A MODEL-BASED APPROACH TO DETERMINE THE EFFECT OF HANDRIM COMPLIANCE ON PROPULSION EFFICIENCY

W. Mark Richter MSME[1], Peter W. Axelson MSME[2], Rory A. Cooper PhD[3]
[1]Department of Mechanical Engineering, Stanford University, Stanford, CA
[2]Beneficial Designs, Inc., Santa Cruz, CA [3]University of Pittsburgh, Pittsburgh, PA

ABSTRACT

Manual wheelchair users are at risk of developing upper extremity injuries. A compliant handrim is a proposed technology that serves to reduce impact and peak forces during propulsion. Use of a compliant handrim was shown to reduce metabolic demand during propulsion, but the mechanism by which this occurs is not well understood. A dynamic wheelchair propulsion model was developed and used to study the effects of compliance on propulsion efficiency. The compliant handrim has two independent degrees of freedom, radial translation and rotation with respect to the wheel. The model predicted an increase in propulsion efficiency within an optimal compliance band. Results suggest that rotational compliance improves efficiency while translational compliance adversely affects efficiency. Future research will focus on validating and improving the model.

BACKGROUND

It has been established that manual wheelchair users who push on the handrim with higher peak and impact forces during propulsion are more likely to develop an upper extremity injury (1). A compliant handrim is a standard handrim that is elastically rather than rigidly connected to the wheel, such that it can displace relative to the wheel when impacted by the hand. Compliant handrims are designed to reduce peak and impact forces during propulsion and therefore may be an effective injury-prevention mechanism. It was suspected that the use of a compliant handrim might increase metabolic demand during propulsion and therefore diminish its value as an injury-prevention mechanism. Oxygen consumption was measured during propulsion while using three different handrim prototypes of varying compliance. Metabolic demand was not found to increase and in fact decreased for two of the prototypes tested (2). It was hypothesized that the decrease in metabolic demand was due to either 1) the ability of the compliant handrim to store the kinetic energy from the arm during impact and to release it to the wheel, later in the push, or 2) the increased degrees of freedom of the handrim allowed the user to better optimize their propulsion stroke.

RESEARCH QUESTION

The use of a compliant handrim was shown to reduce metabolic demand during propulsion for two prototype designs, yet the reason for this is not understood. How does handrim compliance reduce metabolic demand and how does varying the compliance characteristics affect this result?

METHOD

A simplified dynamic wheelchair propulsion model was developed. The model is two dimensional, and is similar to propulsion on a dynamometer in that the wheelchair does not move forward but rather remains stationary as the rear wheel rolls. In the model, the mass of the rear wheel is modified such that the inertial characteristics of turning the wheel are equivalent to that of the wheelchair-user system rolling forward. The model consists of four rigid bodies: an upper arm, forearm-hand combination, handrim and wheel (Figure 1). The mass and geometric properties for the arm segments were based on anatomical measurements (3). The shoulder joint and the hub of the wheel are fixed in an inertial reference frame. The hand is constrained to the handrim by a penalty potential (very stiff springs). The handrim has two degrees of freedom with respect to the wheel. It can translate radially as well as rotate. Resistance to handrim displacement is provided by independent spring and damping elements for both degrees of freedom. Three external torques are applied to the system: a shoulder torque, an elbow torque and a resistive wheel torque. The shoulder and elbow torques are modulated such that they generate a prescribed force vector on the handrim. The resistive wheel torque used in the model was determined by a coast-down test (4).

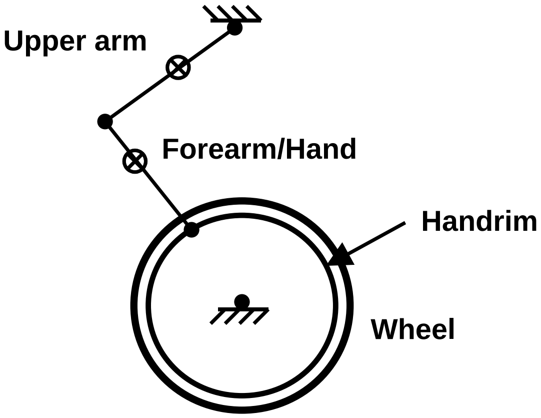

Figure 1. Wheelchair propulsion model

The penalty potential constraining the hand to the handrim is released during the push when the acceleration of the wheel decreases to zero. Propulsion efficiency is defined as the ratio of the output work to the input work for the cycle. The output work for the cycle is defined as the integral of the instantaneous output power over the cycle. The instantaneous output power is defined as the torque applied to the wheel multiplied by the angular velocity of the wheel. The input work is defined as the sum of the integrals of the elbow and shoulder joint torques verses time over the cycle, multiplied by a metabolic scaling factor. The metabolic scaling factor was determined such that the propulsion efficiency using a rigid handrim was similar to that which is commonly measured.

