ORIGINAL ARTICLE

Manual wheelchair stroke characteristics during an extended period of propulsion

I Rice^{1,2}, B Impink^{1,3}, C Niyonkuru¹ and M Boninger^{1,2,4}¹Human Engineering Research Laboratories, VA Rehabilitation Research and Development Center, VA Pittsburgh Healthcare Systems, Pittsburgh, PA, USA; ²Department of Rehabilitation Science and Technology, University of Pittsburgh, Pittsburgh, PA, USA;³Department of Bioengineering, University of Pittsburgh, Pittsburgh, PA, USA and ⁴Department of Physical Medicine and Rehabilitation, University of Pittsburgh, Pittsburgh, PA, USA**Study Design:** Cross-sectional study.**Objectives:** The purpose of this study was to examine stroke characteristics of long-term manual wheelchair users during an extended manual wheelchair propulsion trial and the extent to which changes in propulsion biomechanics occurred.**Setting:** Human Engineering Research Laboratories, VA Rehabilitation Research and Development Center, VA Pittsburgh Healthcare Systems, Pittsburgh, PA, USA.**Methods:** Kinetic data were recorded from 21 subjects with paraplegia at four time points over the course of a 10-min propulsion trial at a steady state speed of 1.4 m s⁻¹. Upper extremity kinetic parameters were recorded using Smartwheels, force and torque sensing pushrims.**Results:** Subjects for propulsion biomechanics changed from early to late during the 10-min trial. Individuals displayed decreased maximum rate of rise of resultant force ($P=0.0045$) with a simultaneous increase in push time ($P=0.043$) and stroke time ($P=0.023$), whereas stroke frequency remained static. In addition, there was a decrease in out of plane moment application ($P=0.032$).**Conclusion:** Individuals seemed to naturally accommodate their propulsive stroke, using less injurious propulsion biomechanics over the course of a 10-minute trial on a dynamometer. The findings may have occurred as a result of both biomechanical compensations to a challenging propulsion trial and accommodation to propelling on a dynamometer. These results suggest that subjects may be capable of independently incorporating favorable biomechanical strategies to meet the demands of a challenging propulsion scenario.*Spinal Cord* (2009) 47, 413–417; doi:10.1038/sc.2008.139; published online 11 November 2008**Keywords:** spinal cord injury; biomechanics; propulsion; fatigue; kinetics; wheelchair dynamometer

Introduction

Recent literature published in the field of spinal cord injury (SCI) has emphasized methodologies, which can help identify and prevent the development of upper limb pain and injury associated with repetitive activities like manual wheelchair propulsion.¹ For example, Subbarao *et al.*² found that individuals with SCI and upper limb pain failed to find relief from the majority of available treatments. They believed that poor treatment outcomes could be explained, partially, by the fact that performing activities of daily living, like wheelchair propulsion and transfers, were largely unavoidable tasks, and thus could be considered primary contributing factors related to the development of upper limb pain.

In addition to daily activities, it is likely that fatigue can place an individual at further risk of developing pain and injury. Fatigue can be a complex process having multiple physiological and psychological components however this study focuses on muscular fatigue or diminished ability of muscles to generate force over time.

The consequences of fatigue occurring during wheelchair propulsion are of particular concern because propulsion in and of itself is a demanding activity involving repetitive loading of the upper extremities through a precarious range of motion. Multiple studies have reported that propulsion involves the shoulder being maintained at approximately 40° of abduction throughout the stroke.^{3,4} Upon initiation of the propulsive phase of motion, the shoulder is extended and internally rotated, and subsequently ends up flexed and externally rotated upon initiation of the recovery phase.^{3,4}

One method of studying fatigue has been to employ demanding protocols in an attempt to reproduce the

Correspondence: I Rice, Rehabilitation Science Human Engineering Research Laboratory, University of Pittsburgh, Human Engineering Research Laboratories VA Pittsburgh 7180 Highland Dr 151R-1, Pittsburgh, PA 15206, USA.
E-mail: ricei@herlpitt.org

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conditions that have been suggested to contribute to overuse injuries.^{5,6} Rodgers *et al.*⁵ employed a graded wheelchair exercise test progressively adding resistance to induce volitional exhaustion and found increased peak handrim forces occurring with fatigue. Other stroke changes often associated with inefficient propulsion include reduced force effectiveness, such as increased inward handrim force (F_z), and reduced contact time, which can lead to faster application of handrim forces, and ultimately upper extremity joint forces. Furthermore, rapid loading of the arms during propulsion has been associated with a variety of overuse injuries including carpal tunnel syndrome.⁷

