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Reconfiguration of the upper extremity relative to the pushrim affects load distribution during wheelchair propulsion

Joseph M. Munaretto [a,*], Jill L. McNitt-Gray [a,b], Henryk Flashner [c], Philip S. Requejo [d]

[a] Department of Biomedical Engineering, University of Southern California, Los Angeles, CA, USA
[b] Department of Biological Sciences, University of Southern California, USA
[c] Department of Aerospace & Mechanical Engineering, University of Southern California, USA
[d] Rehabilitation Engineering Program, Rancho Los Amigos National Rehabilitation Center, Downey, Los Angeles, CA, USA

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ABSTRACT

Objective: Repetitive loading during manual wheelchair propulsion (WCP) is associated with overuse injury to the upper extremity (UE). The aim of this study was to determine how RF redirection and load distribution are affected by changes upper extremity kinematic modifications associated with modifications in seat positions during a WCP task. The aim of this study was to determine how RF redirection and load distribution are affected by upper extremity kinematic changes associated with seat position adjustment during a WCP task.
Design: Dynamic simulations using an experiment-based multi-link inverse dynamics model were used to generate solutions for redistributing UE mechanical load in different seating positions without decrements in WCP task performance.
Methods: Experimental RF and kinematic data were collected for one subject propelling at a self-selected speed and used as input into the model. Shoulder/axle distance, wrist angular position, and RF direction were systematically modified to simulate how the mechanical demand imposed on the upper extremity (elbow and shoulder net joint moments (NJMs) and net joint forces) may vary.
Results: Load distribution depended on UE orientation relative to the wheel. At peak force, lower shoulder/axle distances and more anterior wrist positions on the pushrim allowed for more extended elbow positions and reduced total NJM load.
Interpretation: Simulation results incorporating subject-specific data may provide mechanically based information to guide clinical interventions that aim to maintain WCP performance and redistribute load by modifying RF direction, seat configuration and hand/rim interaction.

1. Introduction

Individuals with lower extremity or spinal cord injury rely on manual wheelchair propulsion (WCP) to maintain independence and community participation. Unlike more expensive powered wheelchairs, manual wheelchair use promotes upper extremity strength and cardiovascular conditioning as part of activities of daily life. Manual WCP entails the generation of a tangential force at the hand/rim interface during hand contact to accelerate the mass and regulate the momentum of the entire system (wheelchair user and chair) [1]. Chronic use of manual WCP exposes the upper extremity (UE) to repetitive loading from the reaction forces (RFs) at the hand/pushrim interface. Mechanical loading experienced by the UE during WCP has been associated with the high incidence of acute and overuse shoulder injuries in manual wheelchair users [2–4]. Disability – secondary to the primary injury – contributes to a loss of autonomy and a decrement in quality of life. Experimental results indicate that there is more than one solution to satisfy the mechanical objective of this propulsion task [5–9]. The causal relationship between manual WCP techniques and UE injury patterns remains unknown.

Knowledge of the advantages and disadvantages of different WCP techniques can aid clinicians when making decisions regarding pre- and re-habilitation interventions that aim to maintain the client's functional performance while reducing injury risk. Simulation studies indicate that maintaining the tangential component of the reaction force (RF) and altering the radial component provide multiple solutions for redistributing the mechanical loading across the upper extremity without a decrement in propulsion speed [9]. RF redirection combined with alteration in upper extremity segment positions and configurations is expected to provide additional solutions for UE load redistribution.

* Corresponding author at: University of Southern California, 3560 Watt Way, PED 107, Los Angeles, CA 90089-0652, USA. Tel.: +1 440 376 0761.
E-mail address: jmunaretto@gmail.com (J.M. Munaretto).

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Modification in seat position is one way to alter shoulder and wrist positions of the wheelchair user relative to the pushrim. Different seat positions have been reported to alter upper extremity kinetics and metabolic efficiency [10], however understanding of changes in underlying UE mechanics is lacking, however understanding of how changes in UE kinematics (due to changes in seat position) cause changes in UE mechanical loading needs further research. Reconfiguration of the upper extremity segments associated with different seat positions is expected to affect how the RF at the hand/pushrim interface is generated and how load is distributed across the shoulder and elbow during manual WCP. Simulation studies using an experiment-based subject-specific model have proven to be an effective means for evaluating the consequences of systematically modifying variables that cannot be controlled experimentally [9,11,12]. Determining how individual wheelchair users can maintain performance and effectively distribute load by redirecting the RF and reconfiguring the UE during WCP would provide clinicians and wheelchair users with a priori knowledge of feasible solution spaces in different kinematic contexts such as those that arise during chair fitting process.

