Can biomechanical variables predict improvement in crouch gait?

Jennifer L. Hicks a,b,*, Scott L. Delp a,b, Michael H. Schwartz c,d

a Department of Orthopaedic Surgery, University of Minnesota, Minneapolis, MN, USA
b Center for Gait and Motion Analysis, Gillette Children’s Specialty Healthcare, St. Paul, MN, USA
c Department of Bioengineering, Stanford University, Stanford, CA, USA
d Department of Mechanical Engineering, Stanford University, Stanford, CA, USA

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ABSTRACT

Many patients respond positively to treatments for crouch gait, yet surgical outcomes are inconsistent and unpredictable. In this study, we developed a multivariable regression model to determine if biomechanical variables and other subject characteristics measured during a physical exam and gait analysis can predict which subjects with crouch gait will demonstrate improved knee kinematics on a follow-up gait analysis. We formulated the model and tested its performance retrospectively analyzing 353 limbs of subjects who walked with crouch gait. The regression model was able to predict which subjects would demonstrate ‘Improved’ and ‘Unimproved’ knee kinematics with over 70% accuracy, and was able to explain approximately 49% of the variance in subjects’ change in knee flexion between gait analyses. We found that improvement in stance phase knee flexion was positively associated with three variables that were drawn from knowledge about the biomechanical contributors to crouch gait: (i) adequate hamstrings lengths and velocities, possibly achieved via hamstrings lengthening surgery, (ii) normal tibial torsion, possibly achieved via tibial derotation osteotomy, and (iii) sufficient muscle strength.

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1. Introduction

Crouch gait, a walking pattern defined by excessive flexion of the knee during stance phase, is a debilitating problem that affects the population of children with spastic cerebral palsy. Many patients benefit from treatments for crouch gait, including hamstrings lengthening surgeries [1–4], tibial derotation osteotomies [5–7], and multi-level surgery [8,9]; however, treatment outcomes are unpredictable.

Clinical decision-making is challenging, in part because there are no standardized protocols for determining which surgeries a patient should receive. Three-dimensional gait analysis helps clinicians identify which gait abnormalities should be targeted with treatment [10–12], but there are no uniform guidelines for interpreting the wealth of information provided by gait analysis. For example, two clinical teams might examine the same set of patient data and develop two different treatment plans [13].

Several studies have utilized biomechanical modeling and simulation of the musculoskeletal system to objectively identify the contributors to an individual’s crouch gait. For example, the work of Arnold and colleagues [14,15] suggests that a subject’s hamstrings lengths and velocities during gait may provide information to more effectively prescribe hamstrings surgery. Several investigations have demonstrated that excessive tibial torsion reduces the capacity of muscles to extend the knee [16–18], suggesting that subjects with crouch gait and excess tibial torsion may benefit from a tibial derotation osteotomy. Sufficient strength of the extensor muscles may also be a key component in achieving normal knee motion. Analyzing the dynamics of normal and crouch gait has demonstrated that the gluteal muscles, plantarflexors, and vasti play a crucial role in extending the knee during stance [18–20].

These biomechanical modeling studies have examined individual mechanical contributors to excess knee flexion for small, specialized groups of subjects, yet a typical patient has many possible contributors to his or her crouch gait. Further, there may be other variables, such as the severity of a subject’s gait pathology or the presence of concomitant gait abnormalities, that affect how crouch gait progresses over time.

To improve clinical decision-making and address the limitations of past biomechanics research, we developed and tested a multivariable linear regression model that used biomechanical variables to predict subjects’ improvement in crouch gait. We retrospectively analyzed subjects with moderate to severe crouch gait to determine if data from a subject’s initial visit to the gait analysis laboratory could predict the change in the subject’s knee
kinematics measured on a follow-up gait analysis. We hypothesized that i) adequate hamstrings lengths and velocities, ii) good torsional alignment of the tibia, and iii) sufficient muscle strength would all help predict whether subjects’ knee flexion in stance would improve on the follow-up gait analysis.

2. Methods

We retrospectively analyzed a group of subjects with a primary diagnosis of cerebral palsy, aged 5–18, who had at least two visits to a gait analysis laboratory, with or without intervening treatment, as part of routine care. We studied subjects who walked with a crouch gait [14] at their first gait analysis and had a mean knee flexion angle during the first half of the gait cycle larger than 25°. We examined only subjects who walked barefoot and without assistive devices during gait analysis. We allowed any combination of bony surgery, soft tissue surgery, botox injections, or no treatment between gait analyses, but excluded subjects who received a selective dorsal rhizotomy or intrathecal baclofen pump between gait analyses, since this study focused on the biomechanical contributors to excess knee flexion. A histogram of intervening surgeries for all subjects is included in Supplementary material. Any type of prior surgery was allowed, but we excluded subjects who had botox injections less than 6 months prior or lower extremity surgery or other neurological treatment less than 12 months prior to the first gait analysis. We required that pairs of gait analyses for a subject were between 9 and 36 months apart. If a subject received surgery between gait analyses, we required that the second analysis be at least 9 months after the surgery to ensure sufficient recovery time.

