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Abstract
Pathologic movement patterns are characterized by abnormal kinematics that alter how muscles support the body during walking. Individual muscles are often the target of interventions with physical therapy and surgery alike, yet the tools to assess individual muscles clinically remain limited. The aim of this study is to assess OpenSim as a clinical tool for individualized rehabilitative evaluation of children using orthotics. This anatomic and kinematic modeling study was focused on pre- and post-treatment assessment of gait characteristics in fourteen children using orthotic devices. A range of four to twelve acceptable gait capture trials was collected for each child before therapy began and again after four weeks of treatment. The effects of therapy were significant in four of the lower extremity muscle analyses, three of the temporal parameters, and eighteen of the spatial parameters. All muscle lengths showed less deviation from normal values after physical therapy across all subjects. Results of this study support the further evaluation of OpenSim as a tool to improve quantitative assessment of musculoskeletal dynamics during the course of rehabilitative therapy in children using orthotics.

SECTION I. Introduction
Mobility is essential to health and well-being, and fundamental to growth and development in children. In medical practice, there is no widely applied system for coupling an assessment of muscle length dynamics and gait in a unified analysis. While gait kinematics are more frequently studied, it is difficult to simultaneously evaluate muscle dynamics to guide ambulatory treatment. Recent advances in simulation now improve our ability to couple muscle dynamics and gait kinematics as we seek to improve our understanding of treatment modalities and develop more effective methods to improve ambulatory function.

Dynamic simulation allows estimation of musculoskeletal forces that cannot be directly measured. Results allow a better quantitative basis for understanding individual muscle contributions to resulting ambulatory motion. These results also provide a means for uniquely personalized analysis.

Conventional gait analysis [1] takes advantage of validated dynamic models such as the often used Newington Children's Hospital model [2] and Helen Hayes model [3] . These direct kinematic models use experimental markers to calculate 3D joint kinematics and virtual joint segments. Vicon (Vicon Motion Systems, Oxford, UK) users can implement this with the Plug-in-Gait model. With no joint constraints, Wells, *et al.* report that direct kinematic solutions result in apparent segment length fluctuations averaging around 2% [4] . Kainz, *et al.* reported similar results [5] . On the contrary, inverse kinematics use experimental markers to optimize joint angles while matching the original model with prior experimental anatomical marker positions. The inverse kinematic approach was adopted for the current study.

OpenSim [6] is a resource that uses inverse kinematics to further enable analyses not readily available to the clinician. OpenSim can address muscle-tendon lengths [7] , muscle-tendon forces [8] , muscle moment arms [9] , and joint contact forces [10] . These additional analyses have the potential to better support clinical planning as many children, especially those with Cerebral Palsy, experience musculoskeletal challenges that are frequently addressed with therapeutic intervention and surgery. While therapeutic intervention is often focused on joint range and strengthening, orthopaedic intervention can focus on muscle transfers, lengthenings and even bony osteotomies. All of these approaches focus on individual muscle contributions to mobility and function.

SECTION II. Methods
Fourteen healthy children (five female, nine male) gave their informed consent to participate in this institutionally approved study. The average age, height, and body weight of the subjects was 13 +3 years, 148.8 +13.3 cm, and 44.7 +14.5 kg, respectively. All subjects used some type of ankle-foot orthotic (AFO) or insole. Five subjects used solid AFOs, four subjects used hinged AFOs, and five subjects used modified insoles. Review of

medical records revealed a history of cerebral palsy in seven subjects, spina bifida in four, genetic alteration in two, and arthrogryposis in one.

Each subject underwent lower extremity (LE) gait analysis with kinematic assessment before beginning physical therapy and once again after daily therapy had been administered for a period of four weeks. Kinematic data of subjects using their orthotics was collected using a 12-camera motion capture system (OptiTrack Flex 13 cameras; NaturalPoint, USA), pixel resolution of 1280x1024, and 42° and 56° fields of view. The camera capture rate was at 120Hz. Cameras used 850nm infrared light to minimize interference from overhead lighting. Cameras were placed on all sides of the capture volume with one camera at each corner, one camera at the beginning and end of the capture volume, and three cameras along each side of the capture volume as the subject walks down the pathway. The capture volume measured approximately 2.0 x 6.0 m. Cameras were mounted on tripods measuring 2.5 x 1.2 x 1.2 m.

