

Modelling and analysis of muscle function in cerebral palsy gait

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Abstract

Introduction

Cerebral palsy (CP) is caused by an injury to the central nervous system and results commonly in abnormal motor control associated with an abnormal gait pattern. Crouch gait is one of the most common gait abnormalities in CP children and is primarily characterized by excessive flexion of the knee during stance, although flexion, adduction, and internal rotation of the hips are also often observed. Most cases of crouch gait are attributed to spastic or contracted hamstrings muscles, but hip flexion contracture and weakness of the ankle plantarflexors are also believed to contribute. An objective assessment of these movement abnormalities can be achieved via gait analysis techniques. In this approach, joint kinematics and force plate data are combined with the inverse dynamics method in mechanics to estimate and compare the net moments exerted about the lower-limb joints. [1] [2]. While these data provide quantitative descriptions of the kinetics of joint movement, they do not specify the actions of individual muscle during walking. Additional insights can be obtained by using musculoskeletal models based on MRI imaging combined with kinematic, kinetic, and EMG data to determine the muscle action during movement.

Few modelling studies have included subject-specific muscle geometry and the actions of individual muscles, and even fewer studies have represented the movements of the body parts in three dimensions [3].

The overall goal of the present study is to obtain a better understanding of muscle function in healthy children compared with age-matched children with cerebral palsy who walk with a crouched gait.

Methods

Magnetic resonance imaging (MRI) and gait data were collected from five healthy children with no known gait disorders and two children with cerebral palsy (age 9.5 ± 1.7 years, height 1.34 ± 0.075 m and weight 30.3 ± 3.8 kg). The parents of the children gave informed consent.

Subject-specific musculoskeletal models were developed to study the individual contributions of 46 lower-limb muscles to body motion as each subject walked at his or her natural speed.

Magnetic resonance imaging

MR images of the lower limbs were recorded from the first lumbar vertebrae down to the calcaneus. The MRI data were segmented so that all muscles and bones were identified and marked using the software AVIZO (Mercury Computer Systems). In addition, we marked anatomical landmarks that could be clearly identified on the MR images (**Figure 1**) [4]. Muscle paths for the individual muscles were defined using wrapping surfaces and via points

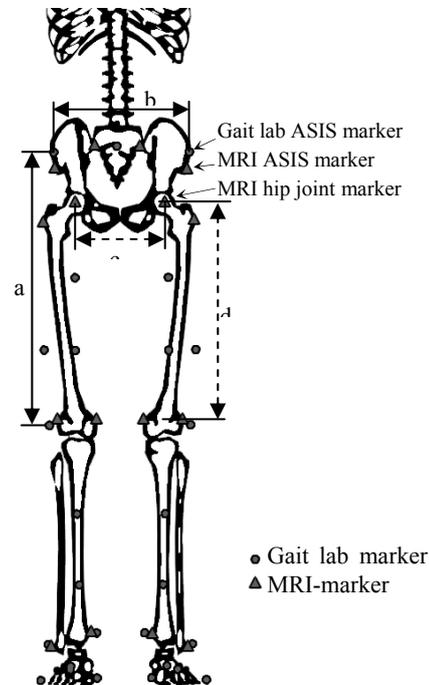


Figure 1 Marker positions for anatomical scaling [4]

Gait experiments

Kinematic, ground force, and muscle EMG data were recorded simultaneously for each subject. Twenty-five passive retro-reflective markers were placed on both the left and right sides of the body to measure the three-dimensional positions of 14 body segments: forefoot, hindfoot, shank, and thigh of each leg, upper and lower arms, plus pelvis and one segment including head and torso. Ground reaction forces and moments were measured using two six-component, strain-gauge force plates. Paired surface EMG electrodes were attached to both legs to record activity from 4 muscles in each leg.

Subject-specific musculoskeletal models of healthy children

A detailed three-dimensional musculoskeletal computer model was developed for each of the subjects. Each model was based on the kinematic structure used in the exemplar model given in OpenSim (<https://simtk.org/home/opensim>, Version 1.9.1) [5]. The generic model was individually adapted based on segmentation results obtained from MR images acquired of each subject. Particular care was taken to accurately determine and model the muscle attachment points and muscle paths.

The scaling of the generic model was based on ‘virtual’ markers that were placed on anatomical landmarks of the MR images [4]. These ‘virtual’ markers were also used to calculate the joint positions during MRI capture and to recalibrate the muscle paths for exact determination of the muscle attachment points. Maximum isometric muscle forces were determined

from muscle volumes calculated from the MRI images of each subject

Results

To compare muscle function in CP patients and healthy children, we examined the actions of individual muscles crossing the hip joint in two representative subjects, one healthy child and one child who walked with a crouched gait.