The Gillette database contained 2300 subjects with a diagnosis of cerebral palsy and available gait kinematics. Our subject selection criteria resulted in a group comprised of 212 subjects and 353 pairs of gait analyses. We analyzed a subject’s right and left sides if both met our selection criteria. We also included more than one pair of gait analyses for a subject if all analyses occurred on different days. In other words, a second visit gait analysis for a subject could not also be used as a first visit gait analysis for the same subject. The individual data points we used to build the regression model were pairs of gait analyses for a subject-side, which we refer to as “limbs”.

Using this set of data, we built a multivariable linear regression model. The general form of the model is:

\[ y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \cdots + \beta_n x_n \]

To assess crouch severity, we calculated the mean stance knee flexion for each limb, between 0% and 50% of the gait cycle (Fig. 1). The outcome variable, Y, was then the change in mean stance knee flexion between the first and second gait analyses, such that a positive value corresponds with improvement in crouch gait. The \( x_i \) are the predictive variables, derived from the first gait analysis, intervening treatment, and prior treatment, used to estimate the expected improvement in crouch gait on the second analysis. The \( \beta_i \) are the linear weighting coefficients for the predictive variables. The interaction terms (\( \beta_i \)) allow for the causal effect of one predictor (\( x_i \)) on the outcome Y to vary according to another predictor (\( x_j \)). The regression model was formulated using Stata (StataCorp, College Station, TX).

**Fig. 1.** Knee flexion kinematics at the initial gait analysis. The black solid curve and dashed curves show the mean knee flexion angle over the gait cycle ±2 SD for the entire group of limbs. The gray lines show the first-visit knee flexion kinematics for each limb analyzed in this study. The black box highlights the portion of the knee flexion curve used to derive the mean stance knee flexion measure, our metric to assess improvement in crouch gait.
3. Results

The multivariable linear regression model was able to predict whether a limb’s mean stance knee flexion was ‘Improved’ or ‘Unimproved’ on the second gait analysis with 73% accuracy. The overall performance of the model is displayed in Fig. 2, which plots the change in knee flexion predicted by the regression model for each limb vs. the observed change between gait analyses. The regression model correctly classified 119 limbs as ‘Improved’ and 139 limbs as ‘Unimproved’. There were 44 limbs incorrectly classified as ‘Improved’ and 51 limbs incorrectly classified as ‘Unimproved’. The $R^2$ value of the fit was 0.49, which indicates that the model was able to explain 49% of the variance in improvement in knee flexion.

When we used 10-fold cross-validation to estimate the ability of the regression model to make predictions for a new group of subjects, there was a slight decrease in accuracy, with 71% of limbs correctly classified on average across the 10 cross-validation folds. The average $R^2$ value computed with cross-validation was 0.44.

Examining the coefficients of the variables in the regression model allows us to assess their individual impact on improvement in knee flexion, when holding the other variables in the model constant (Table 2). There was a significant positive relationship between muscle strength and improvement in stance phase knee flexion, with an expected 1.3° more improvement in knee flexion for each one point increase in strength score. Further, limbs with ‘Good’ hamstrings function and ‘Good’ tibial torsion were expected to have 7.5° more improvement in knee flexion than limbs with ‘Poor’ hamstrings function and tibial torsion.

For each 1° increase in mean stance knee flexion on the initial gait analysis, there was an increase in expected improvement of 0.9°. In contrast, having more severe crouch on the contralateral side was associated with less improvement. More severe involvement, as indicated by cerebral palsy sub-type (triplegic or quadriplegic), was associated with more improvement, while a slower knee flexion velocity at toe-off, a prior tendo-achilles lengthening, and multiple qualifying pairs of gait analyses were associated with less expected improvement. Limbs with a smaller gait deviation index, more equinus, and more anterior pelvic tilt tended to show less improvement in knee flexion, but these relationships were not significant. The receipt of a patellar tendon advancement/distal femoral extension osteotomy or a femoral derotation osteotomy was also associated with significantly more improvement in knee flexion.

4. Discussion

The multivariable linear regression model was able to predict, with 73% accuracy, whether subjects with crouch gait would be ‘Improved’ or ‘Unimproved’ on their second gait analysis using biomechanical variables and other subject characteristics. In contrast, only 48% of the limbs had ‘Improved’ knee flexion on their second gait analysis with 73% accuracy. The reasons for this discrepancy include the presence of confounding variables and the complexity of gait analysis.

