Published in final edited form as:

Gait Posture. 2018 July ; 64: 248–254. doi:10.1016/j.gaitpost.2018.06.005.

How does Patellar Tendon Advancement alter the Knee Extensor Mechanism in Children Treated for Crouch Gait?

Moria F. Bittmann^a, Rachel L. Lenhart^a, Michael H. Schwartz^{b,c}, Tom F. Novacheck^{b,c}, Scott Hetzel^d, and Darryl G. Thelen^{a,d,e,*}

^aDepartment of Mechanical Engineering, University of Wisconsin-Madison, USA

^bGillette Children's Specialty Healthcare, USA

^cUniversity of Minnesota - Twin Cities, Department of Orthopaedic Surgery, University of Wisconsin-Madison, USA

^dDepartment of Orthopedics and Rehabilitation, University of Wisconsin-Madison, USA

^eDepartment of Biomedical Engineering, University of Wisconsin-Madison, USA

Abstract

Background: The patellar tendon advancement (PTA) procedure, often coupled with a distal femoral extension osteotomy (DFEO), is increasingly used to treat persistent crouch gait. In this study, we investigated relationships between patellar position, knee flexion, and the patellar tendon moment arm in children treated with the DFEO and PTA procedures.

Methods: We retrospectively analyzed pre- and post-operative radiographs and gait metrics from 63 knees that underwent DFEO and PTA procedures at Gillette Children's Specialty Healthcare. A computational musculoskeletal model of the knee was used to simulate the PTA procedure and predict the effects on the patellar tendon moment arm.

Results: Approximately 80% of the knees exhibited patella alta prior to surgery. Post operatively, 86% of the knees exhibited patella baja. The surgically altered patella position produced a 13% increase in the patellar tendon moment arm in extended knee postures, which agreed well with model predictions. However, the computational model also suggests that baja may compromise patellar tendon moment arms in flexed knee postures. Crouch gait was significantly reduced postoperatively, with a 27 ± 18 degree reduction in average knee flexion in stance. There was considerable inter-subject variability in outcomes with nine knees not exhibiting a meaningful enhancement of knee extension (<15 degree change). The subjects who improved were significantly younger and exhibited greater enhancement of the patellar tendon moment arm after surgery.

*Corresponding Author, dgthelen@wisc.edu, 608-262-1902.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Conclusions: This study shows that the PTA procedure enhances the lever arm of the knee extensor mechanism, and this factor may be important in resolving crouch gait.

Keywords

Cerebral Palsy; Patella Alta; Moment Arm; Tibiofemoral Joint; Knee Extensor Lag; Quadriceps Insufficiency

Introduction:

Quadriceps insufficiency and patella alta are often present in children with cerebral palsy who exhibit persistent crouch gait¹⁻³. The patellar tendon advancement (PTA) procedure is increasingly used to address these underlying impairments⁴⁻⁵. PTA is often coupled with a distal femoral extension osteotomy (DFEO) in individuals who also exhibit a knee flexion contracture⁶. The PTA distalizes the patella by surgically transposing and fixing the tendon insertion, or the tubercle if growth is complete, at a distal location along the anterior tibia. The PTA was initially described in the 1930's by Chandler⁷, but did not gain broad acceptance, possibly due to inadequate surgical stabilization and pain that led to a loss of correction. Recently the procedure has gained popularity for treating crouch gait with the emergence of outcomes data. Retrospective studies have shown that PTA and coupled DFEO +PTA procedures can elicit significant improvements in knee extension during gait. However, outcomes remain inconsistent with some individuals exhibiting residual crouch^{8,9}. As a result, the selection criteria and surgical approaches continue to evolve^{8,10}.

A primary question that remains with the PTA is how far to advance the patellar tendon in each patient. The purpose of the PTA is to address quadriceps insufficiency, which is reflected in an inability to actively extend the knee through the full passive extension range of motion. PTA is also used to re-tension the quadriceps when a DFEO is performed. The established target for PTA is typically anatomical and involves aligning the inferior pole of the patella with the tibiofemoral joint line⁴. This anatomical placement often advances the patella from alta into baja.

