Inverse Dynamics Modelling of Paralympic Wheelchair Curling

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Abstract

Paralympic wheelchair curling is an adapted version of Olympic curling played by individuals with spinal cord injuries, cerebral palsy, multiple sclerosis, and lower extremity amputations. To the best of the authors' knowledge, there has been no experimental or computational research published regarding the biomechanics of wheelchair curling. Accordingly, the objective of this research was to quantify the angular joint kinematics and dynamics of a Paralympic wheelchair curler throughout the delivery. The angular joint kinematics of the upper extremity were experimentally measured using an inertial measurement unit system; the translational kinematics of the curling stone were additionally evaluated with optical motion capture. The experimental kinematics were numerically optimized to satisfy the kinematic constraints of a subject-specific multibody biomechanical model. The optimized kinematics were subsequently used to compute the resultant joint moments via inverse dynamics analysis. The main biomechanical demands throughout the delivery (i.e., in terms of both kinematic and dynamic variables) were about the hip and shoulder joints, followed sequentially by the elbow and wrist. The implications of these findings are discussed in relation to wheelchair curling delivery technique, musculoskeletal modelling, and forward dynamic simulations.

Keywords: multibody dynamics, biomechanical modelling, kinematic constraints, inertial measurement units, optical motion capture, sports biomechanics

Introduction

Wheelchair curling debuted at the 2006 Paralympic Games. Competing athletes utilize the same stones and ice sheets as Olympic curlers, although sweeping (i.e., using a broom to control the stone's trajectory) is omitted and the stone must be pushed from a stationary wheelchair using a delivery stick.[1] One of the main objectives in wheelchair curling is to launch the stone in such a way that it rectilinearly translates along the ice over 28 m and lands within the 'house' to accumulate points; this is known as a 'draw shot' delivery. Research conducted at the 2010 Paralympic Games noted that 18 % of athletes competing in wheelchair curling (*n* = 50) sought medical attention for musculoskeletal injuries, the majority of which were sustained about the lower back and shoulder joint.[2] To date, there has been no experimental or computational research published regarding the biomechanics of wheelchair curling. These investigations would provide unprecedented insights into the physical demands of this Paralympic sport.

One of the main objectives of biomechanists is to evaluate the dynamics (i.e., forces and moments) associated with human movements. Experimentally measuring the forces of individual skeletal muscles (i.e., dynamometry) is invasive and therefore unpractical in sport environments.[3] With modern advancements in computer science, biomechanical modelling presents a viable method of approximating the dynamics of multibody movements.[3] Considering the emergent interests in determining the physical demands of different Paralympic sports, the objectives of this research were i) to develop a subject-specific multibody biomechanical model of Paralympic wheelchair curling, and ii) to quantify the angular joint kinematics and dynamics throughout the wheelchair curling delivery via experimental measurements and inverse dynamics analysis, respectively.

Methods

Paralympic Athlete

A single wheelchair curler (sex: male, age: 39 y, total body mass: 87.9 kg) was recruited from the Canadian Paralympic Team. The athlete was a gold medalist at the 2014 Paralympic Games and 2013 World Wheelchair Curling Championships. In 2007, the athlete sustained a traumatic incomplete spinal cord injury between the 5th and 6th cervical vertebrae. The athlete was diagnosed with a level 'C' impairment on the American Spinal Injury Association Impairment Scale.[4] The Paralympian provided informed written consent and the University of Waterloo Research Ethics Board approved this research.

Experimental Kinematics

The angular joint kinematics throughout the wheelchair curling delivery were experimentally measured using an inertial measurement unit (IMU) system (MVN Suit, Xsens Technologies, Netherlands). The system consists of 17 IMUs, which were attached to the Paralympian's head, torso, upper arms, forearms, hands, thighs, shanks, and feet (Figure 1). The IMU system utilises a 23-segment biomechanical model and proprietary algorithms to calculate the angular joint kinematics.[5] The Paralympian performed 14 'draw shot' deliveries of the curling stone interspersed with 2 minutes of rest between deliveries; all 14 deliveries were considered in the analyses. The athlete used his right hand to deliver the curling stone. Data were sampled at 120 Hz. High-frequency noise in the joint kinematic measurements was minimized using smoothing splines (MATLAB, MathWorks, USA). Previous research has demonstrated the test-retest reliability[6] and concurrent validity[7] of the IMU system in computing angular joint kinematics compared with optical motion capture.

