Three-dimensional In Vivo Quantification of Knee Kinematics in Cerebral Palsy

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Abstract Cerebral palsy is the most common disabling condition in childhood, involving a diverse group of movement and posture disorders of varying etiologies. Yet, much is unknown about how cerebral palsy affects individual joints because currently applied techniques cannot quantify the three-dimensional kinematic parameters at the joint level. We quantified the effects of cerebral palsy at the knee using fast phase contrast MRI, with the ultimate intent of improving the assessment of joint impairments associated with cerebral palsy, improving clinical outcomes, and reducing the impact of cerebral palsy on function. We addressed three questions: (1) Can patients with cerebral

palsy perform the required repetitive extension task? (2) Which of the 12 degrees of freedom defining complete knee kinematics are abnormal in individual patients with cerebral palsy and is the patellar tendon moment arm abnormal in these patients? (3) Are the individual kinematic differences consistent with clinical observations? All patients were able to perform the required task. We found kinematic differences for each patient with cerebral palsy consistent with clinical findings, in comparison to an able-bodied population. Fast phase contrast MRI may allow differentiation of patellofemoral and tibiofemoral function in various functional subtypes of cerebral palsy, providing insights into its management.

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Introduction

Cerebral palsy (CP) is the most common disabling condition in childhood. It is a diverse group of movement and posture disorders of varying etiologies, the most common of which is believed to be injury to the developing brain during the prenatal period [4]. This upper motor neuron injury has a wide-ranging impact on neurologic function and overall movement control [6, 30]. To improve accuracy and specificity of assessing joint impairments associated with CP, improve clinical outcomes, and reduce the impact of CP on function, we must be able to quantify the demands placed on the musculoskeletal system and the capabilities of these systems to meet such demands in individual patients. In doing so, treatments can be better targeted to the specific impairments experienced by an individual patient and more accurate assessments of interventions can be achieved. For example, numerous surgeries (eg, tendon transfers [1], tibiofemoral derotations) are performed on patients with CP to restore more normal

function to the joints of the lower limb. Yet, typical assessments of the knee focus primarily on one parameter, tibiofemoral extension-flexion [3], and the other degrees of freedom and function of the patellofemoral joint often are ignored. Thus, alterations to the three-dimensional (3-D) dynamic knee kinematics and patellar tendon moment arms in individual patients, preintervention and postintervention, are virtually unknown.

Gait analysis [17, 18, 30, 34] is a typical tool for studying the ambulation limitations placed on a patient with CP. In general, gait analysis does an excellent job at defining the functional deficits associated with CP, but it has limitations. It is often a two-dimensional data acquisition and analysis [12, 17], is prone to skin motion errors [16], and is less accurate in measuring motion in the frontal and coronal planes [15]. Further, gait in patients with limited mobility may be difficult to assess because of short step lengths, slow speed, endurance, and other factors. Because of these shortcomings, knowledge of how individual joints are affected by CP is limited. Thus, a more accurate tool that can directly assess in vivo 3-D joint function is needed, not as a replacement for gait analysis, but to enhance the clinical evaluation in CP.

Fast phase contrast (PC) MRI has the potential to improve the accuracy and specificity of assessing joint impairments associated with this disease by directly and noninvasively measuring 3-D in vivo musculoskeletal kinematics and kinetics. This could lead to improved clinical outcomes by providing new information for making and evaluating treatment decisions. For example, the accurate measures of 3-D patellofemoral kinematics, musculotendon strains, and musculotendon moment arms acquired by fast PC MRI during volitional movement may provide a methodology for assessing the role that moment arm dysfunction plays in muscle weakness. For such measures to have clinical utility, they must relate to

currently available clinical measures/observations and provide new insights into the impairments associated with CP.

Thus, we assessed the viability of using fast PC MRI to study the effects of CP at the knee in a select group of patients with CP by addressing three questions: (1) Can patients with CP perform the required repetitive extension task? (2) Which of the 12 degrees of freedom that define knee kinematics (patellofemoral and tibiofemoral rotations and translations) are abnormal (outside the 95% confidence interval of an able-bodied population average) on a subject-by-subject basis in patients with CP and is the patellar tendon moment arm abnormal in these individual patients with CP? (3) Are the individual kinematic differences consistent with clinical observations (eg, level of involvement, past interventions, pain)?

