Estimates of Gastrocnemius Muscle Length During Simulated Pathological Gait

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The purpose of this study was to compare estimates of gastrocnemius muscle length (GML) obtained using a segmented versus straight-line model in children. Kinematic data were acquired on eleven typically developing children as they walked under the following conditions: normal gait, crouch gait, equinus gait, and crouch with equinus gait. Maximum and minimum GML, and GML change were calculated using two models: straight-line and segmented. A two-way RMANOVA was used to compare GML characteristics. Results indicated that maximum GML and GML change during simulated pathological gait patterns were influenced by model used to calculate gastrocnemius muscle length (interaction: $P = .004$ and $P = .026$). Maximum GML was lower in the simulated gait patterns compared with normal gait ($P < .001$). Maximum GML was higher with the segmented model compared with the straight-line model ($P = .030$). Using either model, GML change in equinus gait and crouch with equinus gait was lower compared with normal gait ($P < .001$). Overall, minimum GML estimated with the segmented model was higher compared with the straight-line model ($P < .01$).

The key findings of our study indicate that GML is significantly affected by both gait pattern and method of estimation. The GML estimates tended to be lower with the straight-line model versus the segmented model.

Keywords: muscle length estimates, crouch, equinus

Recent reports have identified gastrocnemius muscle-tendon length (GML) as a key contributor to aberrant gait kinematics and patients’ symptoms.¹⁻⁶ Restrictions in GML and/or extensibility are often accompanied by an equinus gait pattern characterized by forefoot initial contact and excessive ankle plantar flexion during stance, particularly in children with cerebral palsy.²⁻⁴ With a prevalence of 61% in children with cerebral palsy referred for motion analysis, an equinus pattern is among the most commonly encountered gait deviations in cerebral palsy.⁵⁻¹¹ Because the gastrocnemius is a biarticular muscle, alterations in knee motion may also be expected to influence GML. Excessive stance phase knee flexion defines a crouch gait pattern,¹² and has been reported in approximately 69% in children with cerebral palsy referred for motion analysis.¹⁰ Gait patterns with a combination of ankle plantar flexion and knee flexion have also been noted in children with cerebral palsy.⁶⁻¹⁴⁻¹⁵

In an attempt to provide accurate estimates of GML and facilitate clinical decision making, recent reports have estimated GML using kinematic data from motion analysis combined with an MRI-based, segmented model.⁴⁻⁸⁻¹⁵⁻¹⁶ Estimates using the MRI-based model indicate that the GML attains its maximum length (101% anatomical length) during second rocker, and that the GML shortens to 94% of anatomical length at terminal stance in typically developing children.¹⁵ In contrast, GML in children with equinus gait reached a maximum of 97% anatomical length and a minimum of 89.2% anatomical length during walking.⁸ Following tendo-Achilles lengthening surgery, maximum GML during gait was restored to 99.8% anatomical length.⁸ Quantitative data defining GML during crouch gait or during a combination of crouch and equinus gait are lacking. Crouch gait, characterized by knee flexion in stance phase, is frequently accompanied by ankle dorsiflexion. Consequently, the GML may be expected to shorten at the knee joint and lengthen at the ankle. Similarly, gait patterns involving a combination of ankle plantar flexion and knee flexion during stance (coexistence of crouch and equinus patterns) may be expected to result in a more marked decrease in GML, compared with GML decrease accompanying isolated ankle plantar flexion or knee flexion. However, no objective evidence is available defining GML length behavior during walking in common aberrant patterns other than equinus.

As an alternative to the MRI-based, segmented model, the straight-line model has been used to estimate GML.¹⁷⁻¹⁸ The straight-line model is a relatively simple method that involves computing GML as the Euclidean distance between ankle and knee joints in the sagittal plane.
distance between its origin and insertion points. The origin and insertion points are identified using manual palpation, digitized as virtual landmarks relative to the local reference frame, and subsequently transformed into the global reference frame. The chief advantage of using the straight-line model is that it does not require joint angles (and attendant model assumptions to derive these joint angles), or regression coefficients to estimate GML. While the straight-line model has been used to assess single-joint muscles such as the soleus during walking, and to assess the gastrocnemius during exercises such as the lunge, no data are available quantifying GML length using this model during normal or aberrant gait patterns in children.

