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Upper Extremity Wheelchair Kinematics in Children with Spinal Cord Injury

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Abstract—**Current methods for the evaluation of upper extremity dynamics during wheelchair mobility in children are limited. The goal of this study was to characterize upper extremity joint kinematics during wheelchair mobility. A 3-D biomechanical model of the upper extremities is presented for kinematic assessment of manual wheelchair propulsion in children with Spinal Cord Injury (SCI). The bilateral upper extremity model consists of the thorax, upper arms, forearms, and hands. The model was applied to thirteen (13) children with SCI. Joint angles and joint ranges of motion of the shoulders, elbows, and wrists were quantified. Peak joint motions during the stroke cycle were compared between right and left sides for further insight to mobility patterns. This work will provide insight to be used in future kinetic studies of wheelchair mobility.**

Keywords— Spinal Cord Injury, upper extremity, kinematics, wheelchair.

I. INTRODUCTION

Spinal Cord Injury (SCI) is a leading pediatric pathology associated with wheelchair usage. It is estimated that approximately 259,000 persons are living with SCI in the United States. The estimated annual incidence is approximately 40 cases per million population, or approximately 12,000 new cases each year [1].

Over 90% of all wheelchair users are manual wheelchair users [2]. Manual wheelchair propulsion is highly repetitive and imposes considerable weight-bearing demands on the upper extremities [3]. Joint loads at the shoulder associated with propulsion range from 7% body weight to 11% body weight [4, 5]. In the sagittal plane, maximum glenohumeral loading typically occurs at a peak extension, which may leave the shoulder at risk for injury. It has been documented that over 50% of manual wheelchair users with SCI are likely to develop upper limb pain and injury [6]. Research has shown that long-term usage may lead to the development of pain and upper limb pathologies, including destructive shoulder arthropathy, coracoacromial pathology, degenerative arthritis of the shoulder and wrist, and carpal tunnel syndrome [5, 7, 8]. Estimates of shoulder pain among manual wheelchair users with paraplegia range from 30% to 73% [4, 7, 9].

We propose a 3-D upper extremity kinematic model for the evaluation of wheelchair propulsion in children with SCI. A better understanding of joint demands may help answer many questions about the biomechanical mechanisms associated with upper limb pathology, wheelchair prescription, and propulsive strategies. These data may also be beneficial to further promote injury prevention, patient education, diagnosis, and treatment within the population of pediatric wheelchair users.

II. METHODOLOGY

A. Kinematic Model

The upper extremity kinematic model includes one wheelchair segment and seven rigid body segments: thorax, right/left upper arms, right/left forearms, and right/left hands. Shoulder, elbow, and wrist joints connect the rigid-body segments. Sixteen markers (14 mm diameter) were placed on bony anatomical landmarks of the upper body to determine the kinematics of the thorax, shoulders, elbows, and wrists during mobility (Fig 1). Five markers were also placed on the wheelchair to calculate its motion. The model follows the International Society of Biomechanics (ISB) recommendations for joint coordinate system design [10]. Therefore, the segmental axes were created with the X-axis directed anteriorly, the Y-axis directed superiorly, and the Z-axis directed laterally. The shoulder joint center was determined by locating the humeral head through marker placement and anthropometric measurements. The elbow joint center was located at the midpoint of the medial and lateral epicondyles. The wrist joint center was defined as the midpoint of the radial and the ulnar styloids. Joint rotations are described using Euler angles, sequenced Z-X-Y corresponding to sagittal, coronal, and transverse motions. The distal coordinate system is described with respect to the proximal coordinate system. The custom built biomechanical model was created using BodyBuilder (Vicon, Oxford Metrics, Oxford, UK).

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(a) (b)

Fig. 1. Upper extremity kinematic model. (a) Marker placement and global coordinate system. (b) Subject propelling wheelchair in the motion analysis laboratory.

B. Participants

Thirteen subjects with SCI who were manual wheelchair users participated in the study. The population age range was from 9-25 years. Subjects presented with incomplete or complete SCI. Assessments were completed at Shriners Hospital for Children, Chicago as part of their routine clinical care.

C. Data Collection, Processing and Analysis

Each subject propelled their wheelchair along a 15 meter walkway at a self-selected pace for multiple trials. Three-dimensional (3-D) motion data was collected at 120 Hz using a 14 camera (MX model) motion capture system (Vicon, Oxford Metrics, Oxford, UK). The data was filtered using a Woltring filter with a mean squared error (MSE) value of 20. Workstation software (Vicon, Oxford Metrics, Oxford, UK) was used for processing the motion data and generating 3-D coordinates of the markers. The custom upper extremity biomechanical model was then applied to the kinematic data to compute triaxial shoulder, elbow, and wrist joint angles.