CP	muscle volume [cm ³]	optimal joint angle [°]	opt. fiber length [cm]	PCSA [cm ²]	F _{max} [N]
hams L	198,08	90	10	19,81	653,6
hams R	178,95	90	10	17,89	590,5
ilio L	83,60	-75	7,6	11,00	363,0
ilio R	72,87	-75	7	10,41	343,5
Healthy					
hams L	243,91	103	8,5	28,70	947,0
hams R	226,53	90	9,2	24,62	812,5
ilio L	138,62	60	8,6	16,12	531,9
ilio R	150,14	35	8,6	17,46	576,1

Table 1 Derivation of maximum isometric muscle forces F_{max} of iliopsoas and hamstrings. Maximum isometric muscle force is generated at optimal fibre length which occurs at optimal joint angle.

Table 1 shows the calculated data for the comparison of the maximum isometric forces of iliopsoas and hamstrings of the healthy child and the CP patient. The optimal muscle fiber length (Figure 2 B) was taken at the joint angle with maximum muscle force (Figure 2 A).

$$PCSA = \text{Muscle Volume} / \text{opt. Fiber length}$$

$$F_{\text{max}} = PCSA * \text{Muscle Stress Constant}$$

Where the muscle stress constant was assumed to be 330 kPa [6]. The ratio between the maximum forces of hamstrings and iliopsoas was found to be 1.4-1.8 in both subjects.

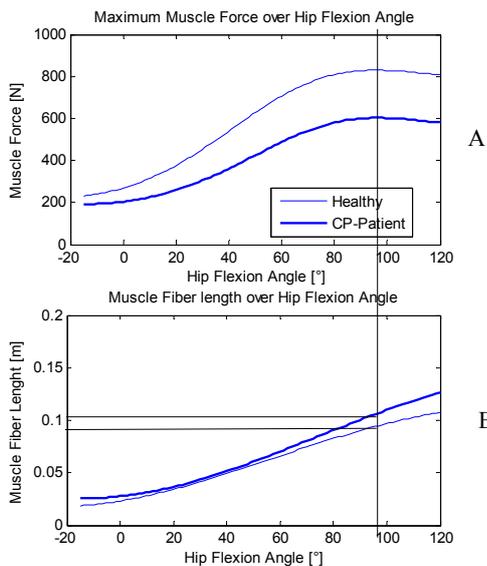


Figure 2: The force-length relation of muscle was used to determine the joint angle at which the muscle optimal fiber length occurred. The curves used in this study were based on the generic model of OpenSim and adapted to subject-specific values. This graph shows the muscle force-angle diagram of the hamstrings for the CP patient and the healthy subject (A) and the Muscle fiber length over the hip flexion angle (B) The hip joint was fully extended at 0°.

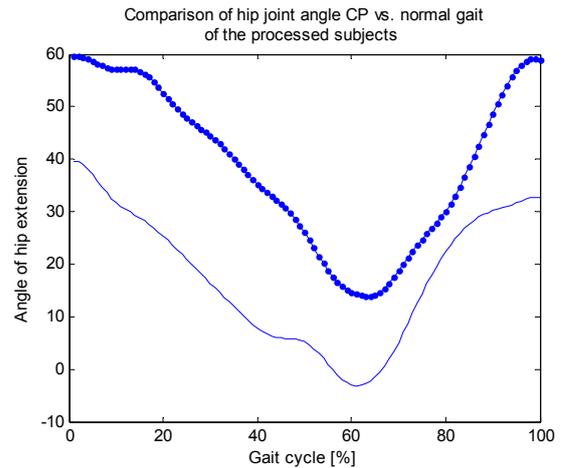


Figure 3: Flexion angle of the right hip joint for one gait cycle starting at initial contact – dotted line, CP patient; continuous line, healthy subject

The typical hip flexion angle during gait is shown in Figure 3 and is highlighted by the gray areas in the following figures. The hip flexion angle ranges from -15° to 40° for the healthy child, which is approximately the same in healthy adult gait, and ranges from 10° to 60° for the CP patient.

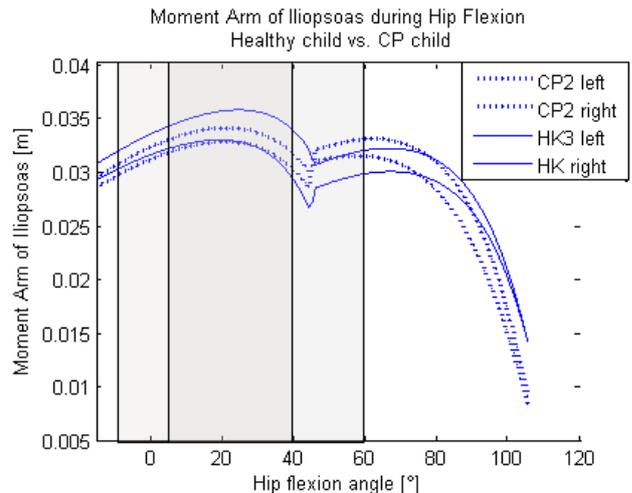


Figure 4: Moment arms of iliopsoas during hip flexion for one CP child and one healthy child.