A recent computational musculoskeletal modeling study found that patellar position has a substantial impact on patellar tendon moment arms (PTMAs), and hence quadriceps torque generating capacity¹¹. The model suggests that patella alta can actually be beneficial in crouch gait by enhancing the leverage of the quadriceps in flexed postures. In contrast, patella baja may enhance moment arms in extended postures, which may be a factor in correcting crouch. However, it remains to be seen how much moment arms change with PTA surgery, and whether our model accurately predicts changes for individual patients.

In this study, we used radiographic and gait analysis data to investigate relationships between patellar position, knee flexion, and PTMA in children treated with the DFEO+PTA procedures. We hypothesized that, preoperatively, patella alta would scale with crouch severity reflecting the mechanical advantage gained by alta in flexed postures. We then tested the hypothesis that distalizing the patellar tendon insertion in an individual with patella alta will enhance knee extensor moment arms in extended postures. Finally, we

investigated the association between post-operative patella position, PTMA, and knee kinematics during gait in children who underwent DFEO+PTA procedures.

Materials and Methods:

Retrospective Study Population

We used the clinical gait database at Gillette Children's Specialty Healthcare (St. Paul, MN) to identify patients with a diagnosis of cerebral palsy who underwent the DFEO+PTA procedures after 2002. Subjects were included if they were a maximum of 22 years old at the time of preoperative gait analysis and also returned for a postoperative gait analysis. Subjects were excluded if pre- and postoperative radiographs were not available (this eliminated over two-thirds of the identified subjects). It is common that other procedures are performed simultaneously with the DFEO+PTA procedure^{7,8}. We did not exclude subjects based on previous or concurrent surgical events. A total of 40 individuals (29 male) with 63 knees (33 left, 30 right) fulfilled our criteria (Table 1). Subjects were an average of 13.7±3 years old at time of surgery (minimum age=8.6, maximum age=22). Postoperative radiographs and gait analysis were performed at initial follow-up, which varied from 6 to 36 months after the procedure (average duration =16 months). We characterized crouch severity by the minimum knee flexion in stance during overground walking: mild crouch (n=15, minimum knee flexion angle of 20–35 degree), moderate crouch (n=27, 35–50 degree), and severe crouch (n=21, >50 degree). Good outcomes ("Improved" in Table 2) were classified as a post-operative change in minimum knee flexion angle during stance greater than 15 degrees or minimum knee flexion angle during stance that was within the 95% confidence interval of normative pediatric values (<18 degree), described in Schwartz et al¹².

Knee Geometry and Function

Patella Height: We used two well established indices to measure patella height on supine lateral radiographs of the knee. The Caton-Deschamps (CD) index (Fig. 1) was determined using the distance between distal patellar articular surface and the anterosuperior border of the tibia, divided by the patellar articular surface length¹³. The Koshino Index (KI) was calculated as the ratio between the distance from the center of the patella to the epiphyseal midpoint line in the proximal tibia and the distance between the distal femur and the proximal tibia¹⁴. The CD and KI were each reported as a normative (z-score) measure relative to healthy children based on the knee flexion angle of the lateral radiograph^{15–18}. Patella *alta* and *baja* were defined as patella height measures that were greater than one standard deviation above and below the normative measures on healthy children. Due to difficulty in locating the epiphyseal midpoint line in adult radiographs, the subsequent analysis will focus on the CD index. We included KI scores as reference for prior literature.

Patellar Tendon Moment Arms: We first performed a circular fit to the posterior portions of the medial and lateral femoral condyles on the radiograph (Fig. 1). The midpoint between the circle centers was considered to be midpoint of the knee rotation axis, as defined via a cylindrical fit of the posterior femoral condyles¹⁹. The line of action of the patellar tendon was defined by locating the most inferior pole of the patella and the tibial tubercle^{20,21}. For children with incomplete ossification of the tibial tuberosity, the distal

attachment was identified by the senior clinician. The PTMA was then computed as the perpendicular distance between the knee rotation axis and the patellar tendon line of action. To facilitate comparison across subjects, PTMAs were scaled to the epicondylar width (measured with frontal plane radiographs)²².

Tibial Slope: The tibial slope relative to the long axis of the tibia was defined as the angle between the anterior cortex of the tibial shaft and the posterior aspect of the transverse line approximating the epiphysis of the proximal tibia²³.

