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Upper extremity dynamics during Lofstrand crutch-assisted gait in children with myelomeningocele

Brooke A. Slavens [a,b,c,*], Peter F. Sturm [c], Ruta Bajournaite [d], Gerald F. Harris [a,b,c]

[a] Department of Biomedical Engineering, Marquette University, 1515 West Wisconsin Avenue, Milwaukee, WI 53233, USA
[b] Orthopaedic and Rehabilitation Engineering Center, 735 North 17th Street, Academic Support Facility, Suite 105, Milwaukee, WI 53233, USA
[c] Shriners Hospital for Children, 2211 North Oak Park Avenue, Chicago, IL 60707, USA
[d] Department of Population Health, Division of Biostatistics, Medical College of Wisconsin, 8701 Watertown Plank Road, Milwuakee, WI 53226, USA

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ABSTRACT

The use of quantitative models for evaluating upper extremity (UE) dynamics in children with myelomeningocele (MM) is limited. A biomechanical model for assessment of UE dynamics during Lofstrand crutch-assisted gait in children with MM is presented. This pediatric model may be a valuable tool for clinicians to characterize crutch-assisted gait, which may advance treatment monitoring, crutch prescription, and rehabilitation planning for children with MM. Nine subjects with L3 or L4 level myelodysplasia (mean ± S.D. age: 11.1 ± 3.8 years) were analyzed during forearm crutch-assisted gait: (1) reciprocal gait and (2) swing-through gait. Three-dimensional (3D) dynamics of the UE were acquired and the Pediatric Outcomes Data Collection Instrument (PODCI) was administered. The goal of this study was to determine if meaningful differences occur between gait patterns in UE kinematics and kinetics, and if correlations exist between dynamics and functional outcomes.

Temporal-distance parameters showed significant differences between reciprocal and swing-through gait in stride length, and stance duration. All joint ranges of motion were greater during swing-through gait. Thorax, elbow and crutch ranges of motion were found to be significantly different between gait patterns. Kinetic results demonstrated significant differences between reciprocal and swing-through gait, bilaterally, at all joints for the force variables of mean superior/inferior force, range of force, and maximum inferior force. Functional outcomes were strongly correlated with joint dynamics. Accurate quantitative assessment is essential for preventing injury in long-term crutch users. This study has potential for improving clinical intervention strategies and therapeutic planning of ambulation for children with MM.

1. Introduction

Myelomeningocele (MM) is the most common central nervous system birth defect in the United States [1]. It occurs when the neural tube fails to close, which results in a cystic dilatation of meninges and protuberance of the spinal cord through the vertebral defect [2]. Approximately 1340 infants are born with MM each year in the United States [3]. From 1999 to 2001, birth incidence of the disease was reported to be 3.7 cases per 10,000 live births [4]. Patients with MM have functional deficits, including lower limb paralysis and sensory loss [5].

Paraplegia from the myelodysplasia typically causes impairment of mobility, thus leading patients to depend on assistive devices, such as Lofstrand (forearm) crutches, for ambulation. Studies have shown that approximately 50–60% of young adult patients with MM are ambulatory, with around 23% of these patients using an assistive device [5,6]. These devices often require significant upper body strength. During crutch walking, peak axial loads are reported to be up to 35% of body weight [7].

Literature has shown that long-term crutch usage may result in upper limb pathologies, such as destructive shoulder arthropathy, degenerative arthritis of the shoulder and wrist, or carpal tunnel syndrome (CTS) [8,9]. Repetitive impulse loading combined with prolonged wrist extension and radial deviation are proposed risk factors associated with crutch use [10,11]. Klimaitis et al. found that bearing weight through the upper limbs may hasten the development of degenerative arthritis [12]. It was found that large, superiorly directed, weight-bearing forces may potentially threaten glenohumeral joint integrity [13]. Patients using forearm crutches have also reported symptoms associated with CTS [11].

Kinematics and kinetics of the lower extremity have been studied extensively in children with MM using three-dimensional

* Corresponding author at: Orthopaedic and Rehabilitation Engineering Center, Marquette University, Milwaukee, WI 53223, USA. Tel.: +1 414 288 0697; fax: +1 414 288 0713.
E-mail addresses: brooke.slavens@mu.edu (B.A. Slavens), psturm@shrinenet.org (P.F. Sturm), ruta@mcw.edu (R. Bajournaite), geraldfharris@msn.com (G.F. Harris).