Given the many injuries associated with propulsion, recent wheelchair research combined with ergonomic principles have lead to the creation of specific recommendations clarifying optimal propulsion technique. These recommendations appear as part of a clinical practice guideline developed by the Consortium for Spinal Cord Injury.¹ These guidelines indicate that wheelchair users should take long smooth strokes that minimize peak handrim and rate of rise forces, maximizing the time spent in propulsion and using the lowest possible cadence.⁷

The purpose of this study was to administer a prolonged propulsion task that was challenging yet sustainable to discover how individuals' biomechanics would change to maintain a target velocity. All dynamometer parameters were held constant to ensure that any biomechanical changes seen were not because of changes in the system. We hypothesized that as wheelchair users were challenged over time, their propulsion biomechanics would deteriorate. Specifically that subjects would show a stroke with higher cadence, reduced push angle, higher rate of rise and peak forces as time passed.

Materials and methods

Subjects

All subjects were provided written informed consent before participation in this study, as approved by the institutional review board. The study population included men and women aged 18–65 with an SCI T2 and below who independently self-propel a manual wheelchair. Subjects were excluded if they had a history of nondominant traumatic upper extremity injury to both wrist and shoulder, and if they were less than 1-year post-SCI.

Instrumentation and data collection

Each subject's own wheelchair was fitted bilaterally with SMART^{Wheels} (Three Rivers Holdings, LLC, Mesa, AZ, USA) and secured to a dynamometer system using a four-point tie-down system. The SMART^{Wheel} measures three-dimensional forces and torques applied to the pushrim at 240 Hz.⁸ The SMART^{Wheel} does not alter wheel placement, alignment or camber, and the pushrim is a standard anodized rim identical to that of all the subjects tested.

Wheelchair dynamometer and testing procedure

The dynamometer is comprised of two independent rollers, one for each wheel. Real time speed and direction feedback were displayed on a monitor in front of the subjects throughout the propulsion trial. During testing, subjects were asked to complete a straightaway push at 1.4 m s^{-1} (3 mph) for 10 min. The target velocity presented was $1.4 \text{ m s}^{-1} \pm 0.25 \text{ mph}$ in the value of a bar range. This velocity was selected because it is close to normal adult walking speed and exceeds what a normative study has shown to be the self selected speed of 39 active wheelchair users ($0.871 \pm 0.382 \text{ mps}$).⁹ We also felt that it would be strenuous to the subjects over a prolonged period of time given the properties of our dynamometer. The rolling resistance of the dynamometer used was found to be 14.28 N, reportedly just under that of rolling on low pile carpeting.^{10,11} Consequently, we felt that subjects would be working at a greater level than self selected. The 10-min trial was chosen to challenge subjects without causing excessive exhaustion that could lead to drop out. When a steady state velocity was achieved, data were collected for 20 s every 2 min with collection at 0, 2, 4, 6 and 8 min, respectively. All data collection occurred consistently for 20 s for all subjects however data analysis was based on only the first and last time points. The time point 'early' indicated time 1 (0–20 s) and 'late' indicated time 4 (8:00–8:20).

Data analysis

Key variables. The propulsion cycle was divided into two phases, push or recovery phase based on the presence or absence of pushrim forces. Key variables included number of strokes per second (cadence), push angle (angle along the arc of the pushrim), maximum F_z (force directed perpendicular to the plane of wheel rotation), maximum M_p (moment out of the plane of the wheel), maximum resultant force (total force), average velocity, rate of rise of force, push time and the stroke time. Tangential force (F_t), the only force contributing to forward motion of the wheel was calculated by dividing wheel torque by the radius of the wheel.

Statistics. A mixed effects model was used to observe the change in mean values from the early to late time points over a 10-min propulsion trial.

Results

Subjects

A total of 21 individuals, 19 men and two women, participated in this study. The subjects had an average height, mass, age and time since injury of 1.79 m (s.d. = 0.04), 79.0 kg (s.d. = 14.96), 44.8 (s.d. = 9.6) years, and 19.1 years (s.d. = 8.8), respectively. It is important to note that there were three subjects unable to complete the entire trial citing fatigue. All three subjects dropped out at 6 min 20 s before the last data collection time point. These individuals were included in the analysis of the 'early' time point (0–20 s), but not the 'late' time point (8 min–8 min 20 s). Consequently, the N changes from the early ($N = 21$) to late

($N=18$) time points. In addition, the target velocity presented to the subjects was $1.4 \text{ m s}^{-1} \pm 0.25 \text{ mph}$, which means a majority of subjects stayed within the target successfully. For example, the overall group mean velocities were $1.24 \pm 0.19 \text{ m s}^{-1}$ in early and $1.18 \pm 0.31 \text{ m s}^{-1}$ in late time points, and the target boundaries were 1.65 m s^{-1} (high end) and 1.15 m s^{-1} (low end) given the $\pm 0.25 \text{ mph}$ tolerance.