Computational Model of PTA

We used a computational knee model to simulate the PTA procedure and predict how the moment arm of the patellar tendon about the knee varies with surgically-altered patella height. The knee model allowed for 6 degree-of-freedom motion in the tibiofemoral and patellofemoral joints²⁴. Fourteen ligament bundles, made up of sets of non-linear spring elements²⁵ connected the segments from the anatomical origins to insertions. Contact pressures between articulating cartilage surfaces were determined using an elastic foundation model²⁶. The knee model was incorporated into a lower extremity model from the literature²⁷, which included 44 muscle-tendon units acting about the hip, knee, and ankle. The model was implemented in OpenSim, a freely available biomechanical simulation package²⁸. Note that patella alta positions the patella in a region that is superior to the most superior aspect of the normal femoral cartilage. For this reason, the femoral cartilage geometry was extended superiorly to simulate contact between the patella and femoral bone in an alta position.

The slack length of the patellar tendon spring elements was first extended to emulate the average patella alta (CD=1.8) measured in the preoperative radiographs. The PTA procedure was simulated by translating the patellar tendon insertion points inferiorly, resulting in postoperative patella heights that would be classified as alta (CD=1.8, 1.7, 1.3), normal (CD=1.1) and baja (CD=0.8, 0.7, 0.4, 0.3). In these simulations, passive knee flexion was prescribed between 0 and 85 degrees. Cartilage contact, ligament, capsule restraint and passive muscle forces guided the other five degrees of tibiofemoral motion and all six degrees of patellofemoral motion. At each knee flexion angle, we calculated the patellar tendon moment arm (PTMA) as the shortest distance between the patellar tendon action line and the cylindrical fit of the posterior femoral condyles. Model simulations were used to construct a 5th order polynomial surface describing PTMA as a function of knee flexion angle and patella height.

The knee model was used to predict the change in PTMA that should be expected as a result of the PTA procedure. To do this, the radiographic knee flexion angle (*KneeFlex*) and the patella height (*CD*) measured on the pre- and postoperative assessments were used as inputs to the model to predict PTMA (Fig. 1). The percent change between the predicted PTMA, relative to the preoperative value, was then compared to the similar metric measured directly on the radiographs.

Statistical Analysis:

Statistics were performed using R (version 3.3.2, Vienna, Austria). Repeated measures ANOVAs were performed to test for changes between the pre- and postoperative gait (minimum knee flexion angle during stance) and physical exam measures (knee flexion contracture, extensor lag). Since multiple knees were included for a portion (23) of the subjects, mixed effect linear regressions and coefficient of determination (R^2) were performed to assess the relationship between minimum stance phase knee flexion and CD index. Effect of age, knee geometry and knee function on surgical outcomes were assessed using a mixed effects logistics regression. Subject was considered a random effect for all mixed effects analyses. Significance for all tests was set at $p < 0.05$ and tests were adjusted using a Holm-Bonferroni correction.

Results:

Preoperative measures

A large proportion of the subjects exhibited patella alta preoperatively, with 81% and 83% of the knees classified as alta by the CD and KI, respectively (Fig. 2). There was strong agreement (86%) of patella height classification between CD and KI. There was a significant, but relatively weak, correlation between minimum knee flexion in stance and patella height, as measured by either the CD z-score ($R^2 = 0.23$, $p < 0.05$) or KI z-score ($R^2 = 0.18$, $p < 0.05$).

Postoperative measures

Many of the subjects exhibited patella baja postoperatively, with 86% and 84% of the knees classified as baja by the CD and KI, respectively (Fig. 2). There was strong agreement (90%) between the postoperative classifications based on the two patella height measures. The patellar tendon moment arms were enhanced by an average of 13% ($\pm 19\%$) between the pre- and postoperative radiographic evaluations. There was a significant reduction in crouch severity after surgery, with average knee flexion in stance decreasing $27(\pm 18)$ degrees ($p < 0.0001$) and minimum knee flexion in stance decreasing $29(\pm 18)$ degrees ($p < 0.0001$). However, there was no significant relationship between patella height and minimum knee flexion in stance present postoperatively.