Movement of the curling stone was recorded with a digital camera (Nikon D3100, Nikon Corporation, Japan) that was positioned perpendicular to the Paralympian's plane of motion. The camera sampled at 29 frames per second. The translational stone kinematics (i.e., displacements and velocities) throughout the delivery were determined relative to an inertial reference frame using markerless feature tracking software (ProAnalyst, Xcitex Incorporation, USA). The delivery is defined as the time duration between the initial displacement of the stone and its moment of release from the delivery stick. High-frequency noise in the stone kinematic measurements was minimized using smoothing splines (MATLAB, MathWorks, USA).

Multibody Biomechanical Model

A novel biomechanical model of the wheelchair curling delivery was developed in MapleSim software (MapleSoft, Canada). The model included a representative torso, head and neck, right upper arm, right forearm, right hand, delivery stick, and curling stone (Figure 2a). The wheelchair is fixed to the inertial reference frame (Figure 2a). The mechanical parameters of each biological body segment were experimentally measured using dual-energy x-ray absorptiometry (Table 1).[8] Synonymous with the Paralympian's equipment configuration, the delivery stick body segment was set to 1.96 m in length, 0.18 kg in mass, and the principal mass moment of inertia was calculated via $I_{zz} = \frac{1}{12}mL^2$. The curling stone body segment was given a mass of 19.96 kg and a height of 0.19 m.[9]

The model also included a representative hip, shoulder, elbow, and wrist, all of which were modelled as revolute kinematic pairs (Figure 2b). The hip, shoulder, and elbow permit flexion-extension while the wrist allows for radial-ulnar deviation, assuming a neutral hand position (Figure 2b). The hip joint was set to 0.62 m above the inertial reference frame (i.e., simulating the height of the wheelchair seat) (Figure 2b). The revolute joints contained angular viscous damping, the quantities of which were taken from previous research.[10-11] A prismatic kinematic pair was used to model the contact between the curling stone and ice (Figure 2b); rotations about the vertical axis were omitted. The contact model also included dry Coulomb friction.[9] The multibody biomechanical model has 3 degrees of freedom and is mathematically represented by 4 ordinary differential equations and 1 algebraic equation (i.e., indicative of the model's kinematic constraints).

Kinematic Constraints

The experimental kinematics were numerically optimized to satisfy the kinematic constraints of the multibody biomechanical model. A nonlinear constrained optimization algorithm was used to minimize the following multi-objective function at discrete time steps (i.e., t = 0…0.65 s and Δt resampled = 0.001 s)

$$\psi_t^{\dagger} = \text{Arg min}\left[\sum_{i=1}^{5} w_i \left(\frac{\psi_{it}-\psi_{it}^{m}}{\Delta\psi_i^{m}}\right)^2 + w_6\left(\frac{AE(\theta_{1t}\ldots\theta_{4t})}{L}\right)^2 + w_7\left(\frac{x_t - f(\theta_{1t}\ldots\theta_{4t})}{\Delta x^{m}}\right)^2\right] \quad (1)$$

subject to: $\psi_{min}^{m} < \psi_t < \psi_{max}^{m}$ (2)

where ψ = [θ_1 θ_2 θ_3 θ_4 x]^{T}, ψ^m represents the experimentally measured ψ variables, $W_1 \ldots W_7$ are weighting terms (i.e., W_1 = 15, W_2 = 0.1, W_3 = 0.95, W_4 = 1.5, W_5 = 200, W_6 = 100, and W_7 = 100), AE ($\theta_{1j} \ldots \theta_{4j}$) is the algebraic constraint equation from the multibody biomechanical model, and L (i.e., 0.43 m) is the vertical distance between the heights of the wheelchair seat and curling stone handle. $f\ (\theta_{1j}\ldots\theta_{4j})$ denotes the modelled displacement (x) of the curling stone in terms of the variables $\theta_1\ldots\theta_4$. Equation (2) specifies the minimum and maximum bounds on each ψ variable. The Paralympian's maximum range of motion about the hip (θ_1), shoulder (θ_2), elbow (θ_3), and wrist (θ_4) were experimentally measured using a digital goniometer. $\Delta\psi$ is the difference between ψ_{min}^{m} and ψ_{max}^{m}.

