Crouch gait is common in children with cerebral palsy (CP) and is perhaps the most debilitating gait deformity for ambulatory individuals with neuromuscular disease. The pathophysiology of crouch gait in CP is multifactorial, beginning with altered muscle function due to increased tone and spasticity, which can lead to joint contractures that can be associated with resultant bony deformities. In crouch gait, an individual walks with excessive hip and knee flexion and exaggerated dorsiflexion during the stance period of gait. This is an inefficient gait pattern because the excessive knee flexion in stance period necessitates large knee extensor internal moments in response. This leads to unusually high patellar tendon force, sometimes double or triple the typical load. In addition to higher patellar tendon forces, crouch gait deformity is common in children with cerebral palsy and is associated with patella alta. Patellar tendon advancement typically is used to correct patella alta and restore normal knee mechanics. The purpose of this study was to determine the mechanical strength of surgical constructs used for fixation during patellar advancement procedures. This study used a cadaveric model to determine which of 3 surgical techniques is biomechanically optimal for patellar tendon advancement in treating patella alta.

Twenty-four human cadaveric knees (8 per group) were prepared using 1 of 3 different common surgical techniques: tibial tubercle osteotomy, patellar tendon partial resection and repair at the distal patella, and patellar tendon imbrication. The patella was loaded from 25 to 250 N at 1 Hz for 1000 cycles. A significant difference in patella displacement under cyclical loading was found between surgical techniques. Tibial tubercle osteotomy exhibited significantly less displacement under cyclical loading than distal patella excision and repair ($P<.0001$) or imbrication ($P=.0088$). Imbrication exhibited significantly less displacement than distal patella excision and repair ($P=.0006$). Tibial tubercle osteotomy survived longest. Based on failure criteria of 5 mm of displacement, tibial tubercle osteotomy lasted between 250 and 500 cycles. The other 2 techniques failed by 25 cycles. This study offers quantitative evidence regarding the relative mechanical strength of each construct and may influence choice of surgical technique. Orthopedics. 2016; 39(3):e492-e497.
also prolongs the duration of these loads by shifting the ground reaction force behind the knee joint for a greater proportion of stance period compared with typical gait. These combined actions increase both the magnitude and duty cycle of the quadriceps during every gait cycle, resulting in considerable stress on the patellar tendon and the extensor mechanism.

The patellar tendon is viscoelastic and displays the property of creep under chronic load; therefore, persistent crouch gait often leads to elongation of the patellar tendon with subsequent displacement of the patella proximally, a condition known as patella alta. This is well classified in skeletally immature children using the Koshino Index, which is defined as the ratio of the distance from the center of the patella to the epiphyseal line midpoint in the proximal tibia to that between the distances of the distal femur and of the proximal tibia. In this condition, the patella sits higher in the trochlear groove and may lead to patellofemoral malalignment, reduced joint contact area, or elevated patellofemoral joint stress.

Using a mathematical model of the patellofemoral joint, Yamaguchi and Zajac concluded that patella alta could increase joint reaction forces at knee flexion angles above 30°. In a cadaver study simulating patella alta and using load cells to directly measure joint forces, elevated joint reaction forces were observed but not until 90° of knee flexion, the equivalent of severe crouch gait. In a clinical study using magnetic resonance imaging of young adults with and without patella alta, Ward et al. found no difference between groups in actual knee extension in stance by advancing the patella alta in neuromuscular patients exhibiting crouch gait deformity using outcome measures derived from instrumented gait analysis. Accounts of acute failure of patellar advancement with early recurrence of patella alta have been noted at several institutions.

Kinematic studies of the natural progression of gait in children with CP showed that during a period of 5 years, less functional walkers (<80 cm/sec) lose an average of 2 grades of strength and experience statistically significant differences in sagittal plane hip and ankle range of motion. These studies provide evidence of increased and progressive knee joint stress when patella alta is combined with a crouch gait pattern, justifying surgical procedures to restore proper patellar alignment in this population. The functional consequences of crouch gait are so devastating that it is essential to treat and improve this gait pattern in ambulatory patients with CP. This usually is accomplished through single event multilevel surgery, which can include corrective osteotomies for knee flexion contractures (distal femoral extension osteotomy), rotational osteotomies, muscle and tendon lengthening or transfer, guided growth, and patellar advancement. These treatments have been shown to improve gait and prevent or delay progression to non-ambulatory status.