Propulsion biomechanics

Table 1 displays all biomechanical mean values taken at two time points, early (0–20 s) and late (8–20 s), during 10 min of propulsion for five steady state strokes. Mixed effects model revealed that individuals' push time ($P=0.043$) and stroke time ($P=0.023$) increased, whereas maxfz ($P=0.045$), maximum rate of rise of resultant force (maxrorFR; $P=0.0045$) and out of plane moment application (maxrorMP; $P=0.032$) decreased from early to late during 10 minutes of propulsion without a significant change in velocity (see Figure 1). Other key biomechanical variables, such as stroke frequency, push angle, tangential force, maximum resultant force and torque, changed favorably, without statistical significance (see Table 1). Stroke frequency was calculated as 1 per stroke time per individual stroke and then average for five strokes rather than 5 per time to complete five strokes. Because of this method of calculation, stroke frequency was not the exact inverse of our average stroke time; consequently, it was not statistically significant, whereas the average stroke time was statistically significant.

Discussion

To our knowledge, this is one of only a few studies to have examined the propulsion biomechanics of individuals living with SCI using their own personal wheelchairs during an extended propulsion trial. It is important to note that our subjects were made-up entirely of individuals living with long-term SCI where other studies measuring propulsion biomechanics have used able-bodied subjects or a combination of able bodied and individuals with disabilities.¹² In addition, similar studies have used ergometers or nonpersonalized, minimally adjustable wheelchairs for data collection rather than subjects' own wheelchairs.^{1,5,13,14}

Our kinetic results stand out from other related works because subjects unexpectedly modified their propulsion biomechanics favorably from early to late in a 10-minute trial without technique coaching or feedback training.^{12,15} Our subjects displayed a steady cadence, increased time on the pushrim and reductions in both rate of rise of force and Fz (inward directional force), all at a steady state velocity. However, it is evident that the three subjects who dropped out and not included in the analysis of the fourth time point may have skewed the results slightly. It would appear then that the data might be representative of only those accustomed to wheeling longer distances. In addition, there were three subjects lasting the entire trial however unable to maintain target velocity. These subjects showed reductions in many of their force variables however this may be because of the drop in velocity rather than the improved stroke technique. It is apparent that the data of those who maintained velocity showed decreases in force-related variables proportional to those who did not maintain speed.

As few have studied the effects of fatigue on propulsion kinetics, there is a limited availability of work to draw comparisons from. Results from the study of Rodgers *et al.*⁵ are valuable however its design differs considerably from ours. Rodgers *et al.*⁵ employed a stress test that progressively changed dynamometer resistance to cause volitional exhaustion, and subjects were stopped when they could no longer maintain a target velocity. These subjects displayed increased peak handrim forces when fatigued however the studies

Figure 1 Variables have been scaled to fit graph where needed (see variable units in graph legend), all variables changed significantly from time 1 to time 4 ($P<0.05$) with the exception of velocity.

Table 1 Temporal and pushrim kinetics data from early to late time points

	Time 1	Time 2	Time 3	Time 4
Velocity (m s^{-1})	1.24 ± 0.19	1.17 ± 0.25	1.20 ± 0.24	1.18 ± 0.31
Stroke time* (s)	0.89 ± 0.15	0.99 ± 0.15	0.97 ± 0.23	1.00 ± 0.29
Push time* (s)	0.41 ± 0.07	0.48 ± 0.11	0.46 ± 0.13	0.48 ± 0.12
Frequency (strokes per s)	1.16 ± 0.17	1.04 ± 0.17	1.20 ± 0.61	1.19 ± 0.63
Contact angle (degree)	96.61 ± 17.14	103.58 ± 22.17	100.72 ± 19.69	100.96 ± 15.41
Max torque (Nm)	18.15 ± 4.95	16.68 ± 4.69	18.41 ± 5.33	16.66 ± 5.62
Max FR (N)	54.27 ± 18.87	50.12 ± 20.60	52.96 ± 18.52	69.34 ± 19.41
Max Ft (N)	59.56 ± 16.25	54.750 ± 15.41	60.42 ± 17.50	54.69 ± 18.45
MaxrorFr* (N s^{-1})	1461.44 ± 554.65	1249.04 ± 541.71	1364.25 ± 492.59	1233 ± 552.55
Max Fz* (N)	16.45 ± 8.39	16.30 ± 8.06	16.57 ± 7.18	15.03 ± 7.23
MaxrorMP* (N s^{-1})	92.71 ± 48.06	86.71 ± 33.64	89.49 ± 31.23	83.77 ± 40.58