Inverse Dynamics

Inverse dynamics is a mathematical technique through which resultant forces and moments about individual joints are calculated by solving the Newton-Euler equations of motion given the kinematics and inertial parameters of adjacent body segments.[3] The MapleSim software was used to solve the Newton-Euler equations of motion for the resultant joint moments about the hip, shoulder, and elbow using the optimized kinematics. The wrist was modelled as a passive joint (i.e., unactuated) in the interests of simulating the limited hand functionality of the Paralympic wheelchair curler.

Results

The shoulder joint displayed the largest range of motion (i.e., Δ 142.7 ± 3.1°) throughout the wheelchair curling delivery compared to the hip (i.e., Δ 27.0 ± 2.9°), elbow (i.e., Δ 96.7 ± 3.3°), and wrist (i.e., Δ 22.8 ± 1.7°) (Figure 3). The mean duration of the delivery was approximately 0.65 seconds. The delivery was initiated through rotations about the hip (i.e., flexion), followed sequentially by the shoulder (i.e., flexion), elbow (i.e., extension), and wrist (i.e., ulnar deviation).

The shoulder joint had the largest magnitude of angular velocity throughout the delivery, with a maximum flexion velocity of 427.2 ± 12.6 °/s and extension velocity of -4.1 ± 16.4 °/s (Figure 4). The hip joint had a maximum flexion velocity of -133.8 ± 10.2 °/s (Figure 4). The elbow joint had a maximum flexion velocity of 21.0 ± 13.3 °/s and extension velocity of -299.7 ± 16.7 °/s (Figure 4). The wrist joint had a maximum radial-deviation velocity of 17.2 ± 9.6 °/s and ulnar-deviation velocity of -126.3 ± 12.1 °/s (Figure 4).

There was minimal translational stone acceleration just before the moment of release (Figure 5); this technique is presumably used by the Paralympian to enhance precision. The translational release velocity (i.e., 2.0 ± 0.1 m/s) correlated with that reported by recent mathematical models of curling stone mechanics.[9] The uncertainties in the translational stone velocities slightly increased as a function of the duration of the delivery (Figure 5). The curling stone displaced a maximum of 0.80 ± 0.02 m throughout the delivery (Figure 5). The Paralympian exhibited a high degree of inter-delivery consistency, as evidenced by the minor uncertainties in the stone kinematics (Figure 5).

The largest joint moments throughout the wheelchair curling delivery were about the hip joint (i.e., maximum of 203.2 ± 34.9 Nm), followed by the shoulder (i.e., maximum of 54.6 ± 6.2 Nm) and elbow (i.e., maximum of 12.6 ± 2.2 Nm) (Figure 6).

Discussion

The objectives of this research were i) to develop a subject-specific multibody biomechanical model of Paralympic wheelchair curling, and ii) to quantify the angular joint kinematics and dynamics throughout the wheelchair curling delivery via experimental measurements and inverse dynamics analysis, respectively. The main kinematic demands throughout the delivery (i.e., in terms of maximum range of motion and angular velocity) were about the shoulder joint; this may explain why previous research found the highest incidences of musculoskeletal injuries in Paralympic wheelchair curling were about the shoulder.[2] The Paralympian initiated the delivery via forward hip flexion, followed sequentially by shoulder flexion, elbow extension, and ulnar-deviation. This kinematic sequencing resembles a 'follow-through' technique. The Paralympian's delivery technique was also highly reproducible, as evidenced by the minor uncertainties in the joint (Figures 3-4) and stone (Figure 5) kinematics. To the best of the authors' knowledge, these findings represent the first documented kinematic analysis of the wheelchair curling delivery. Although the joint kinematics might be considered indicative of an 'optimal' delivery technique (i.e., since the athlete is a Paralympic gold medalist), additional research is needed to ascertain the delivery kinematics of other Paralympic wheelchair curlers to derive statistically significant conclusions.