Data was averaged over 3 trials per subject. Push and recovery phases define 100% stroke cycle. Peak motions within each phase and at initial rim contact were computed. Data was processed every 2% of the stroke cycle. Right and left side joint angles were compared using the Student's t-test for analysis of symmetry. Range of motion was determined from the difference of the maximum and minimum motions. Excel (Microsoft Corp., Redmond, WA) was used for all data analyses.

III. RESULTS

Kinematics of the shoulders, elbows, and wrists were analyzed. The mean flexion and extension of each upper extremity joint were computed for the stroke cycle (Figs. 2-4). The sagittal plane exhibited flexion and extension at the shoulder and wrist, while the elbow demonstrated flexion only. In the coronal plane, the shoulder was abducted and the wrist moved between radial and ulnar deviation. The shoulder and elbow were internally rotated in the transverse plane, while the wrist demonstrated small movements of internal and external rotation. The mean range of motion of the shoulders, elbows, and wrists were most notable in the sagittal plane (Fig. 5). The shoulders presented the largest range of motion.

Mean peak joint angles for right and left sides were computed for the two phases of the stroke cycle (Table I). The sagittal plane was most significant. The elbows presented the largest flexion motions at initial rim contact. The elbows also demonstrated the largest flexion angles during the push phase. During the recovery phase, the shoulders exhibited the largest flexion angles. Mean peak flexion at the elbow joints was found to be significantly different between right and left sides during the recovery phase.

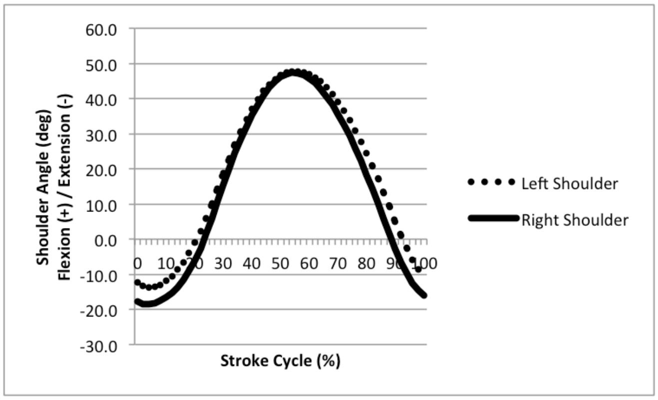

Fig. 2. Mean kinematics of the shoulders. Right is solid and left is dotted. Mean Std. Devs. L: 31.6°; R: 27.8°.

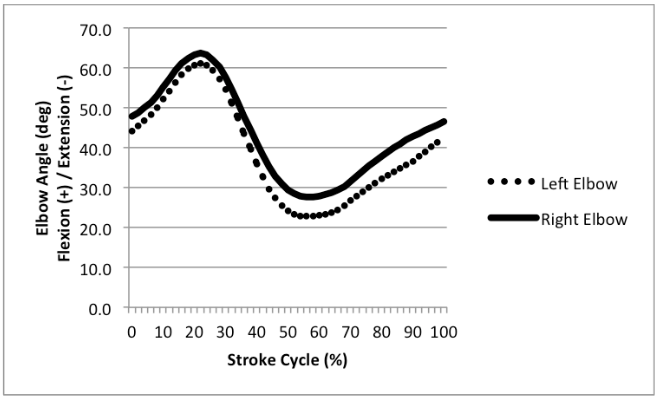

Fig. 3. Mean kinematics of the elbows. Right is solid and left is dotted. Mean Std. Devs. L: 15.7°; R: 17.9°.

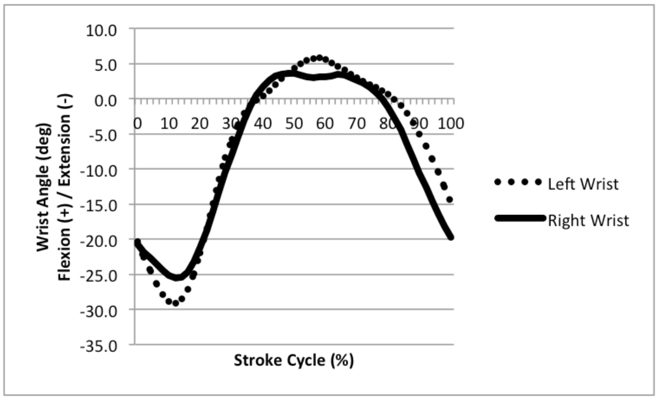

Fig. 4. Mean kinematics of the wrists. Right is solid and left is dotted. Mean Std. Devs. L: 17.2°; R: 20.6°.