Model predictions

Advancing the patellar tendon insertion of the knee model had a significant effect on the moment arm of the patellar tendon about the tibiofemoral joint. The model suggests that patella alta positions enhance the PTMA in flexed postures while patella baja enhances PTMA in extended postures (Fig. 3). For example, a PTA that moves the patella from average preoperative alta (CD=1.5, z-score=1.7) to average postoperative baja (CD=0.7, z-score=-2.1) was predicted to enhance the patellar tendon moment arm by 26% at a knee angle of 20 degrees. However at an 85-degree knee flexion angle, the same PTA would diminish the moment arm by 21%.

Using radiographic measurements of patella heights and knee flexion angles as inputs, the model predicted an average increase of 17% ($\pm 11\%$) in PTMA as a result of the surgery.

This prediction is slightly higher than the 13% enhancement in PTMA measured directly on the radiographs (Fig. 4).

Predictors of clinical outcomes

Based on postoperative measures of knee flexion during gait, there were 54 and 9 subjects who met our criteria for “Improved” and “Unimproved” outcomes, respectively. Subjects who improved were significantly younger ($p=0.004$) and exhibited greater enhancement ($p<0.0001$) of the patellar moment arm after surgery (Fig. 5, Table 2).

Discussion:

The goal of this work was to investigate the effects of a PTA procedure on patella height, PTMAs and knee flexion in children who exhibit crouch gait. The primary purpose of a PTA is to enhance quadriceps operating lengths in extended postures. Indeed, there was a significant reduction in knee extensor lag following PTA (Table 2), which may enhance extensor strength in extended postures. This study also found that PTA enhances the moment arm of the patellar tendon (+13%) in extended postures, which may contribute to the more extended knee seen in gait postoperatively. Interestingly, a subset of subjects that did not have a reduction in crouch postoperatively also did not exhibit enhanced PTMAs.

Our study confirms the prevalence of patella alta among children with cerebral palsy who exhibit crouch gait. The rate (81%) of patella alta seen in this study is similar to prior observations of Lotman (72%)² and Topoleski et al. (93%)²⁹. Prior modeling studies have found that crouch walking postures can necessitate quadriceps forces up to 4 times higher than that used in unimpaired walking³⁰. Hence, it is likely that excessive loading associated with crouch gait contributes to the prevalence of knee pain and elevated patella heights seen clinically. Pre-operatively, there was a weak monotonic relationship between patella height and minimum knee flexion in gait (Fig. 2). Our model demonstrates how patella alta amplifies the PTMA in flexed knee postures (Fig. 3), such that patella alta likely enhances the knee extensor torque capacity of individuals when walking in crouched postures.

Current guidelines for PTA advance the patella such that the inferior pole is aligned with the tibiofemoral joint line⁴. This placement typically results in patella baja, as seen in 86% of the postoperative knees included in this study (Fig. 2). In baja, the patella is pulled further down into the trochlear groove in an extended knee, which moves the patellar tendon insertion more distal and anterior. As a result, the patellar tendon line of action is moved further from the tibiofemoral flexion axis and enhances its moment arm about the tibiofemoral joint. The magnitude of the moment arm enhancement (+13%) was comparable to our model prediction (+17%), and are also generally consistent with predictions of a planar knee model³¹. There was a significant decrease (-14 ± 20 degrees, $p<0.0001$) in the radiographic knee flexion angle between the pre- and postoperative scans. However at the average patella alta position ($CD=1.5$) seen preoperatively, the model predictions of PTMA were relatively independent of knee angle at the more extended knee postures seen in the radiographs (Fig. 4). Hence, the postoperative increase in PTMA would seem primarily attributable to the surgically induced change in patella height rather than a change in radiographic knee angle.

Postoperatively, we did not observe a relationship between surgically altered patella height and knee flexion during gait (Fig. 2). This result would suggest that the specific amount of patellar tendon advancement (which is uniformly planned to be an overcorrection to baja) did not seem to delineate outcomes. Further, there are potential concerns with excessive baja given that it can compromise moment arms in flexed postures (Fig. 2B). This effect is of concern for patients who exhibit residual crouch, and is also relevant when considering patients' abilities to do tasks required flexed knee postures such as stair climbing and sit-to-stand (Fig. 6).