Patellar tendon advancement for the treatment of patella alta and crouch gait initially was described in 1953. Most of the literature discussing this operation has been published since 2006. The main goals of this surgery are to achieve full knee extension in stance by advancing the patella and correcting patellofemoral malalignment, effectively restoring normal force magnitudes and duty cycle requirement of the quadriceps. This operation is now performed routinely at institutions with significant ambulatory neuromuscular populations, particularly children with CP. Studies currently are under way to provide evidence that this operation is effective in improving crouch gait deformity using outcome measures.

Accounts of acute failure of patellar advancement with early recurrence of patella alta have been noted at several institutions. Reported complications of tibial tubercle osteotomy include tibial tubercle nonunion (0.6%), proximal tibia fracture (0.6%), infection (1.2%), phlebitis (0.6%), and deep venous thrombosis (0.6%). There remains a paucity of literature that documents complications of patellar tendon partial resection and repair at the distal patella as well as patellar tendon imbrication.

The purpose of this study was to determine the mechanical strength of surgical constructs used for fixation during patellar advancement procedures. Comparing strength and displacement under load for 3 common repair techniques could provide insight into which surgical technique is biomechanically superior. This will provide insight into the mechanics of failure and may provide insight into the most optimal surgical strategy for treating patella alta in neuromuscular patients exhibiting crouch gait deformity. The hypothesis was that patellar tendon advancement using a
tibial tubercle osteotomy described by Novacheck et al.\textsuperscript{18} would exhibit less displacement during cyclic loading.

**MATERIALS AND METHODS**

This study was approved by the Colorado Multiple Institutional Review Board and used 24 human cadaveric knees.

**Surgical Techniques**

The knees (8 per group) were prepared using 3 different surgical techniques: tibial tubercle, distal patella excision and repair, and imbrication.

**Tibial Tubercle.** This surgical technique consisted of distal advancement of the patellar tendon with tibial tubercle osteotomy and FiberTape (Arthrex Inc, Naples, Florida) augmentation (Figure 1A). A bone block with the patellar tendon attached was created using a sagittal saw. Repair was performed with a 4.5-mm fully threaded cortical screw placed using lag technique. FiberTape (2 mm) cerclage then was placed through transverse drill holes in the patella (Figure 1B). This involved transection of the patellar tendon from the distal patella. Repair involved 2 Krackow stitches (#5 FiberWire; Arthrex Inc) placed in the patellar tendon and passed through 3 transpatellar drill holes (2 sutures through a central drill hole and 1 suture through lateral and medial drill holes), then tied superiorly.\textsuperscript{23} This repair technique is similar to standard repair of a patella tendon rupture.

**Imbrication.** This technique consisted of imbrication of the midportion of the patellar tendon with repair using running locking suture (Figure 1C). The technique involved folding the patellar tendon with 1 cm overlap to advance the patella. Imbrication was secured with 2 rows of running locked suture (#5 FiberWire).

**Specimen Testing**

The knees were mounted in a custom-built fixture to the base of an Instron servo-hydraulic test machine (Instron Corp, Norwood, Massachusetts) at a fixed-flexion angle of 45° simulating severe crouch gait deformity. The 45° fixed-flexion angle was chosen as this has been shown to produce the maximum moment arm for the extensor mechanism.\textsuperscript{24} The quadriceps tendon was freed and connected to the actuator with a cryo-clamp. Each specimen was tested in cyclical loading. To simulate crouch gait, the quadriceps was loaded from 25 to 250 N in 0.1 seconds, held at 250 N for 0.4 seconds, unloaded to 25 N in 0.1 seconds, and held at 25 N for 0.4 seconds for 1000 cycles. This represented a 60/40 duty cycle in stance/swing proportion for a gait cycle of 1 second duration. The cycle force magnitude has been documented and validated previously.\textsuperscript{25}