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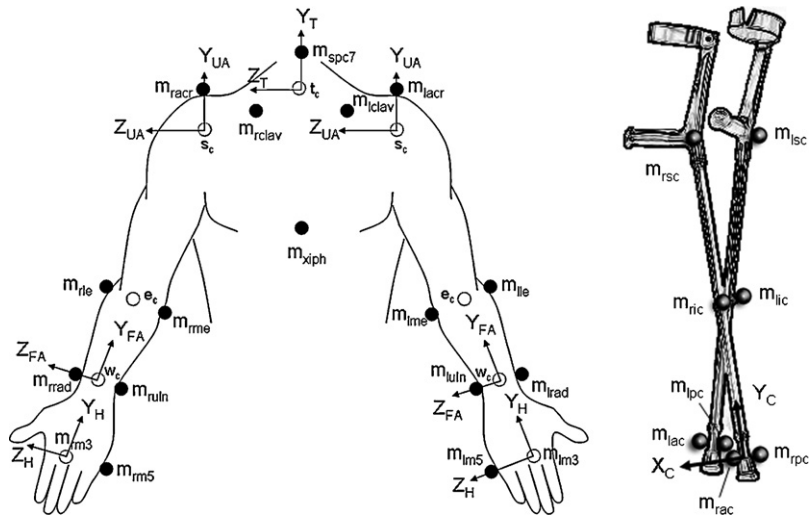

Fig. 1. Upper extremity model marker placement, joint centers, and segmental coordinate systems [1]. Right-handed coordinate systems were constructed following ISB convention with anatomical position being the neutral position [27]. It follows that the *X*-axis is directed anteriorly (abduction/adduction axis), the *Y*-axis is directed superiorly (internal/external rotation axis), and the *Z*-axis directed laterally to the right (flexion/extension axis). Markers are shown as black circles and joint centers are shown as open circles.

(3D) motion analysis [14–18]. However, movements of the upper extremity (UE) during walking have only been investigated to a small extent in children with MM [19–21]. The few existing UE dynamic models lack 3D joint angle calculations, a non-standardized kinematic model, or were not developed for a pediatric MM crutch-user population [19,22–26].

The focus of this study is the design and application of a 3D UE dynamic model for assessment of crutch-assisted gait in children with MM. Current literature does not reveal a standard UE model, therefore, a new model is proposed incorporating International Society of Biomechanics (ISB) standards [27]. Common crutch-assisted gait patterns, reciprocal gait (RG), and swing-through gait (STG), were examined to demonstrate the model's effectiveness.

This study also investigates gait pattern effects and functional correlates. Through evaluation of dynamics and clinical outcomes we will determine how the Pediatric Outcomes Data Collection Instrument (PODCI) could be used more effectively for therapeutic management. It is hypothesized that UE dynamics are strongly correlated with PODCI standardized outcomes. This may further improve our understanding of the relationship among biomechanical and functional parameters, and improve our treatment methods for Lofstrand crutch users.

2. Methods

2.1. Kinematic model

The model consists of seven body segments (i.e., thorax, upper arms, forearms, and hands) and two crutch segments (i.e., right and left crutches) defined using 26 passive markers (Fig. 1 and Table 1). The trunk and upper arm segment are connected by a three degree of freedom shoulder (glenohumeral) joint, which follows the ISB recommendations for segment rotation [23,27]. Two degree of freedom elbow and wrist joints connect the upper arm, forearm, and hand segments. Elbow motion is expressed as dynamic flexion/extension and pronation/supination to control varus/valgus of the elbow [23,28,29]. The thorax coordinate system is based on the method of Nguyen and Baker [21]. The joint coordinate systems of the upper arm and forearm follow ISB suggested convention [27]. Global wrist motion was determined by modeling the third metacarpal of the hand with respect to the forearm. Vicon BodyBuilder V3.6 (Vicon Motion Systems, Ltd., Oxford, England) was used for model development. The kinematic model was previously evaluated for accuracy and precision [23].