Crouch gait is increasingly treated with PTA, which is found to generally produce more consistent outcomes than traditional procedures (e.g. hamstring lengthening). An existing outcomes study found significant improvements in knee extension and extensor lag among crouch patients treated via isolated PTA or coupled DFEO+PTA procedures³². Similarly, we found that 86% of the knees treated with DFEO+PTA exhibited knee extension improvements during gait that were either greater than 15 degrees or within normative bounds of typically developing child gait. The source of the improvement seems to be multifactorial as individuals with improved gait also exhibited enhanced PTMA and reductions in knee flexion contracture, extensor lag, patella height and tibial slope.

The primary characteristics that delineated the unimproved subgroup was their older age and lack of postoperative enhancement of PTMA. One possibility for the age effects is that the older children progress through rehabilitation more slowly^{33,34,35}, and thus may not have fully recovered at the average 1.5 year follow-up of this study. Indeed, a prior study of gait disorders treated surgically found that younger ages led to better outcomes at 1 year, but that longer term outcomes (10 years) may favor older patients³⁶. The lack of enhancement in PTMA in the subgroup of unimproved knees is more challenging to understand. PTA procedures are performed in a way that the primary effect is on the patellofemoral joint. Hence, one would generally expect the tibiofemoral joint to remain substantially unaltered by the procedure and the change in the PTMA to be primarily due to effects on the patellofemoral joint. However in this study, both the unimproved and improved group exhibited a significant reduction of patella height (Table 2, Patella Height (CD z-score) = -3.6 ± 1.2), suggesting that changes in the tibiofemoral joint may have offset the potential PTMA enhancement. One possibility is that the altered joint mechanics influence postoperative healing and growth. Indeed, we did see a trend toward a reduction in the posterior tibial slope, suggesting that surgically induced changes in loading may have affected the tibiofemoral joint.

This study has some limitations which must be noted. First is that our analysis is retrospective and only includes one follow-up data collection at an average of 1.5 years. There is some evidence that gait function may change at longer term follow-up³⁵. All of our data comes from one institution, so information about improved outcomes may not generalize to other institutions. Subjects were included if they had bilateral or unilateral procedures and could have had either previous or concurrent surgical procedures. Also, based on our improvement definition, hyperextension is still considered a good outcome, even though this clinical scenario is not ideal. Our musculoskeletal model is scaled to individual subjects, but is based on normative bony geometry. Children with cerebral palsy

have some abnormalities in bony geometry, including elongated patellae and elevated tibial tubercles^{29,37,38}, which were not considered. Finally, we measured patellar tendon moment arms in planar radiographs, which were not necessarily purely in the sagittal plane.

In conclusion, our work demonstrates that the PTA procedure can enhance the lever arm of the knee extensor mechanism, and that this factor may contribute to the generally positive outcomes seen when using PTA to treat crouch gait in children. However, the potential ramifications of patella baja on patellar tendon lever arms in flexed postures should be considered when repositioning the patella.

Acknowledgements:

We gratefully acknowledge the support provided by NIH R21HD084213 and F30AR065838.

References:

1. Wren TA, Rethlefsen S, Kay RM. Prevalence of specific gait abnormalities in children with cerebral palsy: influence of cerebral palsy subtype, age, and previous surgery. *Journal of Pediatric Orthopaedics*. 2005;25(1):79–83.
2. Lotman DB. Knee flexion deformity and patella alta in spastic cerebral palsy. *Developmental Medicine & Child Neurology*. 1976;18(3):315–9.
3. Winters T, Gage J, Hicks R. Gait patterns in spastic hemiplegia in children and young adults. *J Bone Joint Surg Am*. 1987;69(3):437–41. [PubMed: 3818706]
4. Novacheck TF, Stout JL, Gage JR, Schwartz MH. Distal femoral extension osteotomy and patellar tendon advancement to treat persistent crouch gait in cerebral palsy. *J Bone Joint Surg Am*. 2009;91(Supplement 2):271–86.
5. Das SP, Pradhan S, Ganesh S, Sahu PK, Mohanty RN, Das SK. Supracondylar femoral extension osteotomy and patellar tendon advancement in the management of persistent crouch gait in cerebral palsy. *Indian J Orthop*. 2012 3;46(2):221–8. [PubMed: 22448063]
6. Novacheck TF, Stout JL, Gage JR, Schwartz MH. Distal femoral extension osteotomy and patellar tendon advancement to treat persistent crouch gait in cerebral palsy. Surgical technique. *J Bone Joint Surg Am*. 2009 10 1;91 Suppl 2:271–86. [PubMed: 19805590]
7. Chandler F Re-establishment of normal leverage of the patella in knee flexion deformity in spastic paralysis. *Surg Gynecol Obstet*. 1933;57:523–7.
8. Stout JL, Gage JR, Schwartz MH, Novacheck TF. Distal femoral extension osteotomy and patellar tendon advancement to treat persistent crouch gait in cerebral palsy. *J Bone Joint Surg Am*. 2008;90(11):2470–84. [PubMed: 18984722]
9. Stout J, Beimesch C, Varghese R, Schwartz M, Novacheck T. Long-term effects of patellar tendon advancement on patella height and proximal tibial growth. *Gait & Posture*. 2015;42:S2.
10. Seidl A, Baldini T, Krughoff K, Shapiro JA, Lindeque B, Rhodes J, et al. Biomechanical Assessment of Patellar Advancement Procedures for Patella Alta. *Orthopedics*. 2016;39(3):e492–e7. [PubMed: 27135457]
11. Lenhart RL, Smith CR, Novacheck T, Schwartz MH, Thelen DG. Influence of patellar position on the knee extensor mechanism in normal and crouched walking. *Journal of Biomechanics*. 2017;51:1–7. [PubMed: 27939752]
12. Schwartz MH, Rozumalski A, Trost JP. The effect of walking speed on the gait of typically developing children. *Journal of Biomechanics*. 2008; 41(8):1639–50. [PubMed: 18466909]
13. Caton J, Deschamps G, Chambat P, Lerat J, Dejour H. [Patella inféra. Apropos of 128 cases]. *Revue de chirurgie orthopédique et réparatrice de l'appareil moteur*. 1981;68(5):317–25.
14. Koshino T, Sugimoto K. New measurement of patellar height in the knees of children using the epiphyseal line midpoint. *Journal of Pediatric Orthopaedics*. 1989;9(2):216–8. [PubMed: 2925858]