While there has been increasing interest in estimating GML, limited objective data are available establishing GML behavior during walking in typically developing children using the straight-line model. Further, quantitative data defining GML length behavior during aberrant walking patterns commonly encountered in clinical settings are lacking. The purpose of this study was to compare estimates of GML obtained using a segmented versus straight-line model during normal and simulated pathological gait patterns in children. The findings of this study may help develop a better understanding of GML changes that occur during commonly encountered aberrant walking patterns.

Methods

Subjects

Eleven children (six males) between the ages of 7 and 16 years with no current musculoskeletal or neuromuscular problems affecting their gait volunteered as subjects (mean (SD) height: 1.5 (0.2) m; mean (SD) mass: 42.3 (15.4) kg). Subjects were recruited by advertisement. Before initiation of the study, informed consent and assent was sought following IRB guidelines.

Procedures

Kinematic data were collected using a four-segment model of the right lower extremity. Twelve infrared markers were placed on the subject’s foot, leg, thigh, and pelvis (three markers per segment in a noncollinear arrangement) and secured to the subject’s skin with doublesided tape. Details related to the kinematic model have been published in previous studies. Kinematic data were collected at 60 Hz using an active marker system (Optotrak, Northern Digital Inc., Waterloo, Canada). Anatomical coordinate systems were defined by digitizing palpable landmarks with reference to the technical marker reference frame. Marker locations and digitization are depicted in Figure 1. Kinetic data were collected at 360 Hz using a force plate (Kistler Inc, Amherst, NY) embedded flush with the walkway.

Kinematic data were collected on the right lower extremity as the subject walked barefoot along a 10-m walkway under the following conditions: normal gait, crouch gait, equinus walking, and crouch with equinus gait. Normal gait trials were performed first, with simulated gait trials following in random order. Simulated gait patterns were demonstrated to the subject and subjects were given the opportunity to practice each simulated pattern before the actual data collection. A trial was considered successful if the subject made contact on the force plate with the right foot and did not contact the force plate with the contralateral foot throughout stance.

The simulated patterns were defined as follows:

- **Crouch gait**: (1) Initial contact with heel; (2) knee flexed to about 30 degrees through stance.
- **Equinus gait**: (1) Initial contact and sustained weight bearing subsequently on with ball of the foot; that is, no contact was made with the heel.
- **Crouch with equinus gait**: (1) Initial contact and weight bearing subsequently sustained on with ball of the foot; that is, no contact was made with the heel; (2) knee flexed to about 30 degrees through stance.

Knee flexion angle during stance was reviewed and verified within data collection software (Optotrak, Northern Digital Inc., Waterloo, Canada).

Data Analysis

Temporal and spatial parameters of gait, including walking velocity, stance duration, and stride length were calculated for each trial. Sagittal plane ankle and knee kinematics were computed using custom software.
and GML length change (difference between maximum and minimum GML length).

**Statistical Testing**

A one-way repeated-measures ANOVA was used to assess the effect of gait pattern on walking velocity, stance duration, stride length, ankle and knee kinematics. A two-way (muscle length model × gait pattern) repeated-measures ANOVA (α = .05) was used to compare GML characteristics. Interaction effects were assessed first, followed by evaluation of simple or main effects as appropriate. Bonferroni adjustments were used for post hoc testing of pairwise comparisons relative to normal gait.

**Results**

Walking velocity was comparable across the different gait patterns (Table 1). All subjects were able to appropriately simulate pathological gait patterns, as evidenced by ankle and knee kinematics. Ankle plantar flexion progressively increased from crouch walking to normal gait to crouch with equinus gait, while ankle dorsiflexion decreased in the reverse order. The knee was more flexed during stance in crouch and crouch with equinus gait. Temporal and spatial parameters, ankle and knee kinematics in the different gait patterns are summarized in Table 1. Ensemble-averaged ankle and knee kinematics, and GML are presented in Figure 4.

The effect of gait pattern on maximum GML varied based on the muscle length model used (muscle length model × gait pattern interaction, P = .004). Subsequent analysis of simple effect of gait pattern showed that, overall, maximum GML was lower in the simulated gait patterns compared with normal gait (simple effect of gait pattern: P < .001 and P < .01, segmented and straight-line models, respectively). Pairwise comparisons are summarized in Figure 3. Maximum GML was higher with the segmented model compared with the straight-line model in equinus gait and crouch with equinus gait (simple effect of muscle length model, P = .030, Figure 3).