Materials and Methods

We recruited four patients with CP (Table 1) from the clinical practice of one of the authors (KEA). The patients with CP were screened before the examination to ensure they could perform slow, repetitive leg extension and flexion exercises. Any potential subject was excluded if they had any contraindications to having an MRI scan. Based on a clinical evaluation of the Gross Motor Function Classification System (GMFCS) [10], manual muscle testing, and the physician's rating scale, the knees of the patients with CP were ranked by level of clinical involvement (score = 1, the least involved; score = 5, the most involved). The clinician (KEA) providing the ranking was blind to all results before providing the ranking. For one patient, because time permitted, both knees were examined and two subject numbers were assigned to represent both limbs (S2, left knee; S3, right knee). S2 and S3

Table 1. Demographics of patients with cerebral palsy

Subject number	Diagnosis	Gender	Age (years)	Height (cm)	Weight (kg)	GMFCS score	CIS	Leg	Previous surgical procedures
S1	SD	Male	15	167.6	50.4	1	3	Left	PPL, PGL, PHL
S2*	SD	Female	16	257.5	61.7	1	2	Left	PGL
S3*	SD	Female	16	257.5	61.7	1	1	Right	PGL
S4	SD	Female	15	157.5	50.4	2	5	Left	FDO, STDO, TPL, GL, AL, HFL
S5	SQ	Male	19	172.7	58.5	3	4	Left	FIDO, STDO, PT, MHL, AL, RFT, OCL, SGR, MTCR

* S2 and S3 represent the two limbs from the same subject; GMFCS = Gross Motor Function Classification System; CIS = Clinical Involvement Score; SD = spastic diplegia; SQ = spastic quadriplegia; PPL = percutaneous psoas lengthening; PGL = percutaneous gastrocnemius lengthening; GL = gastrocnemius lengthening; PHL = percutaneous hamstrings lengthening; HL = hamstrings lengthening; MHL = medial hamstrings lengthening; FDO = femoral derotation osteotomy; FIDO = femoral intertrochanteric derotation osteotomy; HFL = hip flexor lengthening; AL = adductor lengthening; TPL = tibialis posterior lengthening; STDO = supermalleolar tibial derotation osteotomy; PT = psoas tenotomy; RFT = rectus femoris transfer; OCL = os calcis lengthening; SGR = Strayer-type gastrocnemius recession; MTCR = medial talonavicular joint capsule reefing.

were similar in that both had experienced minimal surgical intervention (percutaneous gastrocnemius lengthening only) and were ranked as the two highest functioning knees in our population with CP, but knee S3 was more involved than S2. Data from a previous study of knee function in able-bodied volunteers ($n = 34$) were used for comparison [24–26]. In these normal data, no differences in kinematics were found between side or gender. Specifically, across all knee angles, the kinematic differences between the male and female populations ranged from 0.2° to 2.5° and 1.3 to 1.9 mm [24]. Informed assent (with the legal guardian providing consent) or informed consent was obtained from each subject before participating in this study.