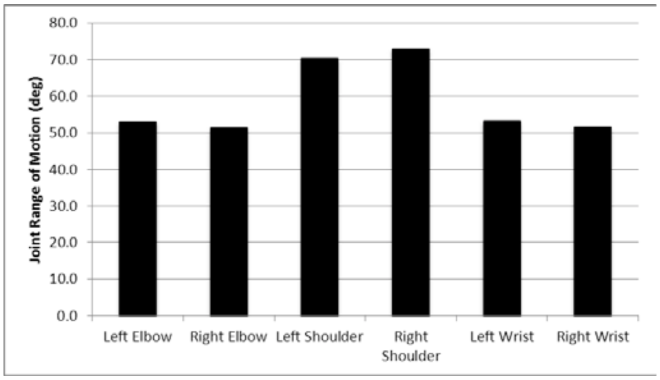

Fig 5. Mean range of motion of the shoulders, elbows, and wrists. Mean Std. Devs. Elbow L: 15.6°, R: 17.9°; Shoulder L: 19.1°, R:16.3°; Wrist L: 16.6°, R: 13.4°.

TABLE I
MEAN PEAK JOINT FLEXION AND EXTENSION ANGLES DURING THE STROKE CYCLE

Joint (N=13)	Initial Rim Contact	Push Phase	Recovery Phase
	Maximum Extension (deg)	Maximum Extension (deg)	Maximum Flexion (deg)
Left Shoulder	-10.4	-17.1	53.3
Right Shoulder	-16.1	-21.8	51.1
	Maximum Flexion (deg)	Maximum Flexion (deg)	Minimum Flexion (deg)
Left Elbow	45.7	68.1	15.1*
Right Elbow	50.1	71.0	19.7*
	Maximum Extension (deg)	Maximum Extension (deg)	Maximum Flexion (deg)
Left Wrist	-20.8	-35.2	16.2
Right Wrist	-20.4	-35.8	17.3

*Significant difference $p < 0.05$. Please refer to Figs. 2-5 for representative St. Dev. values.

IV. DISCUSSION

There are an estimated 12,000 new cases of SCI each year with 20% occurring in children and adolescents. Children with SCI are often lifelong manual wheelchair users and the long-term effects of upper extremity overuse are expected to result in significant morbidity, impaired function and participation, and lowered quality of life. Despite this, little is known about the musculoskeletal demands, limb dynamics, joint pain, or functional outcomes. The current study sets the foundation for understanding these multiple factors through kinematic assessment. Many questions exist about the immediate and longer-term effects of manual wheelchair usage on joint dynamics. Among the anticipated benefits to the targeted pediatric population of wheelchair users is a clarification of the biomechanical demands placed on the extremities during wheelchair mobility. This understanding together with new information on impairment, activity, participation, and quality of life may help to promote injury prevention, patient education, diagnosis, and treatment within the population of pediatric wheelchair users.

Quantification of upper extremity joint dynamics is currently limited for wheelchair mobility in children with SCI [11-13]. An upper extremity kinematic model was developed and applied to children with SCI for preliminary assessment of manual wheelchair propulsion. This model incorporated ISB recommendations for the coordinate system design [10]. The model was successful in quantifying 3-D motions of the shoulder, elbow, and wrist joints. The upper extremity model was effective for distinguishing differences between joints and right and left sides. Implications from asymmetry may help to establish improved training guidelines and wheelchair population techniques incorporating limb dominance factors.

Maximum joint motions were observed at the shoulder joint highlighting the concern of increased demands during manual wheelchair propulsion. It has been shown that joint load related pathologies such as shoulder injury, carpal tunnel syndrome, and arthritis are linked to the prolonged use of wheelchairs [5, 7, 8]. Inappropriate positioning and loading on the upper extremities may also lead to pain and pathology in children with SCI. It is, therefore, essential to characterize upper extremity joint motions and forces during wheelchair usage due to the altered mobility patterns and increased magnitude and frequency of joint loads in an extremely heterogeneous patient population. This model serves as the basis for developing a kinetic model for further insight to joint load demands during wheelchair mobility.

Future directions include the evaluation of joint kinematics and kinetics, along with the correlation among biomechanical measures, pain, and functional outcomes. This may expand our knowledge of effective rehabilitation strategies and therapeutic management for children with SCI.

V. CONCLUSION

A 3-D upper extremity biomechanical model was developed and applied to children with SCI during wheelchair mobility for kinematic evaluation. Quantitative assessment of upper extremity joint kinematics may ultimately assist in wheelchair prescription, therapeutic planning, and clinical intervention for individuals with SCI.

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