KINEMATIC STATE OF THE HAND AT IMPACT WITH THE WHEELCHAIR HANDRIM AS A FUNCTION OF HANDRIM COMPLIANCE

W. Mark Richter[1, 2], Peter W. Axelson[2], Rory A. Cooper[3]
[1]Stanford University, Stanford, CA [2]Beneficial Designs, Inc., Minden, NV
[3]Human Engineering Research Laboratories, Highland Drive VA Medical Center, Pittsburgh, PA

ABSTRACT

A compliant wheelchair handrim is a proposed technology that serves to reduce the risk of developing upper extremity overuse injuries. Handrim compliance was shown to reduce the rate of loading on the handrim, and for select environments, increase propulsion efficiency. The mechanism by which these results occur is not well understood and may be a result of the speed at which the user's hand impacts the handrim. Relevant propulsion kinematics and kinetics were measured during wheelchair propulsion using a rigid handrim and three compliant handrims. Hand velocity prior to impact with the handrim was not affected by handrim compliance. Hand velocity was directed radially into the handrim at an average of 0.34 m/s and tangentially was an average of 28% slower than the handrim. The lag in tangential velocity is believed allow the user to fully grip the handrim prior to advancing the hand along a constrained range of motion.

BACKGROUND

It has been discovered that manual wheelchair users who push on the handrim with a higher rate of loading 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 (Figure 1). Handrim compliance has been shown to reduce the rate of loading on the handrim during the impact phase of propulsion (2). If a reduction in rate of loading is accomplished without changes in propulsion kinematics (motion of the arm), then the reduction is due to the compliance. However, if the user tends to hit the compliant handrim with a slower hand velocity, then the resulting reduction in rate of loading is partially due to the reduced hand velocity at impact.

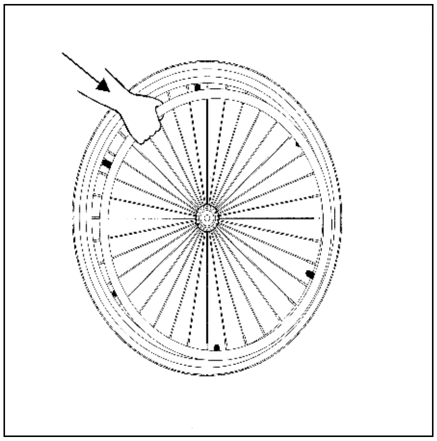

Figure 1. Handrim compliance allows the handrim to displace relative to the wheel when impacted by the hand.

Handrim compliance has also been shown to preserve, and for select environments, even improve propulsion efficiency (3). It was theorized that improvements in propulsion efficiency may have been due to the user impacting the handrim at a higher velocity when using the compliant handrims. 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 would serve to utilize energy that is normally lost at impact. Knowing the hand velocity just prior to impact with the handrim may provide valuable insight into the mechanisms that lead to improved propulsion kinetics and efficiency.

RESEARCH QUESTION

What is the kinematic state of the hand just prior to impact, and is it affected by changes in handrim compliance?

METHODS

Five experienced manual wheelchair users gave written consent and participated in the study. Subjects propelled their wheelchairs on a dynamometer at 1.3 m/s (3 mph) using a rigid handrim and three compliant handrims. The compliant handrims, Min, Max, and Max-R, described previously (2), represent minimal compliance, maximal compliance, and maximal rotational compliance, respectively. The dynamometer resistance was set to simulate propelling up a 2% (1:50) grade. Pushrim kinetics and wheel angular position were measured using a SMART$^{\text{Wheel}}$ (Three River Holdings) mounted on the subject's wheelchair. Propulsion kinematics were measured using an optical marker tracking system (Optotrak). Markers were placed on the 3rd metacarpal and the wheel. Subjects propelled for 20 seconds and the data was filtered using a 4th order Butterworth filter. The kinematic and kinetic data collection systems were triggered to ensure the timing was synchronous. The first 10 pushes were used in the analysis.

Hand velocity was determined by numerically differentiating the three-dimensional hand position coordinates over the trial. A non-zero load applied to the handrim identified the start of a push. The hub of the wheel was defined as the average location of the wheel marker. A line connecting the hub of the wheel to the hand marker was used to determine contact angle. Propulsion and handrim velocities were determined by multiplying the angular velocity of the wheel by the wheel and handrim radii, respectively. The hand velocity vector was transformed from an inertial frame of reference to a wheel-fixed reference frame through a rotation equal to the contact angle. The resulting hand velocity components are radial, tangential, and lateral with respect to the wheel. The ratio of the tangential hand velocity to the handrim velocity was calculated. Results for each subject were averaged over the ten pushes to form a single characteristic value. The results for each compliant handrim were compared to those of the rigid handrim using a two-tailed paired samples t-test and considered to be statistically significant for $p<0.05$.