15. Aparicio G, Abril J, Albinana J, Rodriguez-Salvanes F. Patellar height ratios in children: an interobserver study of three methods. *J Pediatr Orthop B*. 1999;8(1):29–32.
16. Park MS, Chung CY, Lee KM, Lee SH, Choi IH. Which is the best method to determine the patellar height in children and adolescents? *Clinical Orthopaedics and Related Research*. 2010;468(5):1344–51. [PubMed: 19629604]
17. Thévenin-Lemoine C, Ferrand M, Courvoisier A, Damsin J-P, le Pointe HD, Vialle R. Is the Caton-Deschamps index a valuable ratio to investigate patellar height in children? *The Journal of Bone & Joint Surgery*. 2011;93(8):e35. [PubMed: 21508270]
18. Anagnostakos K, Lorbach O, Reiter S, Kohn D. Comparison of five patellar height measurement methods in 90 knee flexion. *International orthopaedics*. 2011;35(12):1791–7. [PubMed: 21416109]
19. O'Brien TD, Reeves ND, Baltzopoulos V, Jones DA, Maganaris CN. Moment arms of the knee extensor mechanism in children and adults. *Journal of Anatomy*. 2009;215(2):198–205. [PubMed: 19493189]
20. Shabshin N, Schweitzer ME, Morrison WB, Parker L. MRI criteria for patella alta and baja. *Skeletal Radiology*. 2004;33(8):445–50. [PubMed: 15221214]
21. Insall J, Salvati E. Patella Position in the Normal Knee Joint 1. *Radiology*. 1971;101(1):101–4. [PubMed: 5111961]
22. Sheehan FT. The 3D patellar tendon moment arm: quantified in vivo during volitional activity. *Journal of Biomechanics*. 2007;40(9): 1968–74. [PubMed: 17161841]
23. Pathanacharoenphon C, Maples DL, Saad C, Forness MJ, Halanski MA. The effects of patellar tendon advancement on the immature proximal tibia. *Journal of Children's Orthopaedics*. 2013;7(2):139–46.
24. Lenhart RL, Kaiser J, Smith CR. Prediction and validation of load-dependent behavior of the tibiofemoral and patellofemoral joints during movement. *Annals of Biomedical Engineering*. 2015;43(11):2675–85. [PubMed: 25917122]
25. Blankevoort L, Huijskes R. Ligament-bone interaction in a three-dimensional model of the knee. *Journal of Biomechanical Engineering*. 1991;113(3):263–9. [PubMed: 1921352]
26. Bei Y, Fregly BJ. Multibody dynamic simulation of knee contact mechanics. *Medical Engineering & Physics*. 2004;26(9):777–89. [PubMed: 15564115]
27. Arnold EM, Ward SR, Lieber RL, Delp SL. A model of the lower limb for analysis of human movement. *Annals of Biomedical Engineering*. 2010;38(2):269–79. [PubMed: 19957039]
28. Delp SL, Anderson FC, Arnold AS, Loan P, Habib A, John CT, et al. OpenSim: open-source software to create and analyze dynamic simulations of movement. *IEEE transactions on Biomedical Engineering*. 2007;54(11): 1940–50.
29. Topoleski TA, Kurtz CA, Grogan DP. Radiographic abnormalities and clinical symptoms associated with patella alta in ambulatory children with cerebral palsy. *Journal of Pediatric Orthopaedics*. 2000;20(5):636–9. [PubMed: 11008744]
30. Steele KM, DeMers MS, Schwartz MH, Delp SL. Compressive tibiofemoral force during crouch gait. *Gait & Posture*. 2012;35(4):556–60. [PubMed: 22206783]
31. Yamaguchi GT, Zajac FE. A planar model of the knee joint to characterize the knee extensor mechanism. *Journal of Biomechanics*. 1989;22(1):1–10. [PubMed: 2914967]
32. Stout JL, Gage JR, Schwartz MH, Novacheck TF. Distal femoral extension osteotomy and patellar tendon advancement to treat persistent crouch gait in cerebral palsy. *J Bone Joint Surg Am*. 2008 11;90(11):2470–84. [PubMed: 18978417]
33. Bottos M, Feliciangeli A, Sciuto L, Gericke C, Vianello A. Functional status of adults with cerebral palsy and implications for treatment of children. *Developmental Medicine & Child Neurology*. 2001;43(08):516–28.
34. Pimm P Cerebral palsy: “A non-progressive disorder”? *Educational and Child Psychology*. 1992.
35. Sung KH, Chung CY, Lee KM, Akhmedov B, Lee SY, Choi IH, et al. Long term outcome of single event multilevel surgery in spastic diplegia with flexed knee gait. *Gait & Posture*. 2013;37(4):536–41. [PubMed: 23041270]
36. SVEHLÎK M, Steinwender G, Kraus T, Saraph V, Lehmann T, Linhart WE, et al. The influence of age at single-event multilevel surgery on outcome in children with cerebral palsy who walk with

flexed knee gait. *Developmental Medicine & Child Neurology*. 2011;53(8):730–5. [PubMed: 21711455]

37. Robin J, Graham HK, Selber P, Dobson F, Smith K, Baker R. Proximal femoral geometry in cerebral palsy. *Bone & Joint Journal*. 2008;90(10):1372–9.
38. Binkley T, Johnson J, Vogel L, Kecskemethy H, Henderson R, Specker B. Bone measurements by peripheral quantitative computed tomography (pQCT) in children with cerebral palsy. *The Journal of Pediatrics*. 2005;147(6):791–6. [PubMed: 16356433]

Figure 1: Patella height (*CD*) and patellar tendon moment arms (*PTMA*) are measured pre- and postoperatively from lateral radiographs. Subject-specific measurements of patella height and knee flexion angle (*KneeFlex*) are used together with a model to predict the change in *PTMA*s following surgery. Radiographs from a representative patient that underwent the DFEO+PTA procedure are shown.

Figure 2:

A) Patella height, here measured by the CD Index, is predominately in alta preoperatively and baja postoperatively. Patella height was weakly correlated to crouch severity (measured by minimum knee flexion angle during stance) preoperatively. Shaded region represents normal patella heights. B) PTMAs are enhanced in gait when moving from alta (CD z-score > 1) to baja (CD z-score < 1). The average and standard deviation of patella height and mean flexion angle in stance are shown for subjects that underwent the DFEO+PTA procedure and from a healthy pediatric control group. Horizontal error bars represent the standard deviation for Knee Flexion and vertical error bars represent the standard deviation for patella height.