Patients were placed supine in a 1.5-T MR imager (LX-9.1M4; GE Medical Systems, Milwaukee, WI) and asked to cyclically extend and flex their knee from approximately 45° flexion to full extension (approximately 0°) at 35 cycles per minute aided by an auditory metronome. A cushioned wedge was placed under the thigh without contacting the posterior knee such that full extension of the leg was attainable. Cushioning supported the head, neck, and lower back. All of these patients were unable to bring their knee through to full extension, so their positioning in the magnet was altered. This limited their motion to a comfortable range that could be consistently repeated at a rate ranging from 22° to 37° per second. Using a sagittal-oblique imaging plane, which was generally perpendicular to the femoral epicondyles and bisected the patella, a full fast PC MRI data set (anatomic and x, y, z velocity images for 24 time frames) was acquired in 2.8 minutes, for a total of 98 cycles. To acquire a data set with sufficient temporal resolution, 46 cycles were required. The data acquired during each of these cycles contributed to all 24 time frames and were not merely averaged. To improve the signal-to-noise ratio, two data sets were acquired (requiring 98 cycles) and the data were averaged in the Fourier domain before being converted into spatial and velocity images [8]. Integrating the velocity data across all time frames allowed the 3-D displacement trajectory of any material point to be tracked throughout the movement cycle without the need to visually locate the point in every time frame [28]. The system bias (0.003 mm; standard deviation, 0.22 mm), accuracy (0.35–0.5 mm), and precision (1.2° , 1.5° , and 0.7° for tibiofemoral flexion-extension, internal-external rotation, and varus-valgus, respectively) are in the same range as tracking implanted beads using biplane radiography [25]. Fastcard images (dynamic anatomic images only) at three axial slice locations were acquired during the movement to establish consistent anatomically based coordinate systems for each data set [24] and to quantify the epicondylar width. The details for the MR scanning were provided previously [24].

The attitudes (the time-dependent 3-D orientation and translation) of the patellofemoral and tibiofemoral joints were individually quantified using the position trajectories of three or more points on each bone derived through the integration of the fast PC data [28]. The initial bone orientation was calculated using anatomically based coordinate systems [24, 29], which were identified in one time frame only (maximum extension). Using matrix multiplication, the attitude of all three bones throughout the movement was defined relative to these anatomic coordinate systems (Fig. 1). Then the patellar and tibial orientations relative to the femur were simplified to three Cardan rotation angles using a body-fixed xyz sequence. The entire movement cycle was used for the integration process, but all further analysis and data presentation were limited to the extension portion of the movement. Thus, an extension movement was defined for knee angles from maximum flexion (approximately 40°) to full extension (approximately 0°).

The 3-D patellar tendon moment arm (Fig. 1) relative to the tibiofemoral finite helical axis (FHA) was determined

Fig. 1 The diagram illustrates primary kinematic parameters. For all bones, the x-direction was medial, the y-direction was superior, and the z-direction was anterior. The femoral origin (not shown) was defined as the most posterior point in the sulcus groove at the level of the epicondyles, the tibial origin (To) was defined as the tibial insertion of the patellar tendon, and the patellar origin (Po) was defined as the most posterior point on the patella midway between the most superior and inferior points on the patella [24]. The 3-D patellar tendon moment arm was defined as the shortest distance (perpendicular distance) from the patellar tendon line of action to the tibiofemoral finite helical axis [25]. For two-dimensional analyses, the tibiofemoral finite helical axis resolves to one point, the center of rotation.

as documented previously [26]. In three dimensions, the patellar tendon moment arm was defined as the shortest distance between the patellar tendon's line of action and

the tibiofemoral FHA (axis of rotation). If the analysis was simplified to two dimensions, then the tibiofemoral FHA resolved to one point (the center of rotation). To perform

Fig. 2 The graphs show scaled patellar and tibial displacements with respect to the femoral coordinate system. All data are scaled by the ratio of the average normal epicondylar width (77.3 mm; standard deviation, 5.9 mm) and the individual subject's epicondylar width. The average of all 34 normal subjects is shown using a solid black line and the solid grey lines indicate the 95% confidence interval (± 2.03 standard deviations). The average is only shown for knee angles where there are more than six subjects (40° to greater than 1°). Each patient with CP is represented by a unique symbol. Although the data were interpolated to single knee angle increments, symbols for each subject are provided at 5° knee angle increments for clarity in the figure. M = medial; L = lateral; I = inferior; S = superior; P = posterior; A = anterior.