In conclusion, the multivariable linear regression model provides a useful tool for predicting improvement in knee flexion, allowing for more informed treatment decisions. Further research is needed to explore the impact of additional variables and to validate the model in different populations.

Table 2

<table>
<thead>
<tr>
<th>First-Visit Variable</th>
<th>Coefficient</th>
<th>Normalized coefficient</th>
<th>Robust standard error&lt;sup&gt;a&lt;/sup&gt;</th>
<th>p-Value&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>GoodHams (1/0)</td>
<td>6.62</td>
<td>1.88</td>
<td>3.28</td>
<td>0.045</td>
</tr>
<tr>
<td>GoodTibia (1/0)</td>
<td>6.18</td>
<td>1.00</td>
<td>3.03</td>
<td>0.043</td>
</tr>
<tr>
<td>GoodHams and GoodTibia (1/0)</td>
<td>7.52</td>
<td>1.18</td>
<td>3.39</td>
<td>0.016</td>
</tr>
<tr>
<td>Strength score [24]</td>
<td>1.28</td>
<td>1.00</td>
<td>0.604</td>
<td>0.035</td>
</tr>
<tr>
<td>Ipsilateral mean stance knee flexion (°)</td>
<td>0.888</td>
<td>1.00</td>
<td>0.108</td>
<td>0.001</td>
</tr>
<tr>
<td>Contra lateral mean stance knee flexion (°)</td>
<td>-0.235</td>
<td>-3.35</td>
<td>0.0639</td>
<td>0.001</td>
</tr>
<tr>
<td>Gait deviation index [29]</td>
<td>-0.136</td>
<td>-1.43</td>
<td>0.105</td>
<td>0.194</td>
</tr>
<tr>
<td>Mean pelvic tilt (°)</td>
<td>-0.213</td>
<td>-1.57</td>
<td>0.127</td>
<td>0.094</td>
</tr>
<tr>
<td>Knee Flex vel at toe-off (% gait cycle)</td>
<td>2.54</td>
<td>2.48</td>
<td>0.923</td>
<td>0.006</td>
</tr>
<tr>
<td>Mean st anus ankle dorsiflexion (°)</td>
<td>0.137</td>
<td>1.88</td>
<td>0.0615</td>
<td>0.027</td>
</tr>
<tr>
<td>Prior Tendo-achilles lengthening (1/0)</td>
<td>-3.04</td>
<td>-1.88</td>
<td>1.67</td>
<td>0.069</td>
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<tr>
<td>Intervening patellar advance/femoral extension osteotomy (1/0)</td>
<td>9.36</td>
<td>2.18</td>
<td>2.18</td>
<td>0.001</td>
</tr>
<tr>
<td>Intervening femoral derotation osteotomy (1/0)</td>
<td>3.87</td>
<td>1.62</td>
<td>1.62</td>
<td>0.018</td>
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<tr>
<td>Triplicegic subtype (1/0)</td>
<td>5.36</td>
<td>2.05</td>
<td>2.05</td>
<td>0.010</td>
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<tr>
<td>Quadriplegic subtype (1/0)</td>
<td>6.11</td>
<td>2.20</td>
<td>2.20</td>
<td>0.006</td>
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<tr>
<td>Multiple qualifying visit pairs (1/0)</td>
<td>8.1</td>
<td>1.81</td>
<td>1.81</td>
<td>0.003</td>
</tr>
<tr>
<td>Constant</td>
<td>-18.7</td>
<td>-7.4</td>
<td>10.1</td>
<td>0.066</td>
</tr>
</tbody>
</table>

<sup>a</sup> Robust standard errors, adjusted for the correlation between limbs from the same subject.
<sup>b</sup> p-Value from a Student’s t-test.
their second gait analysis. This suggests that there are some patients not receiving surgeries that might improve their crouch gait and other patients receiving treatment despite a low probability for improvement. Use of the regression model may avoid this in some cases.

Each of the biomechanical variables – adequate hamstrings lengths and velocities, normal tibial torsion, and muscle strength – was associated with improvement in knee flexion, which lends support to using gait analysis and biomechanical modeling to understand gait pathology and plan treatment. We did not see a large difference between having both ‘Good’ hamstrings function and tibial torsion and having a ‘Good’ value for only one of these variables. Subjects may be able to compensate for one of their biomechanical contributors to crouch gait or there may be diminishing returns for surgically correcting both contributors. Given the positive relationship between muscle strength and improvement in crouch gait, we suggest future research on the benefits of pre-operative strength training. Our finding that prior tendo-achilles surgery is associated with less improvement in crouch gait supports earlier investigations that indicate a tendo-achilles lengthening increases the risk of developing crouch gait [27,28].