The model was evaluated for a 100-kg user with an initial propulsion speed of 0.75 m/s on a 2% incline. The prescribed force on the handrim was constant over the push with a value of 45 N in both the radial and tangential directions. The damping ratio was fixed at one half that of critically damped ($\zeta = 0.5$). The compliance was varied 1) isotropically, such that both the radial and tangential compliance values were equal, 2) only in rotation, and 3) only in translation. The initial velocity of the arm at impact was 3 rad/s and 1 rad/s for the shoulder and elbow respectively. These initial conditions were modified such that the hand velocity matched that of the handrim to simulate propulsion without an impact.

RESULTS

The metabolic efficiency predicted by the model for the isotropic compliance condition increases slightly followed by a dramatic decrease (Figure 2). The minimum compliance value represents a standard rigid handrim. The predicted effect of impacting the handrim on efficiency appears to be minimal (Figure 3). The degrees of the handrim are more influential on predicted efficiency (Figure 4), with purely rotational compliance improving efficiency and purely translational compliance reducing efficiency.

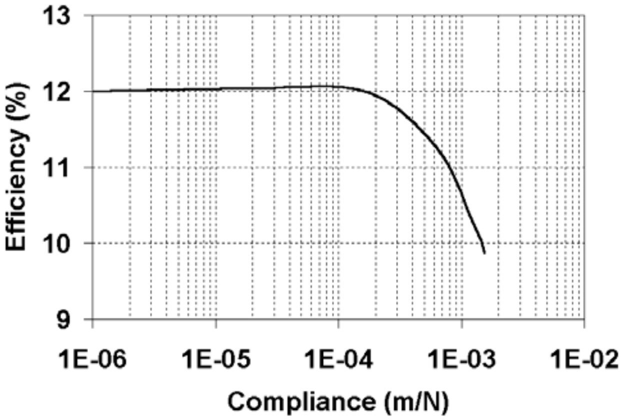

Figure 2. Predicted propulsion efficiency

DISCUSSION

The increase in propulsion efficiency measured when using a compliant handrim was unexpected. The model predicts this unexpected increase and indicates that such results are sensitive to the compliance characteristics. In particular, a critical value exists for compliance, above which significant decreases in efficiency may occur.

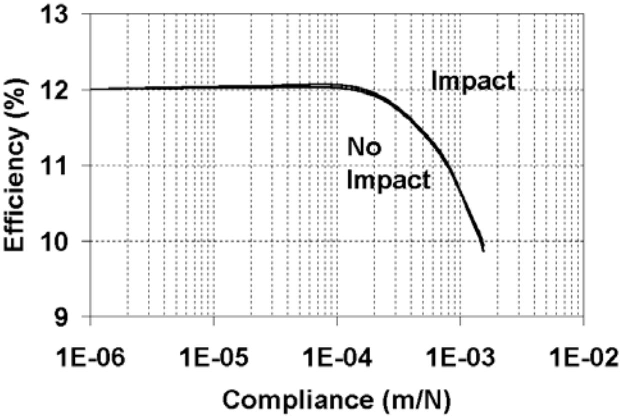

Figure 3. Effect of impact on efficiency

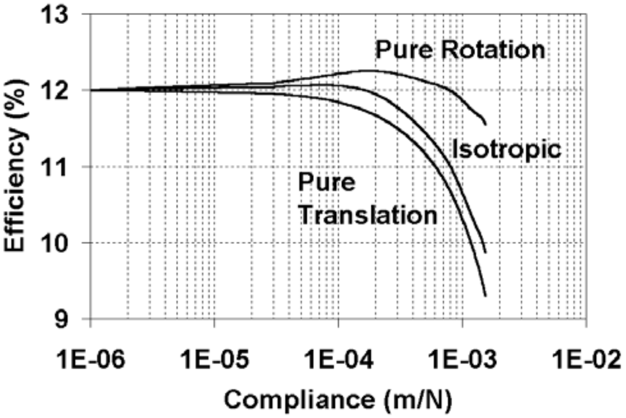

Figure 4. Effect of varying compliance characteristics on efficiency

The role of impact is slight but does agree with our expectations in that impact tends to increase efficiency. The role of the rotational and translational degrees of freedom appear to be of greatest consequence. Rotational compliance, having a positive effect, should be maximized, while translational compliance, having an adverse, effect should be minimized.

The results of the model help to understand how compliance affects efficiency. Translational compliance reduces the moment arm of the tangential force with respect to the hub of the wheel, thus the same applied force results in a smaller moment applied to the wheel. Rotational compliance allows the arm to advance further along the angular path of the wheel, resulting in a more extended elbow at release of the handrim. As the elbow extends, the mechanical advantage of the arm increases thus requiring a smaller shoulder joint torque to create the same tangential force on the handrim.

Limitations of the model will be explored through a validation process in which model predictions will be compared to experimentally measured results. Potential improvements to the model include the force profile applied to the handrim, the addition of primary actuator muscles and the addition of a torso. Once validated, the model will be used to predict an optimal handrim compliance for a wide variety of conditions by varying the propulsion speed, degree of incline, user characteristics and wheelchair set-up.

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Mark Richter, Department of Mechanical Engineering, Stanford University, wrichter@stanford.edu