Calibration of the OptiTrack camera system was performed with a calibration wand and calibration square to index the laboratory origin. The integrated calibration wand process was used to calibrate the system, which involved moving the wand throughout the capture volume for thirty seconds. The software displays the accuracy of the calibration performed between six ranks from “Poor” to “Exceptional.” All calibrations used were met with an “Exceptional” ranking, resulting in estimated errors less than 0.10 mm. Recalibration was performed every day before testing and if camera position was changed. Passive reflective markers where placed in accordance with standard protocol [11] . At self-selected gait speeds, a minimum of four good trials were collected for each subject. A trial was determined acceptable if it obtained two consecutive heel strikes and two toe offs with less than 10 consecutive frames (0.083s) of individual marker loss during that time interval.

Calculations of kinematic gait parameters were performed using OpenSim (NIH Center for Biomedical Computation, Stanford University). A lower extremity musculoskeletal model was used to estimate muscle activity of the subject while walking. Based on marker placement, the OpenSim model was scaled. The locations of muscle origin and insertion were determined by OpenSim and imbedded in their models based on prior experimentation [13] , [14] . Inverse kinematic algorithms were derived from measured marker trajectories and individual patient parameters. Parameters collected for each patient included weight (kg), height (mm), left to right anterior superior iliac spine (ASIS) distance (mm), left and right leg lengths (mm), left and right knee diameters (mm), and left and right ankle diameters (mm). The analysis employed a MATLAB-OpenSim interface previously verified [12] .

SECTION III. Results

Custom MATLAB code was generated to identify temporal stride events during gait. The average walking speeds of the subjects before and after physical therapy were 0.94±0.21 and 0.98±0.21 (m/s), respectively. Seven of sixteen parameters in the Gillette Gait Index (GGI) [15], [16], [17] were statistically different when compared before and after physical therapy. A total of eighteen of thirty-four spatial parameters and three of four temporal parameters were significantly different following physical therapy. Study details are illustrated in Table 1 with an example kinematic output in Figure 1 .

TABLE I. SPATIAL AND TEMPORAL ANALYSIS

Measure	Statistics	Measure	Statistics
	p-value		p-value
Mean Pelvic Tilt	0.4429	Pelvic Tilt Range	0.2955
Mean Pelvic Obliquity*	0.0000*	Pelvic Obliquity Range*	0.0178*
Mean Pelvic Rotation	0.0710	Range of Pelvic Rotation	0.5953
Minimum Hip Flexion*	0.0004*	Range of Hip Flexion	0.2599

Hip Flexion at Initial Contact	0.7123	Max Hip Flexion (Max Hip Angle) in Swing	0.9521
Max Hip Extension (Min Hip Angle) in Stance	0.0747	Range of Hip Sagittal Motion in Stance	0.7942
Mean Hip Abduction Angle in Swing*	0.0001*	Mean Hip Abduction in Stance*	0.0008*
Max Hip Abduction Angle in Swing*	0.0001*	Hip Rotation Angle at MidStance*	0.0075*
Hip Rotation Angle at Mid-Swing*	0.0158*	Mean Hip Rotation in Stance	0.0923
Hip Rotation Angle at Initial Contact	0.0999	Hip Rotation Angle at Toe-Off	0.1167
Knee Angle at Initial Contact	0.8881	Range of Knee Flexion*	0.0000*
Max Knee Flexion (Max Angle) in Stance*	0.0000*	Max Knee Extension (Min Knee Angle) in Stance*	0.0000*
Mean Foot Progression Angle in Stance	0.4523	Ankle Angle at Initial Contact*	0.0005*
Ankle Range During Stance*	0.0086*	Maximum Dorsiflexion in Stance*	0.0032*
Maximum Dorsiflexion in Swing*	0.0000*	Ankle Angle at Mid-Swing*	0.0022*
Time of Toe Off(%)*	0.0012*	Time of Peak Knee Flexion in Swing (%)*	0.0001*
Timing of Max Ankle Dorsiflexion (X) in Stance (%)	0.2596	Time of Max Knee Flexion in Swing(%)*	0.0001

a. p-values for spatial and temporal analysis. Red values with a ‘*’ were considered statistically significant (<0.05). All differences showed a decrease in the value from before to after physical therapy. (Table footnote)