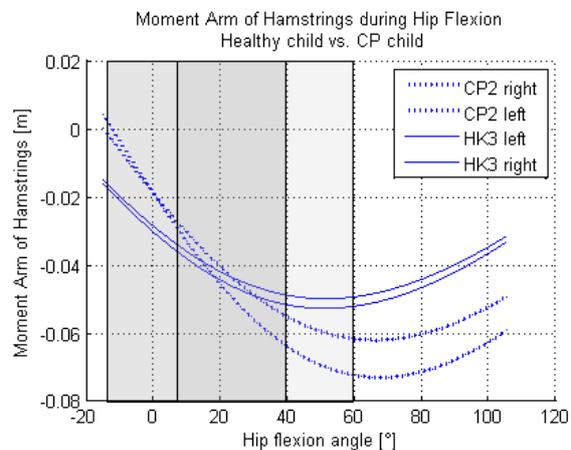


Figure 5: Moment arm of hamstrings during hip flexion

In **Figure 4** the moment arms of the iliopsoas for the healthy subject and the CP patient are given as a function of the hip flexion angle. The hip flexion moment arms for iliopsoas are not significantly different for the healthy child and the CP patient.

Figure 5 shows the moment arms of the hamstrings for the two subjects examined. Compared with the results noted for iliopsoas, the moment arms for hamstrings are noticeably different for the healthy subject and CP patient. In particular, at full extension of the hip the moment arm of hamstrings in the CP patient is roughly one third smaller than that in the healthy subject. Further, hamstrings moment arm tends to zero as the hip joint angle decreases further. For hip flexion angles greater than 20° the moment arm of the hamstrings is larger in the CP patient.

Figure 6 displays the maximum joint moments calculated in the model for hamstrings and iliopsoas for the CP patient. The maximum joint moments were calculated by multiplying the maximum muscle force (**Figure 2**) at each angular position by the corresponding moment arm of the muscle. It can be seen that in the range of joint motion of the CP patient (10° to 60°) during walking, there is only a small moment available for hip extension.

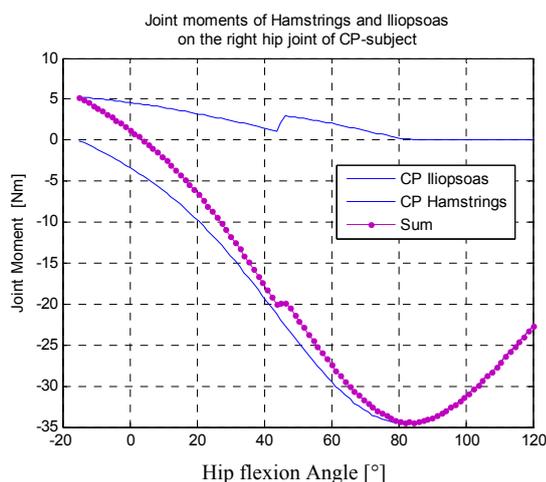


Figure 6: Joint torque on right hip joint of the CP subject from Hamstrings (upper continuous line) and Iliopsoas (lower continuous line). The dotted line shows the net joint moment from these two muscles spanning the hip joint.

Discussion

Abnormal muscle function in both hamstrings and iliopsoas has been found to play an important role in the development of the excessive knee flexion combined with hip flexion that is observed in crouch gait. During normal walking the hamstrings function mainly as hip extensors during the first half of the stance phase and due to dynamic coupling they can also contribute to knee extension during stance [7]. In the example described above, the ability of hamstrings to generate a hip extension moment is strongly reduced by the smaller moment arm of hamstrings evident near full hip extension. The reduced moment arm is caused by an anterior shift of the muscle attachment of the hamstrings relative to the hip joint. The horizontal distance of hip joint to hamstrings attachment is approximately 2 cm in the CP patient and 3 cm in the healthy subject. However, in the more flexed hip position that is seen in crouch gait, the ability of the hamstrings to generate

a hip extension moment is increased. This agrees with the results reported by Hicks et al (2008) [8].

Due to the biarticularity of the hamstrings, excessive hip flexion also causes knee flexion if the hamstrings have normal length. Through dynamic coupling any imbalance of joint torques at the hip joint also influences the intersegmental forces at the other joints throughout the body.

Conclusion

Our results indicate that bony deformities leading to altered muscle paths and moment arms play an important role in the development of pathological gait patterns in cerebral palsy. Our future work involves investigation of other muscles spanning the hip as well as functions of key muscles such as rectus femoris and vasti which cross the knee. Future analyses of our model simulation results will also be based on a larger number of healthy subjects and CP patients.

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