ISB 2013 BRAZIL
XXIV CONGRESS OF THE INTERNATIONAL SOCIETY OF BIOMECHANICS
XV BRAZILIAN CONGRESS OF BIOMECHANICS

OPTIMAL PATELLAR TENDON LENGTH IS GREATER FOR CROUCHED WALKING POSTURES

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INTRODUCTION

Patella alta is a common morbidity seen in children with crouch gait, a walking disorder characterized by excessive knee flexion in stance. It is generally believed that the superiorly tracking patella occurs as a result of spasticity and the larger quadriceps loads needed to ambulate in a crouch posture. While many have cited patella alta as representing extensor dysfunction [1], one imaging study found that children with patella alta may exhibit enhanced patellar tendon moment arms at flexed knee postures [2]. Another study of healthy adults with patella alta showed them to have quadriceps effective moment arms larger than controls [3]. These findings suggest that it could be preferential for children with crouch gait to have a superiorly tracking patella, such that it enhances knee extensor function in flexed postures. Additionally, clinical outcomes following surgical treatment of crouch are enhanced by correction of patellar position [4], further implying a link between patellar locations and walking posture. The goal of this study was to test the hypothesis that patella alta optimizes knee extensor function for an individual walking in a crouch posture. To do this, we used computational modeling and numerical optimization to compare patellar tendon lengths that act to minimize quadriceps and patellar tendon loading during the stance phase of normal and crouch gait of varying severity.

METHODS

Four different walking postures were considered: healthy adult gait, and mild, moderate, and severe crouch gait. Levels of crouch were defined based on minimum knee flexion angle during stance: mild (15-30 degrees), moderate (30-50 degrees), and severe (50+ degrees). For the crouch conditions, we selected our gait analysis data sets that match these conditions from a database of children tested at Gillette Children's Hospital. All subjects were between the ages of 9 and 16, with the crouch gait data collected on patients who were being evaluated prior to orthopedic treatment. The data were collected under the auspices of an IRB approved protocol. For each subject, whole body kinematics and kinetics were collected during a static standing posture and during overground walking.

Biomechanical analysis was performed using a 3D lower extremity model with 44 musculotendon units crossing the hip, knee, and ankle [5]. The nominal model was altered to include a 1 degree-of-freedom patellofemoral joint, in which the patella translated in a fixed path relative to the femur. The position of the patella along this path was a function of knee flexion angle and the patellar tendon length (Fig. 1).

For each subject, we first scaled the model to marker positions recorded in a static standing trial. Inverse kinematics analysis was then used to determine the lower extremity joint angles across a representative gait cycle. The patella position was computed at each time step assuming the patellar tendon was inextensible. Muscle and patellar tendon forces were then computed that generated the current joint accelerations while minimizing the muscle volume-weighted sum of squared normalized forces. Quadriceps muscle and patellar tendon forces at peak stance phase knee flexion angle were extracted, and normalized to values of those forces determined when simulating a nominal patellar tendon length.

A numerical optimization (golden section optimization algorithm [6]) was then used to determine a patellar tendon length that minimized a cost function J

$$J = w_{PT}F_{PT} + w_Q F_Q \ , \qquad where\ w_{PT} = 1 - w_Q$$

representing the weighted sum of normalized patellar tendon (F_{PT}) and quadriceps forces (F_Q) [7]. Quadriceps force was represented as the numerical sum of the three vastii and rectus femoris muscles included in the model. The weighting factors (w_{PT}, w_Q) were varied to determine sensitivity of the optimization to these parameters. Because of the different heights of the subjects, optimal patellar tendon lengths were scaled to the normal adult gait by multiplying by the ratio of patellar tendon slack lengths.

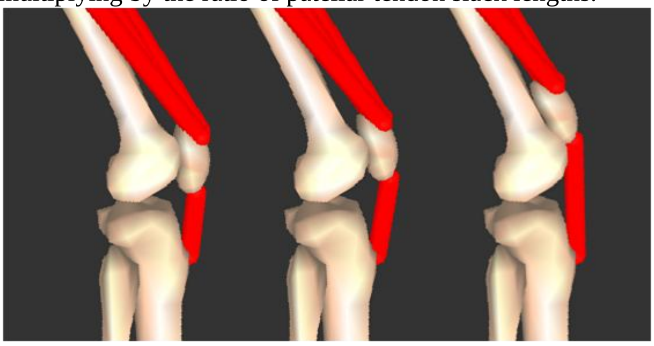

Figure 1: Depiction of model with various patellar tendon lengths at 30 degrees of knee flexion.