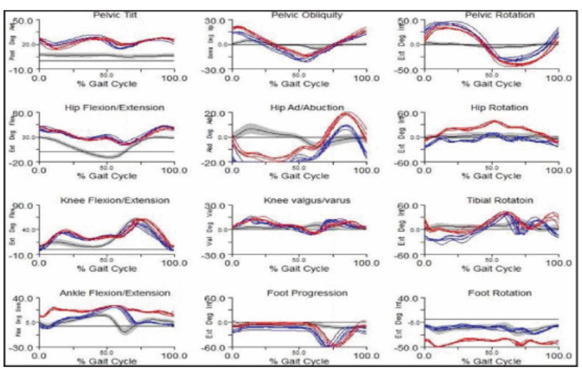

Figure 1. Single subject kinematic data (right in red, blue in left) plotted against a normal (±1 SD) matched population of 20 healthy children (gray). *(figure caption)*

Inverse kinematic analysis was performed with OpenSim. MATLAB code was used to communicate with OpenSim and display results; an example dynamic muscle length output is shown in Figure 2 . The sum of squared error between muscle lengths and the normal range before and after physical therapy was significantly different for the following muscles: semimebranosus, semitendinosus, long head of the biceps femoris, and the rectus femoris. This represents a more normal gait pattern. Details are illustrated in Table 2 . All forty-three of forty-three muscle length values averaged less deviation from the normal range following physical therapy across all subjects.

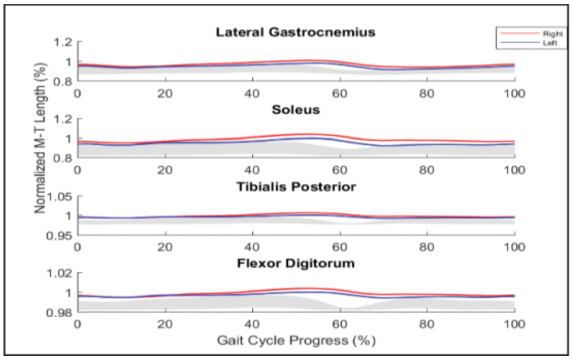

Figure 2. Dynamic muscle length data (right in red, left in blue) plotted against the normal population (gray). Here we show the lateral gastrocnemius, soleus, tibialis posterior, and flexor digitorum.*(figure caption)*

TABLE II. MUSCLE ANALYSIS

Muscle	Statistics	Muscle	Statistics
	p-value		p-value
Gluteus Medius 1	0.112	Gluteus Medius 2	0.914
Gluteus Medius 3	0.736	Gluteus Minimus 1	0.099
Gluteus Minimus 2	0.078	Gluteus Minimus 3	0.856
Semimembranosus*	0.010*	Semitendinosus*	0.016*
Biceps Femoris Long Head*	0.024*	Biceps Femoris Short Head	0.376
Sartorius	0.392	Adductor Longus	0.382
Adductor Brevis	0.745	Adductor Magnus 1	0.542
Adductor Magnus 2	0.600	Adductor Magnus 3	0.376
Tensor Fasciae	0.355	Latae Pectineus	0.356
Gracilis	0.842	Gluteus Maximus 1	0.292
Gluteus Maximus 2	0.269	Gluteus Maximus 3	0.220
Iliacus	0.324	Psoas	0.307
Quadratus Femoris	0.172	Gemellus	0.359
Piriformis	0.801	Rectus Femoris*	0.007*
Vastus Medialis	0.418	Vastus Internus	0.422
Vastus Lateralis	0.417	Medial Gastrocnemius	0.294
Lateral Gastrocnemius	0.290	Soleus	0.173
Tibialis Posterior	0.087	Flexor Digitorum	0.063
Flexor Hallucis	0.115	Tibialis Anterior	0.188
Peroneus Brevis	0.503	Peroneus Tertius	0.176
Peroneus Longus	0.065	Extensor Digitorum	0.175
Extensor Hallucis	0.175		

a. p-values for muscle analysis. Red values with a "*" were considered statistically significant (<0.05) when comparing before to after physical therapy. (Table footnote)

SECTION IV.Discussion

The aim of this study was to assess OpenSim as a clinical tool for individualized rehabilitative evaluation. OpenSim was selected as it offered the potential for a user to assess muscles on an individual personalized basis which supports the goals of rehabilitative therapy and surgery in this pediatric population.

The results of physical therapy were found to be statistically significant for eighteen of thirty-four spatial parameters, three of four temporal parameters, and four of forty-three muscles. All forty-three muscle lengths were found to more closely approximate normal ranges after therapy across all subjects. Further study is supported by this work as the potential of OpenSim in combination with gait kinematics and temporal-spatial parameters are examined to improve individualized measures of mobility and musculoskeletal function.

SECTION V.Conclusion

Results of this study support the further use and evaluation of OpenSim to improve the individualized assessment of musculoskeletal dynamics during the course of rehabilitative therapy in children using orthotics.