The effect of gait pattern on minimum GML did not vary based on the muscle length model used (Muscle length model × gait pattern interaction, P = .082). On average, minimum GML estimated with the segmented model was higher compared with the straight-line model (main effect of muscle length model: 92.11 vs 86.30%, P < .01). Minimum GML during crouch with equinus gait was lower compared with normal gait (post hoc comparisons following main effect of gait pattern: 87.68 vs 90.81%, P < .001).

The effect of gait pattern on GML change varied based on the muscle length model used (Muscle length model × gait pattern interaction, P = .026). A significant simple effect of gait pattern was noted within each muscle length model (P < 0.01 and P < 0.01 for segmented and straight-line model, respectively). Pairwise comparisons are summarized in Figure 3, and indicate that GML change in equinus gait and crouch with equinus gait was lower.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Normal</th>
<th>Equinus</th>
<th>Crouch</th>
<th>Crouch with Equinus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stride length (m)</td>
<td>0.982</td>
<td>0.862*</td>
<td>0.922*</td>
<td>0.895*</td>
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<tr>
<td>Velocity (m/s)</td>
<td>0.867</td>
<td>0.801</td>
<td>0.810</td>
<td>0.802</td>
</tr>
<tr>
<td>Stance duration (% gait cycle)</td>
<td>61.16%</td>
<td>61.62%</td>
<td>63.62%</td>
<td>62.93%</td>
</tr>
<tr>
<td>Peak ankle dorsiflexion in stance (°)</td>
<td>–10.06</td>
<td>13.23*</td>
<td>–19.81*</td>
<td>–1.31*</td>
</tr>
<tr>
<td>Peak ankle plantar flexion in stance (°)</td>
<td>10.46</td>
<td>34.32*</td>
<td>1.24*</td>
<td>18.15*</td>
</tr>
</tbody>
</table>

*Indicates statistical significance compared with normal walking; positive values represent plantar flexion and knee flexion.

**Table 1** Summary of temporal and spatial gait parameters, ankle and knee kinematics

**Figure 3** — Mean (SD) GML during gait, expressed as a percent of GML in neutral standing position. Maximum GML (top), minimum GML (middle) and GML change (bottom) are depicted, with MRI-based model estimates (black circles) and straight-line model estimates (gray squares). Error bars indicate standard deviation. *Indicates significant difference compared with normal. +Indicates significant difference between MRI-based and straight-line models.
compared with normal gait, using the segmented model, as well as the straight-line model ($P < .001$ and $P < .001$, segmented and straight-line models, respectively, Figure 3).

**Discussion**

The key findings of our study indicate that GML is significantly affected by both gait pattern and method of estimation. Maximum GML and length change were both significantly lower in equinus, and crouch with equinus patterns, compared with normal gait. A significant interaction effect (muscle length model × gait pattern) was noted for maximum GML and GML length change indicating that choice of model affects GML estimates differently across the four simulated gait patterns. These findings underscore that the choice of model does not only result in an offset in length, but may also lead to a different interpretation of the effect of gait pattern on muscle-tendon length. In particular, GML estimates tended to be lower with the straight-line model (versus the segmented model) in equinus and crouch with equinus gait. The findings of this study provide objective baseline GML estimates and help define GML changes accompanying commonly seen gait deviations.

Consistent with previous studies assessing GML in typically developing children, we found maximum GML of 100.67% and minimum GML of 93.2% during normal gait using the segmented model. In the equinus gait pattern, we found maximum GML of 97.3% and minimum GML of 92.3%, consistent with 97.3% and 89.2% maximum and minimum GML, respectively, reported previously. Our findings indicated that GML varies from 98.4% to 91.9% during crouch gait, and highlight that decrease in GML in crouch gait compared with normal gait. A combination of ankle plantar flexion and knee flexion (crouch with equinus gait) resulted in the most reduction in GML (96.1 and 91.1% maximum and minimum GML, respectively). Interventions such as botulinum toxin injections, serial casting and surgery, including gastrocnemius recession and tendo-Achilles lengthening have been used to address restrictions in GML in children with cerebral palsy. Accurate estimates of GML may be particularly valuable in providing objective pre- and postintervention outcome measures in children with cerebral palsy.