Fig. 3 The graphs show orientations of the patella and tibia with respect to the femoral reference system, based on a body-fixed xyz rotation sequence. The average of all 34 normal subjects is shown using a solid black line and the solid grey lines indicate the 95% confidence interval (± 2.03 standard deviations). The average is only shown for knee angles where there are more than six subjects (40° to greater than 1°). Each patient with CP is represented by a unique symbol. Although the data were interpolated to single knee angle increments, symbols for each subject are provided at 5° knee angle increments for clarity in the figure. M = medial; L = lateral; I = inferior; S = superior; P = posterior; A = anterior.

this calculation, the tibiofemoral FHA was defined by the direction of the tibiofemoral angular velocity vector (ω) and the location where the tibiofemoral FHA crossed the femoral midsagittal plane ($f_x = 0$), the sagittal plane point [25]. Because the tibiofemoral FHA was ill-defined as ω approaches zero, data concerning the tibiofemoral FHA

were eliminated if $|\omega|$ was less than 0.3 rad/s, which slightly reduced the overall range of the extension covered by these variables.

To compare the kinematics from each patient with CP with the normal average, data were interpolated to 1° knee angle increments because these data were collected in even

temporal rather than even knee angle increments. Twenty-four frames of data were collected for the entire extension-flexion cycle. To eliminate joint size as a factor in the results, we scaled all distance measures by multiplying the specific measure by the ratio of the average normal epicondylar width to the individual subject's epicondylar width, as was previously reported [19].

A Lilliefors test (a subset of the Kolmogorov-Smirnov test) for normality was performed for each kinematic variable in the normal data at every knee angle in which there were more than five subjects. If the data were normally distributed, then the data for each patient with CP data were compared with the normal average using the z-score [32]. The kinematics for each patient with CP were considered abnormal if the average z-score over all knee

angles was outside the 95% confidence interval of the normal average (greater than 2.03: based on a 33 degrees of freedom, two-sided t table). The Lilliefors test showed the data representing the kinematics (Figs. 2, 3) and the patellar tendon moment arms (Fig. 4) for the normal population were evenly distributed ($p < 0.05$) with a few minor exceptions at specific knee angles. Thus, standard parametric statistics were deemed appropriate for these data.

Results

All four patients with CP could perform the required 2.8 minutes of repetitive knee flexion and extension at 35 cycles per minute within ± 0.5 cycles per minute as determined by the triggering output of the MR scanner.

Considerable differences in the individual knee kinematics of the patients with CP as compared with the normal population were found, with the largest number of abnormal patterns (the average z-score was outside the normal 95% confidence interval) being found in the patellofemoral rotational degrees of freedom (Fig. 3). The most common abnormal displacements (Fig. 2) were increased superior displacement of the patella relative to the femur (patella alta) and increased tibiofemoral medial translation (Table 2). Each patient with CP had a unique pattern of kinematic differences from the normal average. For

Fig. 4 The graph shows scaled patellar tendon moment arms with respect to the tibiofemoral FHA. All data are scaled by the ratio of the average normal epicondylar width (77.3 mm; standard deviation, 5.9 mm) and the individual subject's epicondylar width. The average of all 34 normal subjects is shown using a solid black line and the solid grey lines indicate the 95% confidence interval (± 2.03 standard deviations). The average is only shown for knee angles where there are more than six subjects (39° to greater than 2°). Each patient with CP is represented by a unique symbol. Although the data were interpolated to single knee angle increments, symbols for each subject are provided at 5° knee angle increments for clarity in the figure. At smaller knee angles, S2, S3, and S5 had rapid change in the moment arm. These changes are most likely the result of the manner in which the patellar tendon moment arm is calculated. Specifically, as the angular velocity approaches zero, the patellar tendon moment arm begins undefined. The cutoff for the angular velocity was defined based on the normal population. With a larger population of patients with CP, it may be possible to set more realistic cutoffs and such dramatic changes likely will be unrealistic.

Table 2. Average z-scores for patients with cerebral palsy (S1–S5)

Direction	S1	S2	S3	S4	S5
Patellofemoral translations					
X	-0.9	0.9	0.5	2.1*	-0.2
Y	4.6*	0.9	0.9	3.2*	3.6*
Z	-0.6	-0.3	1.5	-2.0*	0.3
Tibiofemoral translations					
X	0.4	0.2	-0.4	2.4*	2.1*
Y	0.3	0.9	-0.2	1.3	0.4
Z	0.7	0.7	1.1	1.1	0.1
Patellofemoral rotations					
01	-2.6*	0.3	0.9	-3.9*	-3.2*
02	3.4*	-1.5	-1.7	1.2	-0.8
03	2.1*	-0.4	-0.4	3.0*	1.1
Tibiofemoral rotations					
01	-2.6*	1.9	-0.3	0.9	-0.8
02	2.2*	1.2	1.1	3.1*	-0.1
03	-0.3	-1.6	-0.3	-1.0	0.4

