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# A Dynamic Model of the Upper Extremities for Quantitative Assessment of Lofstrand Crutch-Assisted Gait

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*Abstract*— **Appropriate models for quantitative evaluation of upper extremity dynamics in children with myelomeningocele are limited. Therefore, a three-dimensional (3D) biomechanical model of the upper extremities was developed for quantification during Lofstrand crutch-assisted gait in children with myelomeningocele. The model accurately tracks the joint angles of the trunk, shoulders, elbows, wrists, and crutches. Lofstrand crutches are instrumented with six-axis load cells to obtain force and moment components. The model is applied while performing crutch-assisted ambulatory patterns (alternate gait and swing-through gait). Analysis indicates that the model is suitable for quantifying upper extremity motion during crutch-assisted gait. This model has been designed for dynamic assessment of ambulatory patterns (upper and lower extremities) that present with pediatric myelomeningocele. It is hoped that the study findings will prove useful through advances in treatment monitoring, crutch prescription and therapeutic planning.**

*Keywords*— **3D motion analysis, Lofstrand crutches, myelomeningocele (MM), upper extremity, and kinematics.**

## I. INTRODUCTION

Myelomeningocele (MM) is the most common major central nervous system birth defect in the United States [1]. Birth prevalence of the disease was reported to be 4.4-4.6 cases per 10,000 live births from 1983-1990 [2]. Due to increased survival of individuals with myelomeningocele it is important that the disease is better understood in order to improve treatment procedures [1].

Kinematics and kinetics of the lower extremity during crutch-assisted gait have been studied extensively in children with MM using 3D motion analysis [3-7]. Movements of the upper extremity (i.e. trunk, shoulder, elbow and wrist) during walking have been investigated to a small extent in children with MM [8-10]. A pediatric upper extremity model may be valuable to clinicians by providing a detailed description of joint motions (kinematics) and forces (kinetics) characteristic of crutch-assisted gait. The few existing UE dynamic models lack 3D joint angle calculations [8] or were not developed for pediatric (MM) application [11-14]. Standardization is a challenge with current upper extremity models. The ISB has written a set of suggested standards for modeling the UE, which are necessary for easy communication among clinicians and researchers [15].

In this study, a new multi-segment 3D kinematic model was applied to examine differences in joint orientation during alternate and swing-through crutch-assisted gait. These patterns are characteristic of those frequently used to ambulate in individuals with myelomeningocele. The analysis is designed to identify differences in upper extremity movement during the two types of Lofstrand crutch-assisted gait. It is hoped that the study findings will prove useful through advances in treatment monitoring, crutch prescription and therapeutic planning.

## II. METHODOLOGY

The UE model is composed of seven segments: 1) trunk, 2) right upper arm, 3) right forearm, 4) right hand, 5) left upper arm, 6) left forearm, and 7) left hand. The upper extremity model was previously evaluated for accuracy and used in a pilot study [16]. Eighteen passive reflective markers were placed on bony anatomical landmarks to define the body segments (Table 1). Four markers were also placed on each crutch. The trunk marker placement and joint coordinate system were designed to give an accurate representation of trunk kinematics in children with MM, as investigated in 2006 by Nguyen et al. [9]. The joint coordinate systems of the upper arm and forearm follow convention suggested by the ISB standards committee. Global wrist motion is determined by modeling the motion of the third metacarpal [12, 15]. Kinematics of the trunk, shoulder, elbow, wrist, and crutches are determined three-dimensionally.

TABLE I
ANATOMICAL LANDMARKS AND BODY SEGMENTS

| Anatomical Landmark | Body Segment |
|---|---|
| C7 Vertebral Process | Trunk |
| L/R Clavicles | Trunk |
| Xiphoid process | Trunk |
| L/R Acromion Process | Upper Arm |
| L/R Lateral Epicondyle | Upper Arm and Forearm |
| L/R Medial Epicondyle | Upper Arm and Forearm |
| L/R Ulnar Styloid | Forearm and Hand |
| L/R Radial Styloid | Forearm and Hand |
| L/R 3rd Metacarpal | Hand |
| L/R 5th Metacarpal (lateral) | Hand |

A 15-camera Vicon 524 system (Vicon Motion Systems, Inc., Lake Forest, CA) captured the UE marker patterns at 120 Hz. Joint angles were determined using 3D Euler calculations. Euler rotations, sequenced Z-Y-X,

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express the joint angles (distal with respect to proximal), utilizing each segment's local coordinate system. The trunk and crutch segments are described relative to the lab coordinate system.