Rotations were described using Euler angles (*Z*–*X*–*Y*). The sequence of Euler angles was chosen such that the first two rotations defined the orientation of the longitudinal axis of the bone or trunk, and the third rotation was about this axis (axial rotation). The Euler rotation sequence corresponds to flexion/extension (*Z*), adduction/abduction (*X*), and internal/external rotation (*Y*). This sequence helps to minimize the potential gimbal lock. The thorax and crutch rotations were described with reference to the global coordinate system, while all other rotations were described with respect to the proximal coordinate system.

2.2. Kinetic model

Kinetic equations were formulated according to the inverse dynamics Newton–Euler approach and programmed using BodyBuilder. The model calculates 3D joint forces and moments for the crutch (crutch/hand interface), wrist, elbow, and shoulder. The joint forces and moments were expressed in the proximal segmental coordinate frame.

The accuracy of the force transducers was examined prior to subject testing. Force data was simultaneously collected from a calibrated force plate (AMTI; Watertown, MA) and crutch transducers during reciprocal and swing-through gait by having the crutch tip contact the force plate for each walking trial completed by one subject. Superior/inferior force data from 10 trials each of reciprocal and swing-through gait were analyzed for the right and left crutch transducers. The mean error of the difference between the force plate and transducer was calculated to determine accuracy.

2.2.1. Crutch hardware

Lofstrand crutches (Walk Easy, Inc.; Delray Beach, FL) were instrumented with MCW-6-500 walker sensors (AMTI; Watertown, MA) to measure applied reaction forces and moments along the *X*-, *Y*-, and *Z*-axes. AMTI MSA-6 high gain amplifiers provided excitation and amplification of the transducers. The sampling frequency of the force transducers was 1800 Hz.

2.3. Patient population

Nine subjects, aged 11.1 ± 3.8 years, participated in the research study. Written parental consent and subject assent was obtained in compliance with the Institutional

Table 1
Upper extremity kinematic model marker names, marker locations, and corresponding segments.

Marker	Location	Segment
m_{spc7}	Spinous process of C7 vertebra	Thorax
m_{xiph}	Xiphoid process	Thorax
$m_{r/lclav}$	R/L clavicle	Thorax
$m_{r/lacr}$	R/L acromion	Upper arm
$m_{r/lme}$	R/L medial epicondyle	Upper arm and forearm
$m_{r/lle}$	R/L lateral epicondyle	Upper arm and forearm
$m_{r/lrad}$	R/L radial styloid	Forearm and hand
$m_{r/luln}$	R/L ulnar styloid	Forearm and hand
$m_{r/lm3}$	R/L 3rd metacarpal	Hand
$m_{r/lm5}$	R/L 5th metacarpal	Hand
$m_{r/lac}$	R/L anterior crutch	Crutch
$m_{r/lpc}$	R/L posterior crutch	Crutch
$m_{r/lsc}$	R/L superior crutch	Crutch
$m_{r/lic}$	R/L inferior crutch	Crutch

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Table 2
Force and moment variable names and descriptions.

Variable name	Acronym	Measure (units)	Abbreviation
Mean force	MF	% Body weight (N/N)	% BW
Maximum force	MAXF	% Body weight (N/N)	% BW
Percent where maximum force occurred	PMF	% Gait cycle	N/A
Range of force	RF	% Body weight (N/N)	% BW
Impulse	I	Newton-second (N s)	Ns
Maximum rate of loading	MRL	Newton/second (N/s)	N/s
Percent where maximum rate of loading occurred	PMRL	% Gait cycle	N/A
Force threshold index	FTI	% Gait cycle	N/A
Mean moment	MM	% Body weight × height (N m/N m)	% BWH
Maximum moment	MAXM	% Body weight × height (N m/N m)	% BWH
Percent where maximum moment occurred	PMM	% Gait cycle	N/A
Range of moment	RM	% Body weight × height (N m/N m)	% BWH
Moment threshold index	MTI	% Gait cycle	N/A

Review Board at Shriners Hospital for Children in Chicago. The subject population included four females and five males, ranging from 6 to 17 years. All subjects had an L3 or L4 level myelodysplasia and were ambulatory using Lofstrand crutches in both reciprocal and swing-through gait patterns. Subjects who had undergone orthopaedic surgery in the past year were excluded from the study.