The average z-score is the average z-ratio over extension for each subject; *abnormal kinematics average z-score ≥ 2.0 ; + X, + Y, + Z: translations in the medial, superior, and anterior directions, respectively; + 01, + 02, + 03: extension, patellofemoral medial tilt or tibiofemoral internal rotation, and varus rotation, respectively.

example, S1 was abnormal in all the rotational degrees of freedom for the patellofemoral joint but only had patella alta for the translational degrees of freedom. Conversely, S4 was abnormal in all the translational degrees of freedom for the patellofemoral joint, but only had abnormal (increased) patellar extension for the rotational degrees of freedom.

The patellar tendon moment arms for the patients with CP followed the same pattern as the normal average (increasing as the knee extended). Although four of the five knees had increased patellar tendon moment arms, none of these could be defined as abnormal (outside the 95% confidence interval of the normal average).

The data were consistent with clinical findings. The patient represented by S2 and S3 was the least involved of all patients with CP and had patellofemoral and tibiofemoral kinematics that were most closely aligned with the normal population. One exception was the patellofemoral tilt, which was considerably decreased (lateral) for S2 and S3. The more involved limb (left S2) had a greater difference from the normal average than the less involved limb, with considerable differences from the normal average in tibiofemoral flexion and varus. The three most involved patients with CP (S1, S4, S5) had the most differences from the normal average. All had patellar alta, abnormal (increased) patellofemoral extension, and abnormal (increased) tibiofemoral internal rotation (S1 and S4 only). S4 and S5 had previous tibial and femoral derotation osteotomies. Clinical history for these two patients included anterior knee pain consistent with patellofemoral dysfunction. The distal tibial derotation osteotomy surgery (Table 1) for S5 was deemed partially successful at improving the pathologic gait patterns. The surgery for S4 was considered unsuccessful. S4 has persistent gait limitations, poor knee flexion-extension, and residual intoeing. Surgeries, including tibial and femoral derotations, have been recommended for S1. Because of this patient's high level of function (eg, the patient plays competitive nonadapted soccer), the surgery has been declined to date. These surgical histories support the finding of increased tibial rotation for patients S1 and S4, but not for S5.

Discussion

One of the many factors leading to difficulty in predicting treatment outcomes in patients with CP is the lack of accurate measurement tools that quantify the impairment (joint, muscular) level [7]. This impedes the ability of clinicians and researchers to directly quantify the source of functional limitations. By providing 3-D knee kinematic data in a preliminary group of patients with CP, showing

differences compared with the knee kinematics of able-bodied control subjects, and relating these to clinical findings, we describe a new tool in the study of joint impairments. For example, although patella alta has been associated with CP, based on single standing positions using lateral radiography [14, 31], this study showed abnormal 3-D knee kinematics remained throughout the extension movement.

This study was limited to a nonweightbearing partial range of anatomically available extension, which did not diminish the findings because the range of motion achieved by the able-bodied population was greater than the range of motion the patients with CP were able to generate. Also, the repetitive knee flexion-extension movement, requiring self-selected activation of the quadriceps, is often part of a clinical evaluation in CP. Thus, the data from this study should be relevant to more functional tasks. Furthermore, as open MRI technology improves, experiments looking at more functional tasks will become available. Although the patients with CP who participated in this study were able to perform the required repetitive task, this requirement will limit the patients who can be studied (eg, patients with a GMFCS score greater than 3 will likely not have the strength to participate). The noninvasive nature of this experiment and its high accuracy and precision [20, 27] justify these delimitations.