The Lofstrand crutches (Walkeasy, Inc., Delray Beach, FL) are instrumented with Advanced Mechanical Technology, Inc (Watertown, MA) walker sensors; model MCW-6-500. The sensors are located in the distal part of each crutch to measure the applied reaction forces and moments (Figures 1 and 2). The sensors measure three orthogonal force and moment components along the X, Y and Z axes, producing a total of six outputs.

In order to demonstrate the application of the model, upper extremity joint motion, crutch forces, and crutch moments were recorded from a normal subject during repeated walking trials. An alternating gait pattern and a swing-through gait pattern were performed by the subject to simulate the patterns typical of a subject with myelomeningocele. The subject walked at a self-selected pace along a 6 meter walkway until five successful trials were completed for each gait pattern. The subject used the instrumented bilateral forearm crutches, which recorded the applied reaction forces and moments while walking.

Fig. 1. Instrumented Lofstrand crutches

Fig. 2. Six-component AMTI sensors

Analysis was completed with a Vicon Workstation (Vicon Motion Systems, Inc.; Lake Forest, CA), Excel software (Microsoft Corporation, Redmond, WA), and Matlab (The MathWorks, Inc.; Natick, MA). All data was averaged over five gait cycles and time normalized for right and left sides to 100% gait cycle. The data was processed for every 2% of the gait cycle. Trunk, shoulder, elbow and wrist range of motion in the sagittal plane was calculated during alternate and swing-through gait. Lofstrand crutch mean peak force was determined for alternate gait and swing-through gait.

## III. RESULTS

The mean sagittal plane joint motion during alternate gait and swing-through gait patterns are displayed in Figures 3 and 4, respectively. The joint angles of the right and left sides are overlaid in the plots, where right is solid and left is dashed.

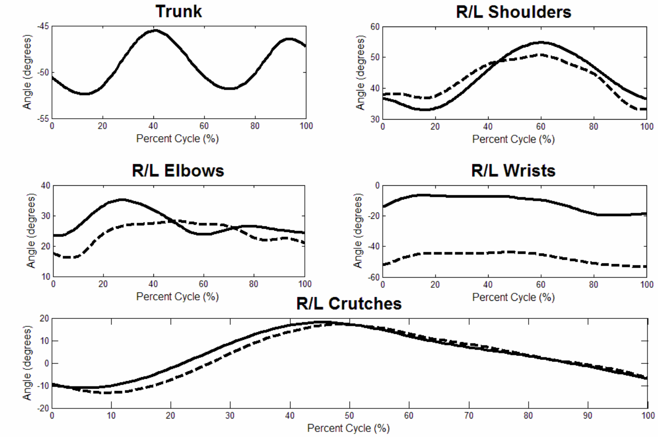

Fig. 3. Mean joint angles during alternate gait. The right side is solid and the left side is dashed.

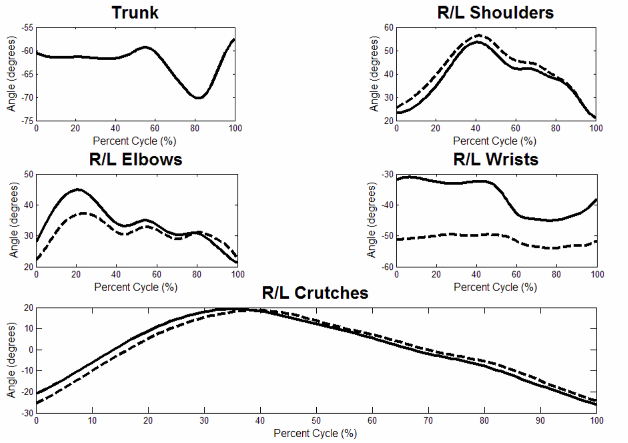

Fig. 4. Mean joint angles during swing-through gait. The right side is solid and the left side is dashed.

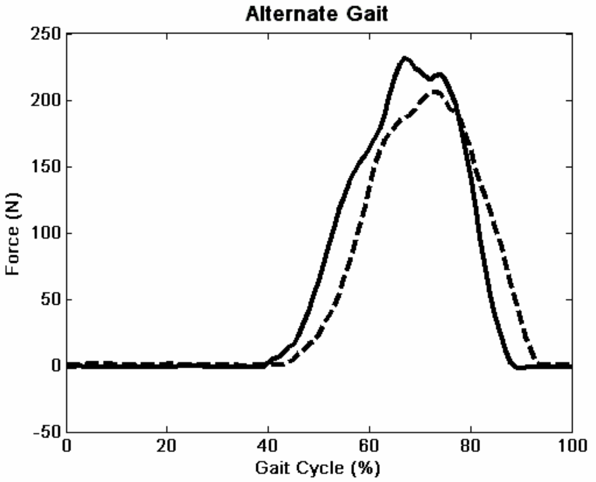

Fig. 5. Lofstrand crutch distal forces (superior) during alternate gait. The right side is solid and the left side is dashed.