RESULTS

The resulting hand position at impact and velocity just prior to impact are listed in Table 1. Both hand position and velocity are described relative to the handrim. Propulsion speed was not found to differ statistically between the rigid handrim trials and the compliant handrim trials. Neither hand position nor velocity differed statistically between the rigid handrim trials and the compliant handrim trials.

Table 1. Hand position and velocity just prior to impact with the handrim (Average (SD)).

Handrim	Propulsion Speed (m/s)	Contact Angle (deg)	Hand Velocity (m/s)	Radial Hand Velocity (m/s)	Tangential Hand Velocity (m/s)	Lateral Hand Velocity (m/s)	Tangential Hand Velocity Ratio
Rigid	1.28 (0.23)	-21 (8)	0.90 (0.20)	0.34 (0.13)	0.80 (0.23)	0.00 (0.09)	0.72 (0.06)
Min	1.30 (0.15)	-18 (7)	0.84 (0.14)	0.32 (0.08)	0.78 (0.20)	0.00 (0.06)	0.67 (0.15)
Max	1.22 (0.25)	-21 (12)	0.88 (0.28)	0.38 (0.15)	0.76 (0.32)	0.02 (0.10)	0.70 (0.15)
Max-R	1.29 (0.18)	-24 (7)	0.89 (0.16)	0.33 (0.10)	0.80 (0.20)	0.02 (0.08)	0.73 (0.08)

DISCUSSION

Hand position and velocity prior to impacting the handrim were not affected by handrim compliance. These results indicate that reductions in the rate of loading of the handrim when using a complaint handrim are due to compliance characteristics and not the result of a slower hand velocity. Additionally, any improvements in propulsion efficiency are due to factors other than an increased hand velocity.

Perhaps most informative are the hand velocity characteristics across all the handrims. The radial component of hand velocity indicates that the hand is being driven into the handrim in a direction the handrim does not move. The lateral component of hand velocity indicates that there is little or no relative lateral movement at impact. The tangential component of hand velocity for this propulsion speed is approximately twice that of the radial component. The tangential hand velocity ratio indicates that the hand is moving slower than the handrim at impact. These results help explain why the radial component of force on the handrim exhibits an impact spike while the tangential component is initially in the reverse direction, resulting in a negative torque on the wheel (Figure 2). Boninger et al. found similar kinetic characteristics for propulsion at 2 and 4 mph on a simulated level surface (4). It is believed that tangential hand velocity lag serves to allow the user to fully grip the handrim prior to advancing the hand along the push arc, thus utilizing a full range of motion on the handrim.

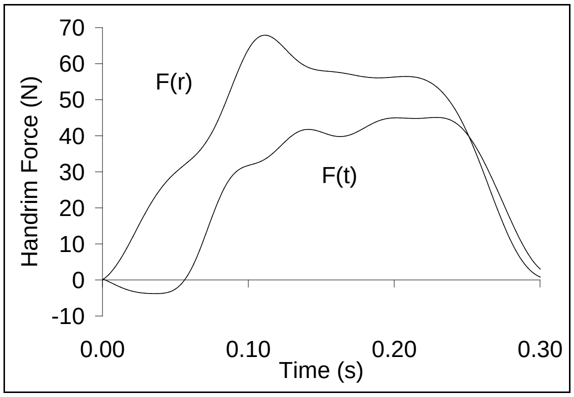

Figure 2. Handrim force profile measured for one subject. Radial force component, F(r) has a characteristic impact spike. Tangential force component, F(t) has a characteristic reverse direction at the beginning of the push.

REFERENCES

1. Boninger ML, Cooper RA, Baldwin MA, Shimada SD, Koontz AM (1999). Wheelchair pushrim kinetics: body weight, and median nerve function. *Arch Phys Med Rehabil*, (75), 513-518.
2. Richter WM, Baldwin MA, Chesney DA, Axelson PW, Boninger ML, Cooper RA (2000). Effect of pushrim compliance on propulsion kinetics. *Proceedings of the RESNA 2000 Annual Conference*. Arlington, VA: RESNA Press (396-398).
3. Richter WM, O’Connor TJ, Chesney DA, Axelson PW, Boninger ML, Cooper RA (2000). Effect of pushrim compliance on propulsion efficiency. *Proceedings of the RESNA 2000 Annual Conference*. Arlington, VA: RESNA Press (381-383).
4. Boninger ML, Cooper RA, Robertson RN, Shimada SD (1997). Three-dimensional pushrim forces during two speeds of wheelchair propulsion. *Am J Phys Med Rehabil*, (76), 420-426.

ACKNOWLEDGMENTS

Research funding was co-provided by the National Institute of Child Health and Human Development at the National Institutes of Health, and the National Center for Injury Prevention & Control (NCIPC), Centers for Disease Control and Prevention (CDC) through SBIR Phase I grant # 1 R43 HD36533-01.

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