The multibody biomechanical model was used to evaluate the resultant joint moments about the lower back and upper extremity joints throughout the wheelchair curling delivery. Resultant joint moments are mathematical summations of the dynamics from all neighbouring biological elements (e.g., skeletal muscles, tendons, ligaments, and bursae).[3] Consequently, the forces and moments from individual skeletal muscles cannot be determined. For example, the positive resultant joint moment about the elbow joint throughout the wheelchair curling delivery (Figure 6) could be attributed to either activations of the agonist muscles (e.g., biceps brachii) or deactivations of the antagonist muscles (e.g., triceps brachii). Musculoskeletal models would be needed to evaluate the activations and dynamics of individual skeletal muscles throughout the wheelchair curling delivery. These models could provide further insights into the documented musculoskeletal injuries amongst Paralympic wheelchair curlers.[2]

Considering a wide variety of individuals with physical disabilities compete in wheelchair curling, including those with spinal cord injuries, cerebral palsy, multiple sclerosis, and lower extremity amputations,[1] it is important to quantify the maximum physical demands associated with the delivery movement. The resultant joint moments throughout the wheelchair curling delivery were calculated using inverse dynamics analysis. The maximum dynamic loads were computed about the hip joint, followed sequentially by the shoulder and elbow. Nevertheless, inverse dynamics is not predictive, and requires expensive and time-consuming experiments. Forward dynamics, by contrast, computes the multibody kinematics by numerically integrating the Newton-Euler equations of motion given the forces and moments as inputs; these dynamic inputs are often elicited from mathematical models of neural excitations.[3] Forward dynamics has the distinct capability of i) predicting the effects of model parameters (e.g., height of the wheelchair seat) on performance outcomes, and ii) optimizing equipment designs *in silico*.[12] Consequently, the authors intend to further investigate the biomechanics of wheelchair curling using forward dynamic simulations.

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Conflict of Interest

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Table 1. Body segment parameters of the Paralympic wheelchair curler as experimentally measured using dual-energy x-ray absorptiometry.[8] The quantities are presented as arithmetic means ± 1 standard deviation over multiple scans. Segments in the upper extremity are of the right side. The position vector of the center of mass was determined relative to the proximal endpoint.

Parameter	Head & Neck	Torso	Upper Arm	Forearm	Hand
Length (m)	0.265 ± 0.005	0.588 ± 0.008	0.291 ± 0.005	0.276 ± 0.002	0.123 ± 0.002
Mass (kg)	6.967 ± 0.085	44.616 ± 0.677	3.099 ± 0.192	1.371 ± 0.009	0.396 ± 0.011
Center of Mass (m)	0.1231 ± 0.0025	0.2237 ± 0.0031	0.149 ± 0.002	0.108 ± 0.001	0.022 ± 0.001
Mass Moment of Inertia ($kg \cdot m^2$)	0.1963 ± 0.0102	2.8508 ± 0.0349	0.0238 ± 0.0022	0.0106 ± 0.0002	0.0022 ± 0.0001