Receiving a femoral derotation osteotomy or patellar tendon advancement/distal femoral extension osteotomy was associated with significant improvement in crouch gait. The observed effect corresponds to the amount of improvement expected when these surgeries are prescribed using standard practice at Gillette. Future research should elucidate and test biomechanical guidelines for these procedures. Patients with crouch gait also frequently receive foot stabilization surgeries and gastrocnemius lengthenings, but the variables associated with these surgeries were not retained in crouch gait. We cautioned that further, prospective testing is needed to validate this approach may not fully correct for the lack of independence in the other gait and physical exam measures. In addition, we were unable to account for motor control, patient motivation, variability in surgical technique, compliance with post-operative rehabilitation, and potential recurrence of hamstrings tightness or tibial mal-alignment.

In this study, we built and tested the first statistical model of its kind to predict improvement in crouch gait using knowledge about the biomechanical contributors to excess knee flexion. This statistical model can help improve treatment outcomes by identifying good candidates for common surgeries performed on

<table>
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<th>Table 3</th>
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</thead>
<tbody>
<tr>
<td>Predictive data and predictions for a hypothetical subject with crouch gait subject has excess tibial torsion and short and slow hamstrings at his first gait visit.</td>
</tr>
<tr>
<td><strong>First-visit variable</strong></td>
</tr>
<tr>
<td>Strength score [24]</td>
</tr>
<tr>
<td>Ipsilateral mean stance knee flexion (°)</td>
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<td>Mean stance ankle dorsiflexion (°)</td>
</tr>
<tr>
<td>Prior tendo-achilles lengthening (1/0)</td>
</tr>
<tr>
<td>Planned patellar advance/femoral extension osteotomy (1/0)</td>
</tr>
<tr>
<td>Planned femoral derotation osteotomy (1/0)</td>
</tr>
<tr>
<td>Triplicegic subtype (1/0)</td>
</tr>
<tr>
<td>Quadruplegic subtype (1/0)</td>
</tr>
<tr>
<td>Multiple qualifying visit pairs (1/0)</td>
</tr>
<tr>
<td>Constant</td>
</tr>
<tr>
<td>Expected improvement without hamstrings lengthening or TDO</td>
</tr>
<tr>
<td>Expected improvement with hamstrings lengthening and/or TDO</td>
</tr>
</tbody>
</table>

* The clinical team has decided to perform a femoral derotation osteotomy for this hypothetical subject, but not a patellar advance.

* This is the first time the patient has visited the gait lab exhibiting a moderate crouch gait pattern.

Interpretation of the regression model must be undertaken with caution. For new subjects, cross-validation estimated that the model would explain only 44% of the variance in our outcome measure. Additionally, while we adjusted the standard errors to account for the correlation between limbs from the same subject, this approach may not fully correct for the lack of independence in our subject pool, inflating the cross-validation prediction accuracy. The p-values reported for the regression coefficients may be too small, since backwards selection was used to formulate the reduced model and no standard technique is available to correct for the multiple statistical comparisons used in backwards selection.

We did not penalize subjects for receiving an ‘unnecessary’ hamstrings lengthening or tibial derotation osteotomy. Receiving an ‘unnecessary’ hamstrings lengthening can have a detrimental effect on pelvic motion, but a similar negative effect on knee kinematics has not been demonstrated [15]. Since surgeons adjust the amount of correction to the severity of a subject’s tibial deformity, we did not expect a tibial derotation osteotomy to have a detrimental effect on knee kinematics in subjects whose pre-operative tibial torsion was within our defined “normal” range.

We were only able to explain 49% of the variance in subjects’ improvement in knee flexion because there were many factors that we could not measure accurately or at all. For example, manual strength measures are an approximate assessment of a subject’s muscle strength and the thigh foot angle is an approximation of a subject’s tibial torsion angle [30]. There may have also been errors in the other gait and physical exam measures. In addition, we were unable to account for motor control, patient motivation, variability in surgical technique, compliance with post-operative rehabilitation, and potential recurrence of hamstrings tightness or tibial mal-alignment.

In this study, we built and tested the first statistical model of its kind to predict improvement in crouch gait using knowledge about the biomechanical contributors to excess knee flexion. This statistical model can help improve treatment outcomes by identifying good candidates for common surgeries performed on
subjects with crouch gait, in particular hamstring lengthenings and tibial derotation osteotomies. The methods used to build the regression model in this study could be used to develop similar predictive models for other patient populations and gait pathologies. For example, we are currently investigating a linear regression model to predict improvement in overall gait kinematics after multi-level surgery. As demonstrated here, retrospective statistical analysis of patient data and biomechanical modeling are powerful and complementary tools to improve the treatment of movement disorders and make outcomes more predictable.

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Conflict of interest statement

The authors declare that they have no competing interests.

Appendix A. Supplementary data


References