The GML was also quantified using the straight-line model. The chief advantage of the straight-line model is that it is relatively clear-cut, easy to implement, and involves the use of digitized points or virtual markers.
In addition, the straight-line model does not require ankle or knee joint angles, moment arms, or regression coefficients to estimate GML. Our findings showed that GML estimates tended to be lower with the straight-line model versus the segmented model, particularly in equinus and crouch with equinus gait. Because, the straight-line model computes GML as the Euclidean distance between origin and insertion points, GML changes may be underestimated due to the absence of wrapping points in the model. In the absence of a gold standard method of evaluating in vivo GML during walking conclusions about validity of either the segmented or straight-line model cannot be made. Nevertheless, our results illustrate the nature and extent of discrepancy between the segmented or straight-line model across a variety of commonly seen gait patterns.

The chief advantage of the MRI-based, segmented model is that it allows estimation of GML using ankle and knee kinematics combined with subject’s height and regression coefficients. No additional data need to be acquired during motion analysis. Further, segmented estimates of GML are not susceptible to digitizing error introduced by variation in identification of landmarks and poor intertester reliability. An alternative computational method that combines ankle and knee kinematics with graphics-based model has been used by several recent studies to quantify GML in children with cerebral palsy. Maximum preoperative GML during walking was estimated at 98% to 100% in children with equinus gait who went on to have gastrocnemius recession or tendo-Achilles lengthening surgery. These estimates are slightly higher than those reported for equinus gait pattern using the segmented model. The differences in anthropometric parameters used to compute GML as well as intrinsic differences in subjects studied may explain the discrepancy in GML estimates obtained with different models. While SIMM allows researchers to scale the model to their specific subject, the original biomechanical model used in SIMM was developed on a single adult male. In contrast, the MRI-based, segmented model was originally developed on a cohort of 15 able-bodied children, ranging in age from 3 to 15 years of age, similar in age, gender, and BMI to the current study. Additional studies are needed to compare GML obtained using SIMM to those obtained using the segmented model.

One recent investigation compared GML estimates obtained using the segmented model to those obtained using regression-based models derived from in vitro and in vivo kinematic data. The authors noted that the GML estimates obtained with the segmented model were strongly related to knee kinematics, possibly due to the longer moment arm of the gastrocnemius at the knee (versus ankle), and greater range of knee (versus ankle) motion used during walking. The greater reliance on knee kinematics and knee moment arm may underestimate GML changes in crouch gait. Due to the use of second order polynomials to define knee and ankle moment arms of the gastrocnemius, the ratio of knee to ankle moment arm is particularly high at low heights when using the segmented model. The high ratio may suggest that GML estimates in shorter subjects may be biased toward contributions from the knee. Additional studies are needed to clarify the role of gastrocnemius moment arm on estimates of GML.

Previous studies indicate that surgery is accompanied by an approximately 8–15 degree increase in dorsiflexion, similar to the 10 degree increase in peak dorsiflexion noted in our study when comparing equinus to normal walking. In clinical studies, these kinematic changes were accompanied by an increase in GML. Following gastrocnemius recession, one study reported postoperative peak GML of 101.6% compared with preoperative GML of 98.4%. Following tendo-Achilles lengthening, peak GML has been reported to increase to 99.5% from 97.3% in children with equinus. Clinical studies report GML change of 2–8%. Based on these estimates, our data suggests that differences between GML length change computed by the two models falls within the range of physiologically relevant values. Additional studies are needed to clarify the use of muscle length estimates in quantifying severity of gait impairment, and its role in treatment planning.

While a number of models have been proposed to estimate GML during walking and other functional activities of daily living, no single gold standard technique is available to assess in vivo GML during walking and other functional activities of daily living. Each method of GML estimation has its merits and weaknesses. We compared GML across four commonly seen gait patterns using two different muscle length models. The chief advantage of simulating gait patterns is that the experimental design allowed us to assess the effects of wide range of ankle and knee kinematics on estimates of GML. The unique findings of our study indicate that GML is significantly affected by both, gait patterns and method of estimation. Maximum GML and length change were both significantly lower in equinus and crouch with equinus patterns, compared with normal gait. The GML estimates tended to be lower with the straight-line model (versus the segmented model), particularly in equinus and crouch with equinus gait. Future studies should compare GML estimates obtained using SIMM to those obtained using the segmented model, to address the effect of gastrocnemius moment arm on muscle length.

Acknowledgments

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References