To accurately measure proximal patellar migration relative to the tibia, optical markers were placed on the patella and the tibia, and tracked during the testing procedure. Motion was captured at 30 frames per second with a digital camera and tracked with MaxTRAQ (Inovision Systems Inc, Columbiaville, Michigan) motion analysis software. Displacement greater than 5 mm at the repair site was considered repair failure.\textsuperscript{23}

To compare the surgical constructs in cyclical loading, the maximum displacement of the patella was measured at 1, 10, 25, 50, 100, 250, 500, 750, and 1000 cycles for each sample. To describe the behavior of each construct for every sample, the maximum displacement data at the 9 time intervals were first log transformed on each axis and then fit to a mixed-effects linear model with random coefficients. The slopes of these 3 linearized curves describing each construct then were compared pairwise to look for significant differences using each model’s $t$ statistic at an alpha level of .05. Post-hoc power analysis then was performed to confirm the sample size was sufficient.

**RESULTS**

**Cyclical Loading**

Results from the cyclical loading test are shown in Tables 1-2 and Figures 2-3. The tibial tubercle osteotomy group exhibited less maximum displacement at each recording interval compared with either the distal patella excision and repair or imbrication group (Table 1). Imbri-
cation exhibited less displacement than distal patella excision and repair after the 50th loading cycle.

**Figure 2** is a plot of group maximum displacement plus standard error of the mean versus loading cycle for the 3 constructs. All 3 curves exhibit logarithmic behavior during the 1000 cycles that were tested, clearly diverging at each interval.

Because of this apparent logarithmic response, the unequal sampling interval, and the loss of a few samples during the cyclical loading test, both displacement and cycle count were log transformed at each data point and then fit to a mixed-effects linear model with random coefficients to represent the entire displacement response and to facilitate further statistical testing. **Figure 3** shows a plot of the resultant linear model for each construct, plotted against the log cycle count. **Table 2** shows the pairwise comparisons of the 3 slopes for the linear models of each construct.

There was a significant difference between the slopes of the linear models associated with the 3 constructs at an alpha level of .05, reflecting a significant difference in the repair displacement during the cyclical loading test. Tibial tubercle osteotomy exhibited less displacement than distal patella excision and repair ($P<.0001$) or imbrication ($P=.0088$). Imbrication exhibited less displacement than distal patella excision and repair ($P=.0006$) (Table 2). Post-hoc power analysis confirmed a sufficient sample size in each group had been achieved to make these pairwise comparisons, assuming sufficient power at 75%.

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### Table 1

<table>
<thead>
<tr>
<th>Surgical Technique</th>
<th>Cycle 1 (n=24)</th>
<th>Cycle 10 (n=24)</th>
<th>Cycle 25 (n=24)</th>
<th>Cycle 50 (n=22)</th>
<th>Cycle 100 (n=22)</th>
<th>Cycle 250 (n=24)</th>
<th>Cycle 500 (n=24)</th>
<th>Cycle 750 (n=24)</th>
<th>Cycle 1000 (n=24)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DISTAL PATELLA EXCISION AND REPAIR</td>
<td>2.72 (1.43)</td>
<td>4.89 (2.87)</td>
<td>6.49 (4.01)</td>
<td>8.66 (5.82)</td>
<td>10.42 (6.83)</td>
<td>13.92 (8.58)</td>
<td>16.49 (9.77)</td>
<td>18.44 (10.57)</td>
<td>19.51 (10.91)</td>
</tr>
<tr>
<td>IMBRICATION</td>
<td>3.37 (1.76)</td>
<td>5.54 (3.15)</td>
<td>6.78 (3.72)</td>
<td>7.29 (4.27)</td>
<td>8.47 (4.97)</td>
<td>10.28 (4.55)</td>
<td>11.23 (4.71)</td>
<td>11.69 (4.44)</td>
<td>12.22 (4.29)</td>
</tr>
<tr>
<td>TIBIAL TUBERCLE</td>
<td>2.59 (2.21)</td>
<td>3.35 (3.15)</td>
<td>3.72 (3.39)</td>
<td>4.02 (3.54)</td>
<td>4.37 (3.80)</td>
<td>4.82 (4.05)</td>
<td>5.40 (4.19)</td>
<td>5.55 (4.19)</td>
<td>5.76 (4.29)</td>
</tr>
</tbody>
</table>