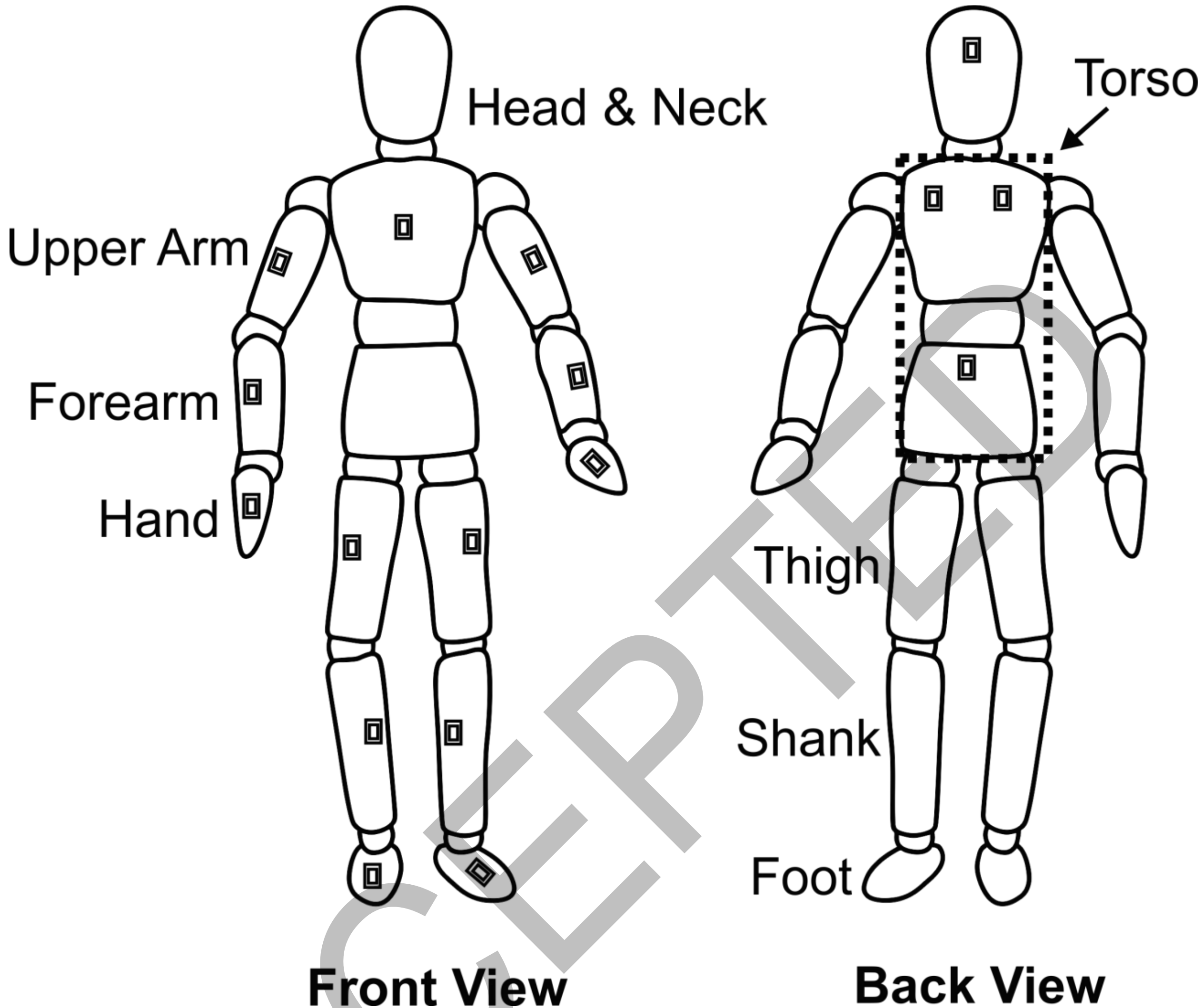

Figure 1 – Locations of the inertial measurement units on the Paralympic wheelchair curler.