2.4. Data collection and analysis

Subjects ambulated with reciprocal and swing-through gait patterns at a self-selected speed using the instrumented Lofstrand crutches. Three-dimensional motions of the reflective markers were recorded by a 14-camera Vicon MX motion analysis system (Vicon; Oxford, England). The sampling frequency of the motion capture data was 120 Hz. Mathematical synchrony was provided through the Vicon system. The analog data was down sampled to the frequency of the motion data, similar to previous techniques [30,31]. Vicon Workstation V4.6 (Vicon; Oxford, England) was used to generate 3D coordinates of the markers, filter the data, and implement the model. Matlab (The MathWorks, Inc.; Natick, MA) was used for additional analyses, including calculation of joint ranges of motion, joint reaction force and moment parameters, statistical computation of the Wilcoxon paired-sample test, and graphics. Data were time normalized to 100% gait cycle and averaged over the gait cycles, in a similar manner to our previous work [23,32–34].

Temporal-distance parameters including cadence (steps/min), walking speed (m/s), stride length (m), and stance duration (%) were calculated for all subjects. Joint range of motion (degrees) was calculated for kinematic comparison of gait patterns. Kinetic parameters were computed for comparison of the joint forces and moments for all subjects (Table 2). Impulse (Ns) was determined by computing the area of the force over the gait cycle. Maximum rate of loading (N/s) was determined from the slope of the force for the entire gait cycle. The force threshold index was the total percent of the gait cycle that the force exceeded 90% of the maximum force. The moment threshold index was the total percent of the gait cycle that the moment exceeded 75% of the maximum moment. The dynamic parameters were statistically compared using the nonparametric paired-sample Wilcoxon signed rank test ($p = 0.05$).

All subjects were evaluated by the PODCI to examine how UE joint stresses affect health and function. Five functional categories serve as the focus of this study: (1) upper extremity and physical function, (2) transfers and basic mobility, (3) sports and physical function, (4) pain/comfort, and (5) global function and symptoms. The Pearson's and Spearman rank correlation coefficients were computed to identify the strength of the relationships between the dynamic parameters and PODCI categories.

3. Results

3.1. Temporal-distance parameters

Cadence, walking speed, stride length, and stance duration were compared during reciprocal gait (RG) and swing-though gait (STG). Cadence (RG: 70 steps/min, STG: 77 steps/min), walking speed (RG: 0.5 m/s, STG: 0.7 m/s), and stride length (RG: 0.8 m, STG: 1.0 m) were greater during swing-through gait than reciprocal gait, while stance duration decreased (RG: 60%, STG: 50%). Significant differences between reciprocal and swing-through gait were found for stride length ($p = 0.035$) and stance duration ($p = 0.016$).

3.2. Upper extremity kinematics

Joint motion in the sagittal plane during reciprocal and swing-through gait was analyzed (Fig. 2). Right and left sides were found to be similar for all joint ranges of motion.

3.2.1. Crutches

The crutches demonstrated fore and aft tilt throughout the gait cycles. The mean crutch ranges of motion were significantly different between reciprocal (39°) and swing-through (47°) gait on right ($p = 0.016$) and left ($p = 0.008$) sides.

3.2.2. Wrists

The wrists displayed extension throughout the gait cycles. The mean wrist joint ranges of motion were similar (right: 17°, left: 15°) between gait patterns.

3.2.3. Elbows

The elbows remained in flexion during the gait cycles. The mean elbow joint ranges of motion were significantly different between reciprocal (29°) and swing-through (38°) gait for right ($p = 0.008$) and left ($p = 0.039$) sides.

3.2.4. Shoulders

The shoulders moved between flexion and extension during the gait cycles. Mean shoulder joint ranges of motion were not significantly different between gait patterns (RG: 41°, STG: 47°).

3.2.5. Thorax

The thorax remained in flexion throughout the gait cycles. The thorax range of motion (RG: 13°, STG: 21°) was significantly different between gait patterns ($p = 0.023$).

3.3. Upper extremity kinetics

The superior/inferior force of the transducers was compared to the force plate to determine accuracy. The mean error ranged from 2.9 N (RG) to 6.8 N (STG). This represented an average difference of 0.4% BW (RG) and 1% BW (STG).

The mean joint forces (superior/inferior) and moments (flexion/extension) during reciprocal and swing-through gait were analyzed (Figs. 3 and 4). Forces were greater during swing-through gait than reciprocal gait for all joints bilaterally.