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### Table 2

<table>
<thead>
<tr>
<th>Slope Difference Comparison</th>
<th>Estimate</th>
<th>SE</th>
<th>df</th>
<th>t Value</th>
<th>P</th>
<th>Power at .05</th>
</tr>
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<tbody>
<tr>
<td>Tibial tubercle vs distal patella</td>
<td>-0.1738</td>
<td>0.0283</td>
<td>164</td>
<td>-6.13</td>
<td>&lt;.0001</td>
<td>100%</td>
</tr>
<tr>
<td>Tibial tubercle vs imbrication</td>
<td>-0.0751</td>
<td>0.0283</td>
<td>164</td>
<td>-2.65</td>
<td>.0088</td>
<td>75%</td>
</tr>
<tr>
<td>Distal patella vs imbrication</td>
<td>0.0987</td>
<td>0.0283</td>
<td>164</td>
<td>3.48</td>
<td>.0006</td>
<td>93.37%</td>
</tr>
</tbody>
</table>
Discussion

These data suggest patellar advancement using the tibial tubercle osteotomy technique provides the strongest biomechanical construct in the acute postrepair period, yielding the least displacement at the repair site with cyclical loading and later failure based on a clinical failure threshold of 5 mm. Although it is understood that patients with open physes are not candidates for tibial tubercle osteotomy, the findings of this study make a strong argument for the use of this technique in skeletally mature individuals with crouch gait and patella alta.

Previous studies have supported the use of tibial tubercle osteotomy patellar advancement with or without concomitant distal femoral extension osteotomy for the treatment of patella alta. Specifically, Stout et al. reported on a series of patients with persistent crouch gait supporting the use of patellar tendon advancement. It was concluded that patellar advancement has the potential to restore knee and hip joint kinematics to values within typical limits as well as promote gains in community function. Das et al. reported a series of patients treated with this operation and found that it is effective in improving knee extensor strength, reducing knee pain, and improving function. Of note, the majority of patients in both studies underwent concomitant distal femoral extension osteotomy.

When interpreting these results, limitations of this and any biomechanical study should be considered. The specimens tested were cadaveric knees that did not have elongated patella tendons caused by creep from crouched gait. Therefore, the displacement found may be larger than what would be found in patella alta specimens because the displacement is a combination of patellar tendon creep and the repair technique.

Another limitation to this study is that it may not reflect the clinical strength of these repairs, as a cadaveric model cannot account for soft tissue or bone healing at the repair site. This concept was well understood during study design; however, the goal of this study was to assess the biomechanical strength of the repair constructs in a model of crouch gait rather than the healing potential. The current authors have experienced multiple acute postoperative failures with recurrence of patella alta following patellar advancement procedures and therefore believed it was appropriate to test the acute biomechanical strength without factoring healing. Evaluating long-term clinical and kinematic results after complete healing would be impossible in a cadaveric situation; however, this study provides a framework for a prospective randomized controlled clinical study to assess the strength and integrity of each construct.

Another consideration is that the imbrication procedure resulted in slight patellar advancement compared with the other methods, which did not advance the patella. This is due to the fact that it was performed in cadavers with normal preprocedure patellar tendon length and patellar height. The goal was to test the repair constructs with the patella in anatomic position, which is the desired corrected position when this surgery is performed in patients with crouch gait deformity. Despite these limitations, the 3 constructs were subjected to the same loading pattern over the same number of cycles with similar specimens, thus their relative performance can be evaluated from these experiments.

Conclusion

Patella alta is a serious problem in children with CP and crouch gait. The ideal surgical intervention to address patella alta would restore biomechanics of the extensor mechanism of the knee while limiting complications and the need for revision surgery. This study adds a biomechanical component to previous studies offering clinical and kinematic support for the use of tibial tubercle patellar advancement in patients with crouch gait and patella alta. This may help guide the choice of surgical technique when performing patellar advancement in patients with crouch gait and patella alta.

References


13(2):192-199.