* $P<0.05$ from time 1 to time 4, values reported as mean (s.d.), all means have been adjusted with a mixed model to account for subject drop out.

design may have in part contributed to these findings. For example, the change in resistance of the dynamometer, in and of itself, could elicit biomechanical stroke changes.¹⁶ In addition the pushrim diameter of their simulated wheelchair set up was very small (15") providing reduced mechanical advantage as compared to our 19" pushrim. It is possible that the addition of progressive resistance to the dynamometer combined with the small diameter pushrim may have lead to more pronounced changes in stroke mechanics compared to our study. Our protocol set up and design may have offered subjects the ability to more successfully adapt their biomechanics to maintain a target velocity overtime.

Although our findings suggest improvements in subjects' biomechanics over time, there are inherent limitations in the studies' design. Because our protocol was designed to view a challenging task over time, while minimizing drop out, it was not possible to ensure that all subjects were sufficiently or equally challenged. Despite this limitation, it is likely that subjects found the trial challenging to complete and or maintain because of the dynamometer rolling resistance and target velocity which led to the dropping out of three individuals, and three not maintaining target velocity. Additional measures of fatigue could have been used to confirm this point and is a limitation in the studies design. Future work should incorporate multiple measurement systems to qualify fatigue beyond biomechanics alone. These methods include perceived exertion questionnaires, such as the Borg scale, muscle lactate production, EMG and metabolics.

Factors that may have impacted study findings include our subjects' demographic characteristics. Subjects showed a large range in age and time since injury, which could have affected propulsion and should be explored in future study. Other variables important to consider include pain history, level of SCI, fitness level and wheelchair type/configuration. In addition, the target speed presented to subjects during the propulsion trial may have been submaximal for some and more challenging to others. It has been suggested that under submaximal conditions, propulsion technique may be considered less vital to performance, and therefore, biomechanical differences may become more evident only at higher intensities.^{12,17}

Furthermore, it is likely that study results reflect both the way in which the individual reacted to propelling on a dynamometer and also to the occurrence of fatigue. The extent to which one factor plays a more significant role than the other remains unclear without overground comparison data and additional measures of fatigue. It is possible that the improvements seen from early to late, not related to fatigue, occurred because individuals needed time to accommodate or warm-up to the dynamometer. In addition, the presentation of feedback targets in combination with knowing how long the trial was ahead of time may have been helpful in encouraging users to conserve energy and/or find a more streamlined technique.

The question of how to best judge the wheelchair propulsion proficiency is also critical to this topic of study. Our definition of proper technique indicates that the ideal propulsive stroke would be one occurring at a steady speed

that maximizes contact angle while keeping stroke frequency, and forces to a minimum (rate of rise of resultant force, peak forces and braking torques and so on). This is consistent with the clinical practice guideline, which describes optimal propulsion technique in terms of pain and injury prevention rather than through maximizing gross mechanical and or metabolic efficiency. Others have indicated that propulsion should be viewed from both a mechanical and physiological approach.^{12,17} Because propulsion is related to multiple interacting factors like user characteristics, environment and intensity, it may be beneficial to apply a broad approach to future study. Researchers and health care professionals should encouraged technique training with all of these approaches in mind as well as taking into account the individuals' experience, fitness level and wheelchair configuration.

These findings may have meaningful and clinically significant implications as propulsion occurring inefficiently may place a person at significant risk for developing upper extremity pain and injury.^{1,7,18} Because wheelchair propulsion involves impacting the pushrim thousands of times per day and clearly exceeds what the ergonomics literature considers a high force, high repetition task, any improvements could have an impact on the development of upper extremity pain and injury.¹

Conclusions

Contrary to our hypothesis, researchers found that experienced wheelchair users significantly improved many aspects of their propulsion biomechanics from early to late during extended propulsion trial. Our subjects showed propulsion improvements over time by maintaining a steady cadence, increasing the amount of time on the pushrim and exhibiting decreased rate of rise of force. These findings provide information regarding how individuals adapt their stroke mechanics over time. Future study design should incorporate rigorous measures of fatigue along with dynamometer and overground biomechanical assessments to fully capture these changes.

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