3.3.1. Crutches

The mean compressive (inferior) and tensile (superior) peak crutch forces during swing-through gait exceeded those of

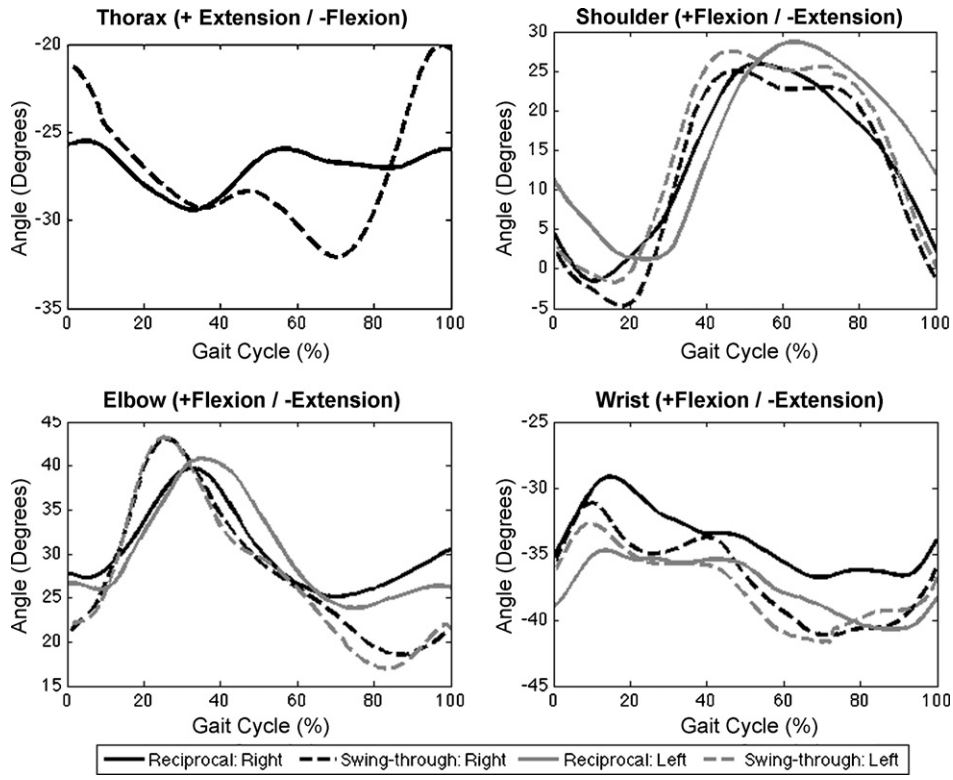

Fig. 2. Mean upper extremity kinematics (sagittal plane). Mean joint angles of the thorax, shoulders, elbows, wrists, and crutches during reciprocal gait (solid) and swing-through gait (dashed) are plotted from 0% to 100% of the gait cycles. Right (black); Left (gray).

reciprocal gait. Significant differences between gait patterns at the crutch forces included the mean (right: $p = 0.004$; left: $p = 0.004$), range (right: $p = 0.004$; left: $p = 0.008$), impulse (left: $p = 0.039$), maximum inferior force (right: $p = 0.004$; left: $p = 0.008$), percent where maximum inferior (right: $p = 0.004$; left: $p = 0.008$) and superior force occurred (left: $p = 0.039$), and threshold index of inferior force (left: $p = 0.008$).

The mean crutch moment was significantly greater during swing-through gait than reciprocal gait (right: $p = 0.004$; left: $p = 0.008$). In addition, the maximum flexion moment was