The aim of this study was to determine how RF redirection and load distribution are affected by changes upper extremity kinematic modifications associated with modifications in seat positions during a WCP task. Simulations using a 2D inverse dynamic model estimating elbow and shoulder net joint moments (NJMs) and axial component of the net joint force (NJF) of the shoulder were used to determine the sensitivity of load distribution to shoulder/axle distance, wrist location relative to the rim, and RF direction. Solution spaces generated from model simulation results are expected to provide a means for quantifying how changes in upper extremity kinematics (forearm relative to the pushrim (global) and elbow angle (local)) affect force generation and load distribution.

2. Methods

2.1. Approach

To estimate mechanical load distribution of the UE during WCP in different seat positions, a previously validated developed inverse dynamics model of the UE [9] was used. This 2D multilink model of the UE was evaluated by comparing and quantifying the differences between simulated and experimental wrist, elbow, and shoulder positions. Based on patterns observed in experimental kinematics across 12 subjects, we assumed the wrist followed a circular track when the hand is in contact with the rim, motion of the UE was planar, and that the shoulder position was maintained in a fixed position during WCP. These simplifications were reasonable and allow the fundamental effects of the model to be illustrated. Work by Munaretto has shown that a 2D model accurately represents 3D kinematics and kinetics when viewed in the shoulder/elbow/wrist plane. Model simulations systematically modified wrist angular position on the pushrim ($\theta_W(t)$) and shoulder/axle distance (r_S) and kept pushrim excursion (θ_P) constant (Fig. 1).

2.2. Experimentation

One wheelchair user with spinal cord injury (SCI) volunteered to participate (age: 27; weight: 63.5 kg; injury level: L2; yrs post injury: 8) in a previous study in accordance with the Institutional Review Board at the Ranchos Los Amigos National Rehabilitation Center, Downey, CA [13]. The participant manually propelled a wheelchair at a self-selected speed (~1.2 m/s) for 15 s while on a wheelchair ergometer. The last 10 s were recorded and 11 push cycles were collected. Reflective markers were used to monitor the 3D motion of the hand, forearm, upper arm, and trunk segments

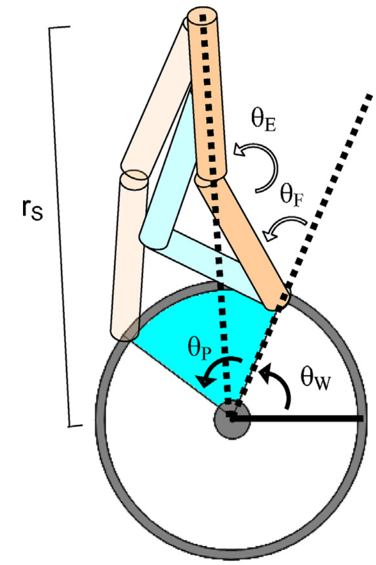

Fig. 1. Kinematic coordinates describing position of upper extremity relative to the pushrim. Simulations varied θ_W and r_S and results are reported in relation joint angle (elbow angle θ_E) and forearm angle (θ_F) relative to radial direction (dotted line passing from axle to wrist). When modifying shoulder/axle position r_S, the shoulder/axle angle is kept constant and the elbow θ_E and forearm θ_F angles are constrained in change (shoulder position translates along the dashed line).

(VICON, 50 Hz) [13]. Three markers were also placed on the right wheel to track wheel rotation. Marker coordinate data were used to define a global (x, y, z) reference frame where x axis represented anterior/posterior direction, y axis represented superior/inferior direction, and z axis represented mediolateral direction. The sagittal plane xy was oriented in global space to symmetrically bisect the wheelchair user. The force applied to the wheelchair during propulsion was measured using force transducers (SmartWheel 2500 Hz) in the radial, tangential, and mediolateral directions of the wheel reference system. The markers and upper extremity model to estimate wrist, elbow, and shoulder joint centers followed methods are consistent with those described in [14].

2.3. Modeling

A two-segment model of the upper extremity that incorporated subject specific segment lengths, body segment parameters, and segment motion during manual WCP was created. A set of generalized coordinates that reflects known kinematic constraints associated with systematic modifications in seat position (e.g. hands must contact rim to propel wheel chair) was selected. The level of agreement between the model simulated and experimental kinematics was established by evaluating the root mean square of the positional error at the shoulder, elbow, and wrist (0.016 m, 0.017 m, 0.012 m). Finally, simulations were performed across shoulder/axle distances, wrist positions, and force directions.

2.3.1. Model development

Based on experimental results, a two segment, 2D model of the upper extremity was used to represent the salient features of upper extremity (UE) kinematics during manual wheelchair propulsion. In order to describe orientation of the UE relative to the pushrim under different seating conditions, experimental kinematics were defined using the following variables (Fig. 1). The location of the wrist on the pushrim (wrist angular position: $\theta_W(t)$) was expressed as a rotation relative to the right horizontal (i.e. top dead center = 90°) over time (t). The shoulder/axle distance (r_S) was defined