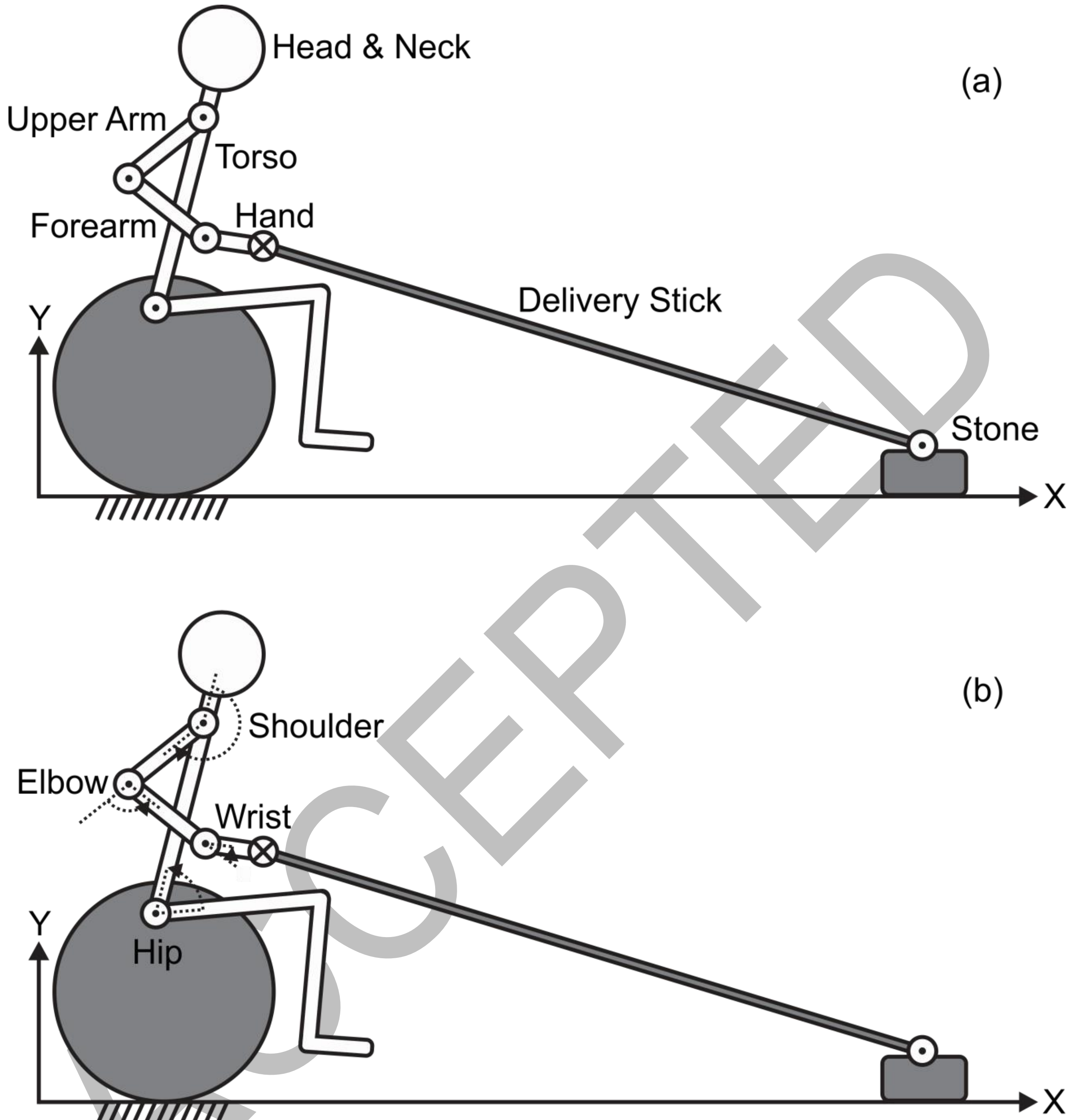

Figure 2 - Schematic of the multibody biomechanical model. The rigid body segments and lower kinematic pairs are presented in (a) and (b), respectively.