Figure 3:

A) Simulation of PTA procedure by advancing the patellar tendon insertion point distally on the tibia from alta to baja. B) Model shows that PTMA is largest in extended postures when in baja and in alta for flexed postures. Patella heights (measured by CD index z-score) reflect the range of values (both preoperatively and postoperatively) seen in patients undergoing the DFEO+PTA procedure, where alta is > 1 , normal is 0, and baja is < -1 . Patellar tendon moment arms were calculated for each patella height across the passive knee flexion cycle.

Figure 4:

The percent change in patellar tendon moment arms (PTMA), measured from radiographs is compared to the predicted change in patellar tendon moments arms calculated for each subject past on their patella height (CD) and knee flexion angle (*KneeFlex*). Error bars represent the standard deviation.

Figure 5:

Factors delineating surgical outcomes include **A)** Age at surgery, **B)** Change in knee flexion contracture, and **C)** Percent change in PTMA. Each data point represents one knee. The top and bottom of each “box” represent the 25th and 7th percentile of the samples, the whisker lines are drawn to the furthest observations.

Figure 6:

Implications of patella height at knee flexion angles for various functional tasks. A) Bar graphs show the % change in PTMA from patella alta to normal and baja for 0°, 45°, and 85° of knee flexion. B) Model representations of patella position across various amounts of knee flexion. C) Range of knee flexion angles at peak loading for functional tasks.

Table 1:

Subject characteristics based on crouch severity where n represents the number of knees in each group (crouch severity is defined by the minimum knee flexion in stance). Values represent the mean $\pm$ 1 standard deviation, all values are in degrees unless noted.

	Preoperative						Postoperative					
	Age (years)	Min. knee flexion in stance	Mean knee flexion in stance	Radiographic Knee Angle	Knee flexion con- tracture	Knee extensor lag	Min. knee flexion in stance	Mean knee flexion in stance	Radiographic Knee Angle	Knee flexion con- tracture	Knee extensor lag	
Mild (n=15)	13.6±3	24±7	36±11	14±14	7±8	7±8	12±7	20±7	5±7	-1±4	3±4	
Moderate (n=27)	13.4±2	43±4	49±6	17±19	15±8	11±11	9±10	18±9	2±8	-1±6	4±7	
Severe (n=21)	13.8±3	59±10	64±13	29±27	19±12	22±19	25±18	33±15	10±13	2±11	9±8	

Table 2:

Mean ($\pm 95\%$ CI) changes in select knee geometry and function metrics between pre- and postoperative evaluations for all knees (Column 2), the Improved Group (Column 4), and the Unimproved Group (Column 5). Improvements in gait were related to age and post-surgical changes in contractures and PTMA. A negative change indicates a decrease from the original value.

Metric	All Knees (n=63)	<i>p</i>	Improved Group (n=54)	Unimproved Group (n=9)	<i>p</i>
Age at surgery (years)	13.7 $\pm$ 3	--	13.2 $\pm$ 2	16.5 $\pm$ 5	0.004
Radiographic Knee Flexion (deg)	-14 $\pm$ 20	<0.0001	-12 $\pm$ 8	-20 $\pm$ 11	0.08
Knee Flexion Contracture (deg)	-15 $\pm$ 12	<0.0001	-16 $\pm$ 12	-5.6 $\pm$ 11	<0.0001
Extensor Lag (deg)	-9 $\pm$ 14	<0.0001	-7.7 $\pm$ 14	-13 $\pm$ 17	0.4
Patella Height (CD z-score)	-3.6 $\pm$ 1.2	<0.0001	-3.7 $\pm$ 1.2	-3.1 $\pm$ 1.2	0.6
PTMA (% change)	13 $\pm$ 19	0.0055	16 $\pm$ 18	-8 $\pm$ 12	<0.0001
Tibial Slope (deg)	-2 $\pm$ 4	<0.0001	-1.4 $\pm$ 4	-5.1 $\pm$ 5	0.2