RESULTS AND DISCUSSION

Figure 2 shows an example of cost function results for the healthy adult walking simulations with various patellar tendon lengths. The function was evaluated with different weighting factors put on the patellar tendon and quadriceps forces. The cost function is much steeper, and reaches a lower value at its minimum when dependent on quadriceps force compared to patellar tendon force. The minimum of the cost function occurs at a longer patellar tendon length when the weighting factor of the quadriceps force is larger.

The optimization results clearly show the strong dependence of patellar tendon and quadriceps loading on patellar position for the different walking postures (Fig. 3). In normal gait, optimal patellar tendon length varied between 5.2 cm and 6.1 cm which are just slightly greater than the 5.0 cm patellar tendon assumed by the nominal lower extremity model. However in crouched postures, optimal patellar tendon lengths elongate reaching values of 7.2-8.7 cm in the most severe crouch gait (83 deg minimum stance phase knee flexion angle) considered. Regardless of crouch severity, increased weighting of the quadriceps force tended to result in longer optimal patellar tendon lengths.

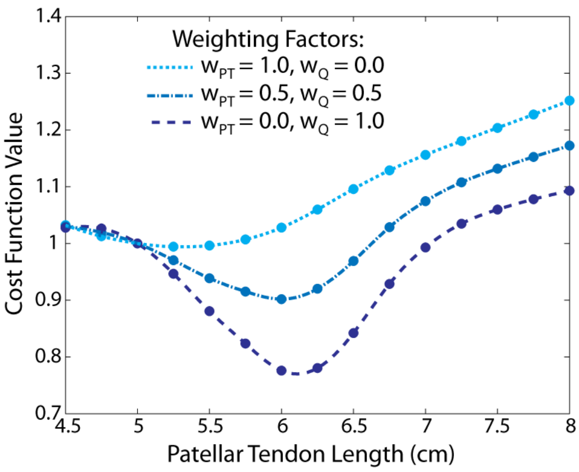

Figure 2: Cost function evaluation for different patellar tendon lengths for healthy adult walking. Values of patellar tendon and quadriceps force were normalized based on the values determined when simulating with a 5 cm patellar tendon.

CONCLUSIONS

The results suggest that the patellar tendon may be of a length that minimizes forces on the quadriceps and patellar tendon during normal walking. Further, it seems that children walking in crouch may benefit from a superior tracking patella, as it reduces these loads by enhancing quadriceps and patellar tendon moment arms in flexed postures. Perhaps increasing patella alta in crouch represents an adaptation to increasing crouch, allowing for continued ambulation even in the compromised posture. These findings also imply that when surgically treating crouch, the patellar position should also be corrected to attain an optimal configuration for the desired walking posture. This may begin to explain the enhanced clinical outcomes when the patella is lowered concurrently with procedures correcting knee flexion contractures [4]. Future studies will look into how well the optimization prediction of patellar tendon length matches the patellar tendon length of individual patients.

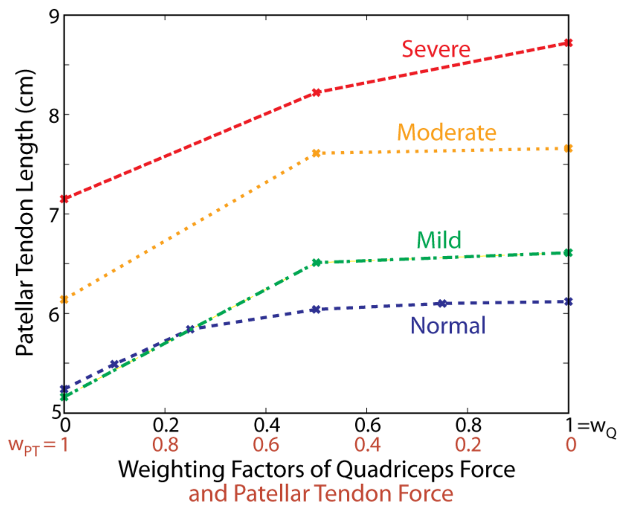

Figure 3: Optimal patellar tendon length found with different weighting factors put on the patellar tendon and quadriceps force during weighted sum optimization. Results are presented for normal gait and different degrees of crouch (mild, moderate, and severe).

ACKNOWLEDGEMENTS

The authors would like to thank Drs. Matthew Halanski MD, Tom Novacheck MD, Krishnan Suresh PhD, the UW Medical Scientist Training Program, the UW Institute for Clinical and Translational Research, and the Burroughs Wellcome Fund.

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