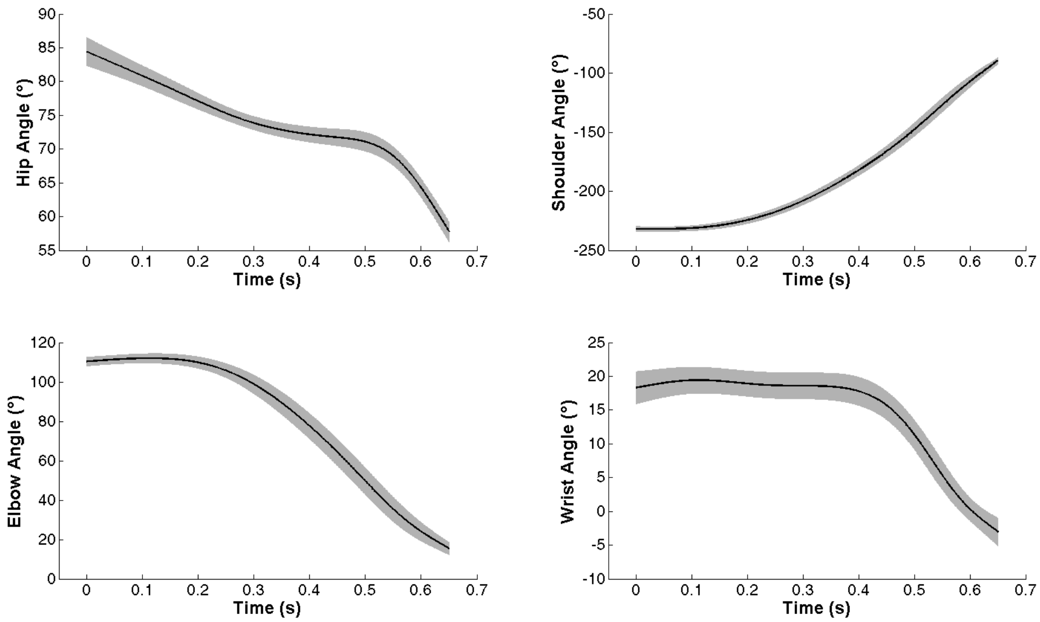

Figure 3 - The relative joint angles of the hip, shoulder, elbow, and wrist throughout the wheelchair curling delivery. The quantities are presented as arithmetic means ± 1 standard deviation over 14 consecutive deliveries.

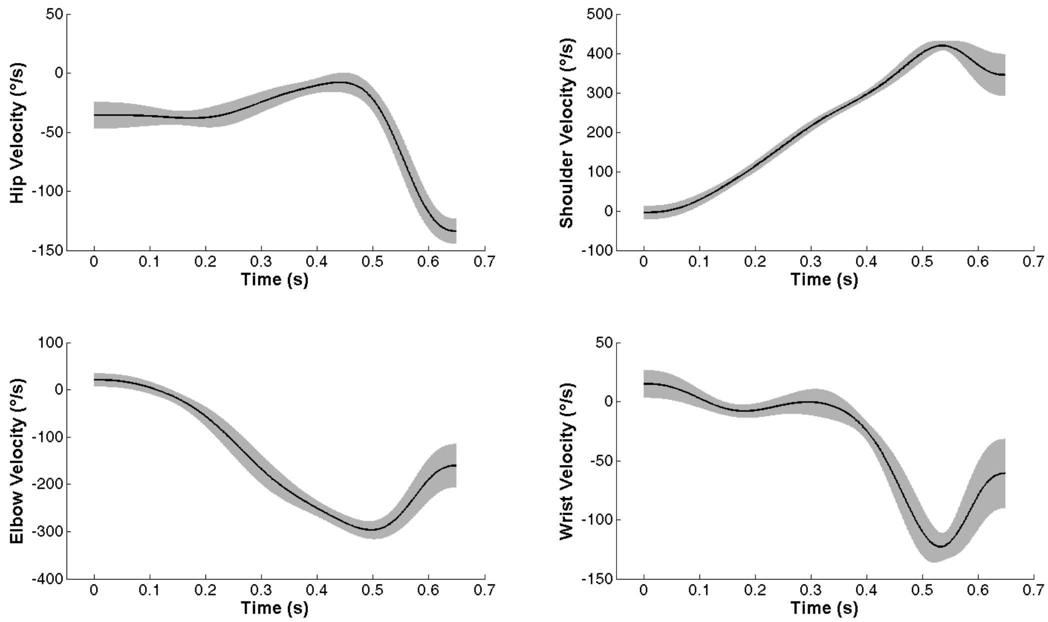

Figure 4 - The angular joint velocities of the hip, shoulder, elbow, and wrist throughout the wheelchair curling delivery. The quantities are presented as arithmetic means ± 1 standard deviation over 14 consecutive deliveries.