The patellofemoral, in contrast to the tibiofemoral, joint was the most affected in the patients with CP, which agrees with the fact that clinically patients with CP frequently have patellofemoral joint dysfunction [11, 13, 21, 23], limited knee extension strength, and spasticity, all of which contribute to long-term mobility impairments. This could have serious consequences for knee pain and integrity. In adults with CP, the loss of previously obtained functional mobility skills is common. This often is attributed to pain, disuse, restricted joint range of motion, weakness, and endurance. Biomechanical factors are also a major contributing factor. Accurately describing the cause of joint dysfunction [5] may allow more directed treatments and preservation of mobility in patients with CP.

The patellar tendon moment arms could not be compared directly with past work, as there is no literature available concerning the patellar tendon moment arms in CP. Based on the lever-arm dysfunction theory [9, 22, 31], the observed increase, from the normal average, in four of the five knees was unexpected. It is critical to note this theory [9] was established for the hip, ankle, and knee (hamstrings only), based primarily on static radiographs and these internal lever-arm dysfunctions were attributed to bony deformations. In addition, two earlier reports stated, with patella alta, a decrease in patellar tendon moment arm was expected in terminal knee extension [14, 31], but supporting data were not provided. In contrast, a recent

static, two-dimensional MRI study reported no differences in patellar tendon moment arm between patients with patella alta and able-bodied individuals [33]. In our study, three patients with CP presented with patella alta (the patellofemoral superior position was outside the 95% confidence interval), but this did not translate into a decrease in patellar tendon moment arm. A larger cohort of patients with CP currently is being studied so the average patellar tendon moment arm can be compared statistically with that of the normal populations.

The consistency observed between clinical observations and the alterations in joint kinematics and kinetics in the CP population of this study suggests fast PC MRI has potential as a clinical assessment and evaluation tool. For example, S3 and S4 had the largest and smallest patellar tendon moment arms, respectively. This agreed with the clinical finding that S3 was the least and S4 the most involved of all the patients with CP. Also, S4 had the most limited knee movements based on a previous clinical gait analysis. Furthermore, the data obtained in this study may have been influenced by femoral derotation osteotomy and rectus femoris transfer surgeries that S4 and S5 had to correct their reported lever-arm dysfunction. S4 and S5 were the most severely impaired patients, having undergone more extensive corrective surgeries, but only S4's surgery was deemed unsuccessful. This was mirrored in S4's abnormal and S5's normal tibial internal rotation during extension. Studies of subjects' presurgical and postsurgical corrections for reported lever-arm dysfunction are important to determine the extent of lever-arm dysfunction and the effect of surgical treatment on lower extremity function. It seems patellar tendon moment arm lever-arm dysfunction may not exist in all patients with CP and the amount of this dysfunction may indicate the level of impairment.

A previous study used cine PC MRI [2] to study the movement of the rectus femoris and vastus intermedius after rectus femoris transfer surgery in CP ($n = 6$), but data were acquired during passive knee movements. Thus, an understanding of the volitional dynamic control of the knee was not obtained. Given the influence that spasticity and impaired motor control have on active range of motion in patients with CP, this is a serious limitation. Assessing voluntary activation and movement is crucial in determining functional capacity of an individual. Also, our study used a more advanced version of cine PC MRI (fast PC MRI), which decreased the imaging time from 7.5 minutes to 2.8 minutes.

This study describes an approach focused on improving assessment accuracy and specificity, injury prevention, and reducing the influence impairments have on function. This was accomplished by establishing a preliminary comparison of knee kinematic and kinetic properties

between a large population of able-bodied subjects and a population with CP. Considerable differences were observed between the patients with CP and the able-bodied subjects and these differences were consistent with clinical findings. Studying a larger population with CP, including various functional subtypes, before and after major surgery, will allow correlations between various dynamic quantities, clinical findings, and treatment outcomes to be established. This may allow differentiation of the character of patellofemoral and tibiofemoral function in various functional subtypes of CP, which will provide insights into the management of these specific patients. Given that multiple biomechanical, musculoskeletal, and neurologic factors can influence joint function, it is critical to determine the influence of each factor. Accurately assessing the role of lever-arm dysfunction and altered joint kinematics on bone, joint, tendon, and muscle function should help clinicians determine the most appropriate treatments and by doing so likely improve outcomes in patients with CP.

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