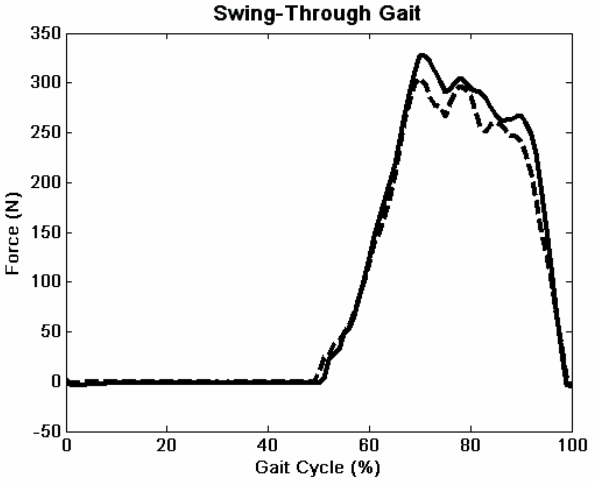

Fig. 6. Lofstrand crutch distal forces (superior) during swing-through gait. The right side is solid and the left side is dashed.

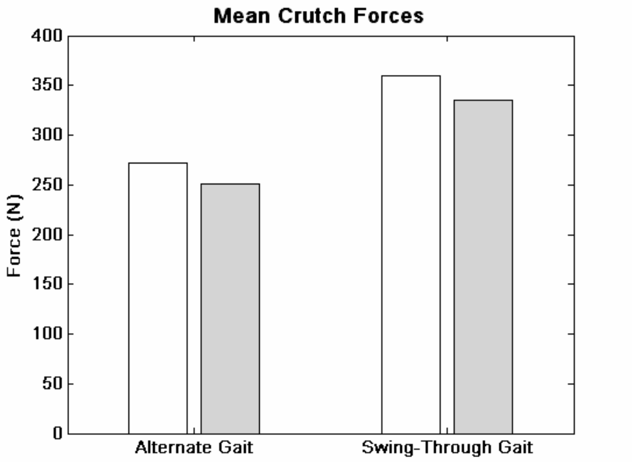

Fig. 7. Mean peak Lofstrand crutch distal forces (superior) during alternate and swing-through gait. Right side is white, left side is gray.

For both gait patterns, the joint angles of the trunk, shoulder and elbow remain flexed throughout the gait cycle, while the wrist joint angles remain extended, although they have differing pattern morphology. Alternate and swing-through gait patterns differ markedly with significant contrast in the range of joint motion (flexion/extension). Swing-through gait statistically shows a larger range of motion in all joints than in alternate gait ($p \leq 0.05$).

Representative trials of Lofstrand crutch distal forces during alternate gait and swing-through gait cycles are displayed in Figures 5 and 6, respectively. The crutch distal forces of the right and left sides are overlaid in the plots, where right is solid and left is dashed. Figure 7 displays the mean peak distal crutch forces for right and left sides during alternate gait and swing-through gait. The mean peak crutch distal forces were higher for both right and left sides during swing-through gait than reciprocal gait.

## IV. DISCUSSION

The model is shown to be effective in detecting differences between upper extremity joint motion patterns and crutch forces during alternate and swing-through crutch-assisted gait. The model is considered to be suitable for further application and study to quantify upper extremity motion in pediatric individuals with MM. The information gained in this study may be useful in future studies to develop an improved assessment protocol and to better understand the upper extremity dynamics of Lofstrand crutch-assisted gait. Future work includes calculating joint kinetics, characterizing these dynamic patterns and identifying correlations with standardized clinical and functional (outcomes) assessment tools.

## V. CONCLUSION

The system has been successfully applied to the evaluation of upper extremity dynamics during gait. The kinematic tracking capability and kinetic acquisition is suitable for pediatric MM application.

Testing with a MM population is planned to quantify differences in alternate gait and swing-through gait patterns. Results of this study may be useful in therapeutic planning, treatment monitoring and crutch prescription.

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