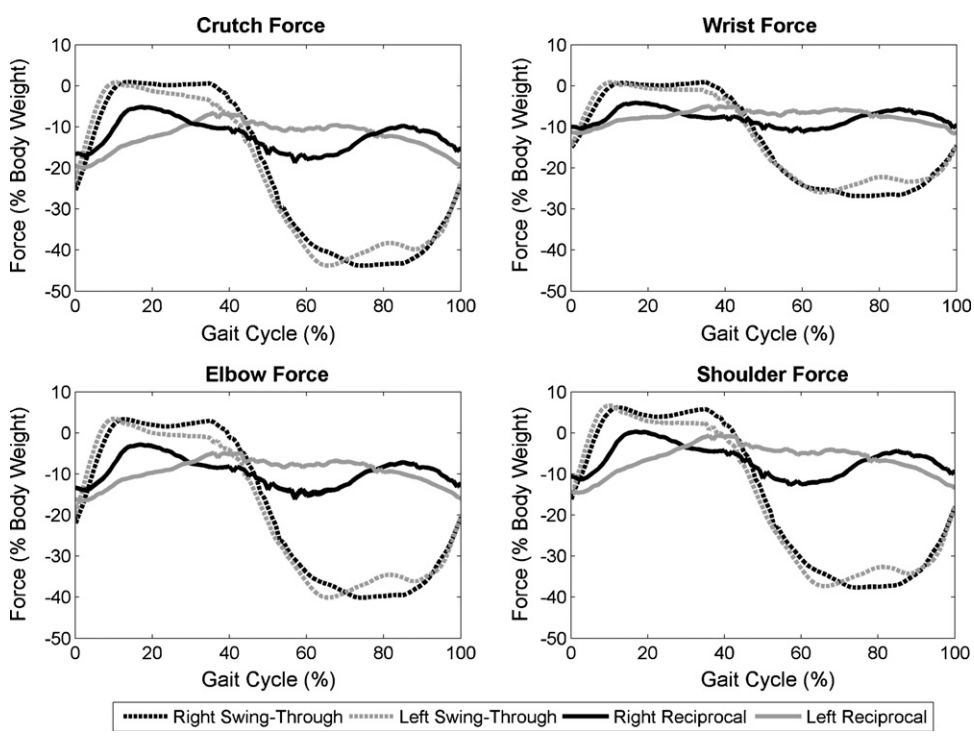

Fig. 3. Mean joint forces for the right (black) and left (gray) crutches, wrists, elbows, and shoulders. Reciprocal gait (solid); swing-through gait (dashed). Superior force (+); inferior force (−). Joint forces are positive if they align with the *Z*-axis (lateral right), *X*-axis (anterior), and *Y*-axis (superior) in the local segmental system. Positive joint forces along the *Y*-axis correspond to tension on the joint, whereas negative joint forces correspond to joint compression.

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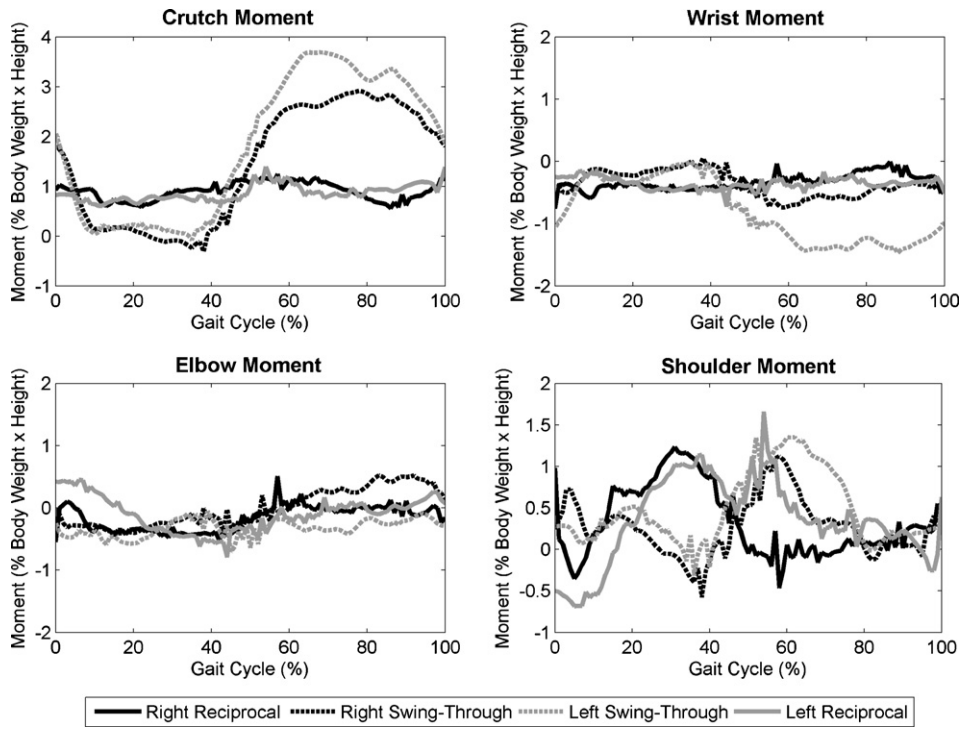

Fig. 4. Mean joint moments for the right (black) and left (gray) crutch, wrists, elbows, and shoulders. Reciprocal gait (solid); swing-through gait (dashed). Flexion moment (+); extension moment (−). Positive joint moments are flexion, adduction, and internal rotation for the right side.

significantly different between reciprocal and swing-through gait (right: $p = 0.008$).

