unloading paths. A large difference in the loading and unloading behavior is of clinical importance because a larger drop in force experienced by the reconstructed ACL during unloading may result in increased nonphysiologic loading of the secondary restraint in the knee joint, predisposing them to early degenerative changes.

Findings of anterior displacement and laxity increase substantiate the data found for "energy loss," which suggest that the linkage materials negatively affect the mechanical properties of the reconstruction. The highest anterior displacement was found when indirect graft fixation was achieved with linkage materials such as suture and tape on both fixation sites (HST_{Button}). The replacement of an indirect with a direct fixation method as seen in the HST_{Washer} group already decreased anterior displacement, with a further decrease seen in direct anatomic reconstruction techniques (HST_{Bio}, PAT). However, the measurements of anterior displacement accounted for the overall elongation of the graft-fixation construct, which consisted of the elongation of the tendon graft itself and the loss of graft fixation in terms of plastic deformation ("stretch-out") of suture/tape materials, knot tightening (extracortical reconstructions), and tendon graft slippage (anatomic reconstructions). It was important to separately quantify the loss of graft fixation following load changes. This is crucial for the evaluation of a fixation method, as a longer tendon graft will undergo larger elongation than a shorter graft because of its inherent lower stiffness. As length of the tendon graft constructs varied among the different reconstruction techniques because of their respective fixation sites, we introduced the parameter "laxity increase" to eliminate the elongation of the tendon grafts from displacement measurements and accurately evaluate the fixation method. Our data showed that, especially toward higher loads, a significantly higher loss of graft fixation was observed when linkage materials were used on both fixation sites (HST_{Button}). The replacement of an indirect with a direct fixation method in the extracortical reconstruction technique HST_{Washer} reduced the loss of graft fixation to the levels of the anatomic reconstruction HST_{Bio}, which still showed increased graft slippage compared with bone-tendon-bone fixation (PAT) and especially compared with the intact ACL.

Although direct anatomic reconstruction showed considerable advantages with respect to anterior stiffness, reproduction of the loading-unloading patterns of the ACL intact knee, reduced lower anterior displacements, and laxity increase, an important disadvantage was found when comparing them with the extracortical reconstruction techniques. All anatomic reconstructions failed at considerably lower loads than the groups with extracortical fixation. More than 50% of the reconstructions in the HST_{Bio} and PAT groups, and 100% of specimens of the HST_{RCI} group had failed at or before the loading level of 400 N, whereas all knees with extracortical reconstructions remained intact. However, these higher failure loads of the extracortical fixation techniques were compromised by large anterior displacements of the tibia with respect to the femur resulting from their lower stiffness. The maximum values found for load, stiffness, and displacement of the different reconstructed knees are well within the range of previously reported data.[16,17,19,27,33]

When discussing the results of biomechanical studies and their clinical implications, caution should be used because of the lack of in vivo data in humans; we can only speculate about the forces the intact ACL withstands during normal knee motion. Some studies suggested these forces to be far below 400 N.[40-44] For example, Corry et al.[6] presented successful clinical outcomes of ACL reconstructions using hamstring tendons with RCI metal interference screw fixation that seem not to be supported by the results of this and other published studies.[19,27,33] During the early postoperative period when excessive loading of the ACL is limited even under aggressive rehabilitation, it might be more important to provide higher anterior stiffness, especially at lower load levels, so that extensive graft elongation can be avoided. Increased anterior stiffness would also potentially reduce intratunnel graft motion, allowing for faster osseous incorporation with the development of a direct tendon-to-bone insertion.[15]

A few limitations apply to this study because we performed only manual preconditioning of the tendon grafts before final fixation and no preconditioning of the whole reconstructed knee joint on the material testing machine, which might have allowed for higher absolute anterior displacements and laxity increases. Due to the incremental load increase, the numbers of cycles were limited, especially when failure occurred at very low loads.

The results of this study suggest that direct anatomic fixation of ACL replacement grafts provided higher anterior knee stability than indirect extracortical fixation under incremental cyclic loading. Among the hamstring tendon reconstruction techniques, this was achieved best with biodegradable interference fit fixation and additional tibial bone block fixation (HST_{Bio}). However, the comparison with a standard patellar tendon reconstruction technique showed that direct tendon-to-bone fixation in both (HST_{RCI}) or only 1 (HST_{Bio}) bone tunnel did not provide the stiffness of bone-to-bone fixation in both bone tunnels.

Additionally, none of the reconstruction techniques was able to restore the tensile properties of the knee with an intact ACL. Therefore, further improvements for the fixation of hamstring tendon grafts are needed to benefit as successful ACL reconstruction. Recent studies[45,46] showed that a backup for interference fit fixation of hamstring tendons, the so-called hybrid fixation, especially on the tibial fixation site, provided significant improvements in stiffness and failure load of these constructs with substantial reduction of graft slippage under cyclic loading even without bone block fixation. Future studies will combine the assessment of the biologic processes with the biomechanical aspects of an ACL reconstruction during the early postoperative period. This would help to develop techniques that will limit graft deterioration, enhance tendon-to-bone healing, and encourage ACL reconstructions that are able to fully compensate for the decreased mechanical properties during the early healing phase, allowing immediate return to strenuous activity.

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