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References

1. O. Pinzone, M. H. Schwartz, P. Thomason, R. Baker, "The comparison of normatice reference data from different gait analysis services", *Gait & Posture*, vol. 40, pp. 286-290, 2014.

2. R. B. Davis, S. Ounpuu, D. Tyburski, T.R. Gage, "A gait analysis data collection and reduction technique", *Human Movement Science*, vol. 10, 1991.

3. M. P. Kadaba, H. K. Ramakrishnan, M. E. Wootten, J. Gainey, G. Gorton, G. V. Cochran, "Repeatability of kinematic kinetic and electromyographic data in normal adult gait", *Journal of Orthopaedic Research*, vol. 6, pp. 849-860, 1989.

4. D. Wells, C. J. Donnelly, B. C. Elliott, J. A. Alderson, "Comparison of two direct kinematic modelling approaches for sport-specific upper limb modeling", *Conference: Congress of the International Society of Biomechanics*, 2015.

5. H. Kainz, L. Modenese, D. G. Lloyd, S. Maine, H. P. J. Walsh, C. P. Carty, "Joint kinematic calculation based on clinical direct kinematic versus inverse kinematic gait models", *Journal of Biomechanics*, vol. 49, pp. 1658-1669, 2016.

6. S. L. Delp, F. C. Anderson, A. S. Arnold, P. Loan, A. Habib, C. T. John, E. Guendelman, D. G. Thelen, "OpenSim: open-source software to create and analyze dynamic simulations of movement", *IEEE Transactions on Bio-medical Engineering*, vol. 11, pp. 1940-1950, 2007.

7. P. O. Riley, J. Franz, J. Dicharry, D. C. Kerrigan, "Changes in hip joint muscle-tendon lengths with mode of locomotion", *Gait & Posture*, vol. 31, pp. 279-283, 2010.

8. K. D. Morgan, C. J. Donnelly, J. A. Reinbolt, "Elevated gastrocnemius forces compensate for decreased hamstrings forces during the weight-acceptance phase of single-leg jump landing: implications for anterior cruciate ligament injury risk", *Journal of Biomechanics*, vol. 47, pp. 3295-3302, 2014.

9. A. S. Arnold, S. Salinas, D. J. Asakawa, S. L. Delp, "Accuracy of muscle moment arms estimated from MRI-based musculoskeletal models of the lower extremity", *Computer aided surgery*, vol. 5, pp. 108-119, 2000.

10. L. Modenese, A. Gopalakrishnan, A. T. M. Phillips, "Application of a falsification strategy to a musculoskeletal model of the lower limb and accuracy of the predicted hip contact force vector", *Journal of Biomechanics*, vol. 46, pp. 1193-1200, 2013.

11. S. Ounpuu, J. R. Gage, R. B. Davis, "Threedimensional lower extremity kinetics in normal paediatric gait", *Journal of Pediatric Orthopaedics*, vol. 11, pp. 341-349, 1991.

12. J. Rammer, "Markerless kinematics of pediatric manual wheelchair mobility", *Doctor of Philosophy (PhD) Dissertation Marquette Univeristy*, 2017.

13. G. T. Yamaguchi, F. E. Zajac, "Restoring unassisted natural gait to paraplegics via functional neuromuscular simulation: a computer simulation", *IEEE Trans Biomed Eng*, vol. 37, pp. 886-902, 1990.

14. C. H. Yeow, "Hamstrings and quadriceps muscle contributions to energy generation and dissipation at the knee joint during stance swing and flight phases of level running", *Knee*, vol. 20, pp. 100-105, 2013.

15. L. M. Schutte, U. Narayanan, J. L. Stout, P. Selber, J. R. Gage, M. H. Schwartz, "An index for quantifying deviations from normal gait", *Gait Posture*, vol. 11, pp. 25-31, 2000.

16. M. Domaglaska, A. Szopa, M. Syczewska, S. Pietraszek, Z. Kidon, G. Onik, "The relationship between clinical measurements and gait analysis in children with cerebral palsy", *Gait Posture*, vol. 38, pp. 1038-1043, 2013.

17. T. Dreher, D. Vegvari, S. I. Wolf, A. Geisbusch, S. Grantz, W. Wenz, F. Braatz, "Development of knee function after hamstring lengthening as a part of multilevel surgery in children with spastic diplegia: a long-term outcome study", *The Journal of Bone and Joint Surgery. American Volume*, vol. 94, pp. 121-130, 2012.