3.3.2. Wrists

The mean peak wrist forces during swing-through gait were greater than during reciprocal gait. Significant differences between gait patterns at the wrist forces include the mean force (right: $p = 0.004$; left: $p = 0.004$), range of force (right: $p = 0.008$; left: $p = 0.008$), and maximum inferior force (right: $p = 0.008$; left: $p = 0.008$). Significant differences at the left wrist were the impulse ($p = 0.008$), threshold index of inferior force ($p = 0.004$), and percent of gait cycle where maximum superior force occurred ($p = 0.020$).

The mean wrist moment ranged between 0% BWH and −1.5% BWH and was greater during swing-through gait than reciprocal gait on right and left sides. The mean left wrist flexion/extension moment was significantly different between reciprocal and swing-through gait ($p = 0.004$).

3.3.3. Elbows

The mean peak elbow forces were greater during swing-through gait than during reciprocal gait. The mean elbow force (right: $p = 0.004$; left: $p = 0.004$), range of force (right: $p = 0.004$; left: $p = 0.008$), impulse (right: $p = 0.039$; left: $p = 0.004$), maximum inferior force (right: $p = 0.004$; left: $p = 0.008$) and percent of gait cycle where maximum inferior force occurred (right: $p = 0.020$; left: $p = 0.004$) were found to be significantly different between reciprocal and swing-through gait. The mean threshold index of inferior force (left: $p = 0.008$), percent of gait cycle where maximum superior force occurred (left: $p = 0.008$), and threshold index of superior force (right: $p = 0.020$) also demonstrated significance.

The mean elbow moment ranged between 0.5% BWH and −0.5% BWH during the gait patterns. The elbow moment did not present significant differences.

3.3.4. Shoulders

Mean peak shoulder forces during swing-through gait exceeded those of reciprocal gait. Significant differences included the mean force (right: $p = 0.004$; left: $p = 0.004$), range of force (right: $p = 0.004$; left: $p = 0.008$), impulse (right: $p = 0.020$; left: $p = 0.008$), maximum inferior force (right: $p = 0.004$; left: $p = 0.008$), percent of gait cycle where maximum inferior force occurred (right: $p = 0.012$; left: $p = 0.004$) and threshold index of inferior force (right: $p = 0.020$; left: $p = 0.012$). Other unilateral significant differences were the percent of gait cycle where maximum inferior force rate of loading (left: $p = 0.008$) and maximum superior force (left: $p = 0.039$) occurred, and threshold index of superior force (right: $p = 0.023$).

The mean shoulder moment ranged between 2% BWH and −1% BWH during the gait patterns. No significant differences at the shoulder moment were found between gait patterns.

Table 3
Summary of significant correlations between dynamic metrics and PODCI.

PODCI	ROM	I	MAXF (inferior)	FTI	MAXM (flexion)	PMM (flexion)	MAXM (extension)	PMM (extension)
Upper extremity and physical function	S, E, W	E, W	W	S, E, W				
Transfers and basic mobility		S		E, W	E, W	W		S
Sports and physical function					S, E			
Pain/comfort			W				S	S
Global function and symptoms		S, E, W		W	S, E			

Significant correlations ($R > 0.7$ and $p < 0.05$): ROM, range of motion; S, shoulder; E, elbow; W, wrist.

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3.4. Pediatric Outcomes Data Collection Instrument (PODCI)

Important clinical findings were revealed from the current study, which may prove useful during continued, longer-term applications. Numerous correlations were found between dynamic parameters and PODCI functional categories (Table 3). Cadence, walking speed, and stride length correlated to global function and symptoms, and transfers and basic mobility during swing-through gait.