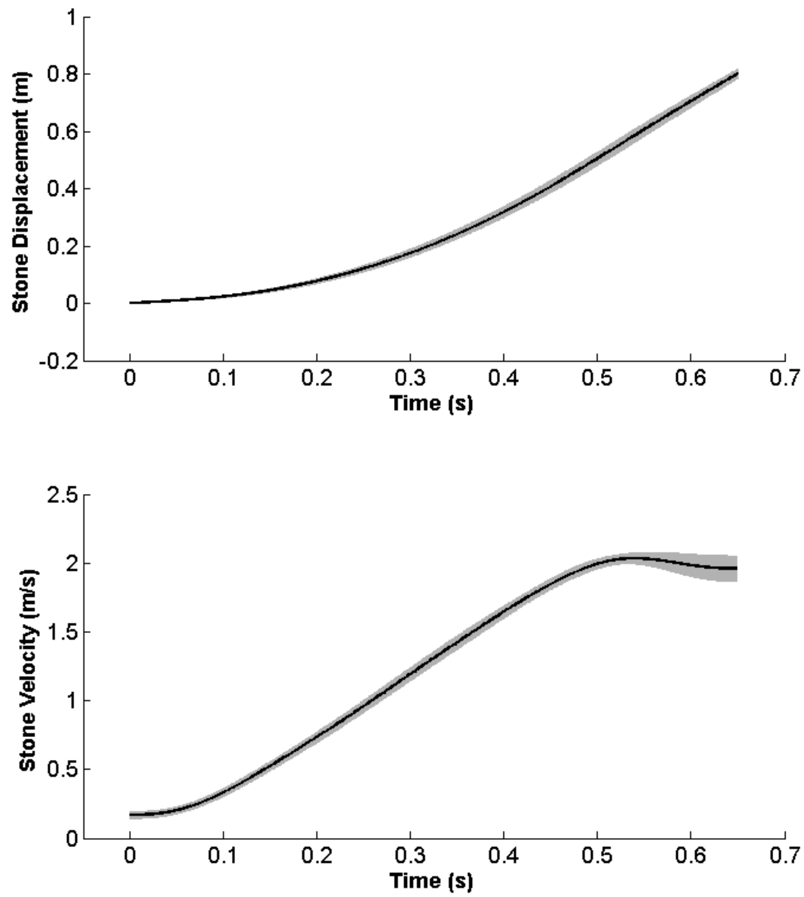

Figure 5 - The translational stone kinematics (i.e., displacements and velocities) throughout the wheelchair curling delivery. The quantities are presented as arithmetic means ± 1 standard deviation over 14 consecutive deliveries.

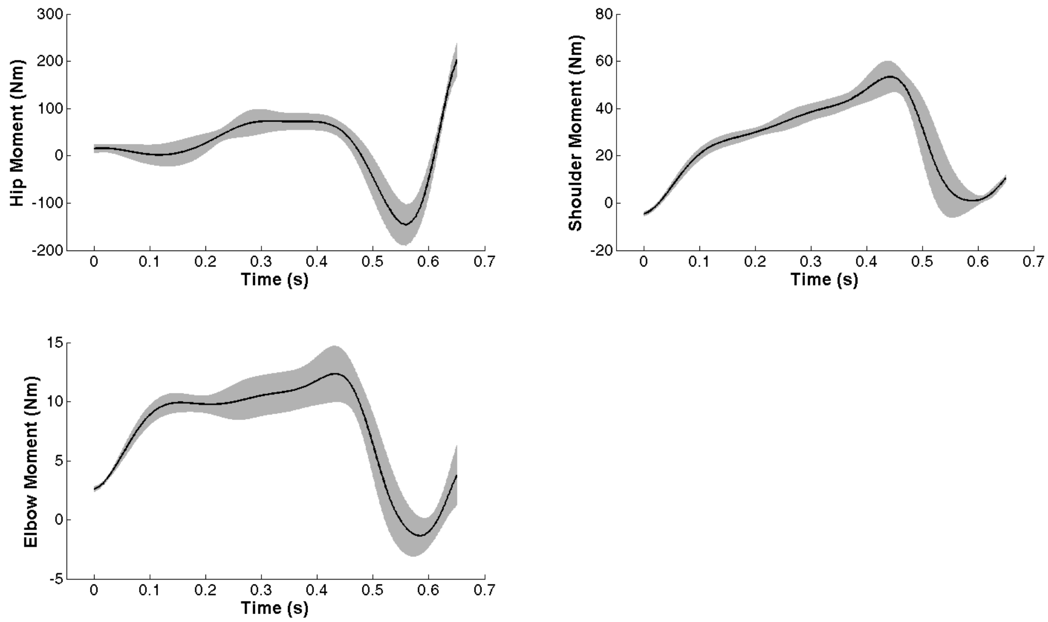

Figure 6 - The resultant joint moments about the hip, shoulder, and elbow as computed via inverse dynamics analysis. The quantities are presented as arithmetic means ± 1 standard deviation over 14 consecutive deliveries.