4. Discussion

A unique UE dynamic model for assessment of crutch-assisted gait in children with MM is presented. The UE model has a three degree of freedom shoulder (glenohumeral) joint, and two degree of freedom elbow and wrist joints. The current model simplifies methods for joint center determination by using fixed centers of rotation. Regression techniques are another option for determining the centers of rotation [29,35–37]. The model was based on previous work and literature [23,27,32]. Data from this study expresses the relative magnitude of UE kinetics as percent body weight (% BW) and percent body weight times height (% BWH). For comparison purposes to the lower extremity, Noreau et al. investigated dynamics of crutch walking and found normal hip moments to peak at approximately 0.4 N m/kg [38]. Other studies investigating lower extremity forces during crutch-assisted gait have been reported [17,39,40]. Novel research to quantify UE motion during crutch-assisted gait in children with MM is presented.

Temporal-distance parameters showed significant differences between reciprocal and swing-through gait in stride length and stance duration. Stance duration decreased when using a swing-through gait pattern, which indicates longer time spent in the swing phase. The longer stride length during swing-through gait suggests this pattern be used for ambulating quickly. The decreased stance duration during swing-through gait indicates longer time spent in the swing phase. All joint ranges of motion were found to be greater during swing-through gait. This can be attributed to the large joint demands placed on the UE during swing-through gait. Significant differences between reciprocal and swing-through gait range of motion were detected at the thorax, elbows, and crutches. The ranges of motion agree with those reported by Requejo et al., Noreau et al., and Liggins et al. [26,38,41]. Model similarities include marker placement, segments, and the use of anthropometric data with the inverse dynamics method for calculating joint reaction forces and moments.

Large joint demands were placed on the UE during crutch-assisted gait. Long-term usage of the swing-through gait pattern may lead to upper limb pathology, such as shoulder arthritis, due to the high compression forces at the joints. Significant differences between reciprocal and swing-through gait were found at all joints (right and left sides) for the force variables of mean superior/inferior force, range of force, and maximum inferior force. Other force variables that were found to be significantly different at most joints include the impulse, percent of the gait cycle where the maximum inferior force occurred, and threshold index of inferior force. The earlier occurrence of peak forces during reciprocal gait than swing-through gait indicates that stability must be established sooner in the reciprocal gait cycle to prevent falling, especially at slow walking speeds. The early load may also be associated with an attempt to slow the walking speed, since the upper extremities largely control balance. Several significant differences between gait patterns were found when analyzing joint moment variables, including mean flexion/extension moment and maximum flexion moment.

The joint forces and moments agree with those reported by Haubert et al., Requejo et al., Noreau et al., and Liggins et al. [7,26,38,41]. Although Haubert et al. investigated UE dynamics during reciprocal gait in subjects with spinal cord injury, the joint force and moment results were similar [7]. Requejo et al. reported handle forces to be similar to the distal crutch reaction force, while cuff forces ranged from 7 N (0.74% BW) to 18 N (1.9% BW) during reciprocal gait in one adult subject [26]. Due to this report, cuff forces were assumed to be negligible and were not included in this model, while the superior/inferior transducer force was assumed to act in the line of the crutch shaft and third metacarpal of the hand. It is possible that future inclusion of handle and cuff forces may alter the dynamic patterns.

The model was shown to be effective for detecting significant differences between reciprocal and swing-through crutch-assisted gait in children with MM. It will be used for future studies involving further characterization of dynamic gait in children with MM. The information gained in this study may also be useful to develop an improved rehabilitation protocol and to gain a better understanding of UE dynamics during Lofstrand crutch-assisted gait.

Currently, no studies exist which quantify the relationship between clinical measures and UE dynamics during Lofstrand crutch-assisted gait in children with MM. Range of motion was correlated to upper extremity and physical function during reciprocal and swing-through gait at the right and left crutches. This demonstrates that crutch range of motion could be used to predict UE function. Main findings from the correlations studies showed strong relationships between the PODCI outcomes and the kinetic metrics of maximum inferior force, impulse, threshold index of inferior force, and maximum flexion and extension moments. The biomechanical metrics of the crutches, wrists, elbows, and shoulders can be used to predict upper extremity function, transfers and basic mobility, sports and physical function, pain/comfort, and global function and symptoms. These outcomes offer insight about a subject's activity, participation, and quality of life. These tools also provide clinicians with additional information about a subject, which may be used to impact further treatment and rehabilitation strategies.

Conflict of interest

There are no conflicts of interest.

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