APPLIED RESEARCH

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Investigation of the Performance of an Ergonomic Handrim as a Pain-Relieving Intervention for Manual Wheelchair Users

*†‡Alicia M. Koontz, PhD, RET, *†Yusheng Yang, PhD, †§David S. Boninger, PhD, *John Kanaly, BS, *†‡**Rory A. Cooper, PhD, *†‡**Michael L. Boninger, MD, ††Kathy Dieruf, PhD, and ††Lynette Ewer, SPT

**Human Engineering Research Laboratories, Veterans Affairs Pittsburgh HealthCare System, Pittsburgh;*
†Department of Rehabilitation Science and Technology, University of Pittsburgh;
‡Department of Bioengineering, University of Pittsburgh;
§Three Rivers Holdings, LLC, Mesa, Arizona;
***Department of Physical Medicine and Rehabilitation, University of Pittsburgh Medical Center Health System; and*
††Physical Therapy Program, University of New Mexico

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Manual wheelchair users commonly experience pain in their hands and wrists associated with the repetitive stress of propulsion. The objective of this research was to examine the effect of an ergonomic wheelchair handrim as an intervention designed to reduce pain in the hands and wrists and improve functional outcomes for manual wheelchair users. Three studies were conducted to achieve this objective. In the first study, 10 individuals with paraplegia underwent a biomechanical analysis before and after a 2-week practice period with a Natural-Fit™ (NF) prototype ergonomic handrim. The biomechanical results showed that grip moments were reduced with the NF handrim prototype as compared to the subjects' current handrim ($p < .1$). Other biomechanical findings were mixed. In the second study, 46 manual wheelchair users who replaced their standard handrim with the commercially available NF handrim completed a questionnaire of retrospective measures of symptom severity. Average duration of use of the NF was 6 months. When asked to compare propelling with the NF to propelling with their prior handrims, 85% of respondents reported less pain in their hands and 80% reported less pain in their wrists. The third study was a replication and extension of Study 2: 82 manual wheelchair users who replaced their standard handrim with the NF completed retrospective symptom severity *and* functional status scales after using the NF for an average of 9 months. Results again confirmed that using the NF led to a reduction in the severity of symptoms and to improved functional outcomes.

Key Words: Ergonomic intervention—Wheelchair handrims—Carpal Tunnel Syndrome—Propulsion biomechanics—Manual wheelchair.

Address correspondence and reprint requests to Alicia Koontz, Human Engineering Research Laboratories (151R1-H), VA Pittsburgh Health Care System, 7180 Highland Drive, Pittsburgh, PA 15206.

BACKGROUND

The single circular metal tube attached to the rear wheels of manual wheelchairs (a.k.a., pushrim, handrim, or push/hand ring) has been the standard for propulsion for over 50 years. This is in part because of its simplistic design, ease of use, low cost, and low maintenance. However, many wheelchair users report that the standard handrim style does not meet their needs for effective propulsion. In a survey of 117 marginal manual wheelchair users, Perks et al. found that only 39% of the users propelled with the handrims only, 54% gripped the tire and rim together, and 7% used only the tire. This suggests that over 60% of the users were dissatisfied with solely using the handrim (Perks, Mackintosh, Stewart, & Bardsley, 1994). Alternative propulsion devices have been developed but have failed to gain widespread acceptance and use. For instance, hand crank and lever drive systems are not very popular because, while they may be ideal for outdoor use, they are more difficult to use indoors, have a tendency to add significant width and weight to the wheelchair, and are cumbersome to deal with when transporting the wheelchair. Despite the increased propulsion efficiency that can be achieved with these devices (Mukherjee & Samanta, 2001; van der Woude, Veeger, de Boer, & Rozendal, 1993), the handrim remains the most widely accepted device on the market today. Yet the single, round tubular design may contribute to the high prevalence of upper limb pain and injury.

The prevalence of carpal tunnel syndrome (CTS) among manual wheelchair users is between 40% and 74% (Gellman, Sie, & Waters, 1988; Pentland & Twomey, 1991; Sie, Waters, Adkins, & Gellman, 1992; Wylie & Chakera, 1988). It is estimated from prior research on daily wheelchair use and propulsion biomechanics (Boninger, Cooper, Robertson, & Rudy, 1997; Hoover et al., 2003) that wheelchair users push on their handrims an average of one time per second when propelling their wheelchair. This research suggests (Boninger et al., 1997; Hoover et al., 2003) that wheelchair users push on their handrims an average of 2,500 times a day (assuming at least 40 minutes of propulsion per day), 17,500 times a week, 75,000 a month, and so on. Peak propulsion forces are around 45 to 110 N (Boninger, Cooper, Robertson, & Shimada, 1997; Dallmeijer, van der Woude, Veeger, & Hollander, 1998). To understand the magnitude of these forces, consider that work-related CTS has been defined as associated with high repetition and high-force tasks, where high repetition is defined as having a cycle time of less than 30 seconds, and force is defined as ranging from 9.8 N on the low end to 39 N on the high end (Silverstein, Fine, &
??2 Armstrong, 1987). Therefore, it is not surprising that cross-sectional studies have found a link between handrim wheelchair propulsion and median nerve injury, the fundamental pathology behind the development of CTS. More specifically, using more propulsion strokes to go a given speed, applying higher forces, and more rapidly loading the handrims (rate of rise) have been found to be associated with poorer median nerve function as measured by bilateral upper extremity nerve conduction studies (Boninger et al., 1999). Longitudinal research has confirmed that an examination of these variables in the present can predict an individual's future risk of median nerve injury (Boninger et al., 2005). These studies support the need for interventions that treat, prevent, or delay the onset of CTS among manual wheelchair users.

The implementation of ergonomic modifications for the management and treatment of CTS is widely advocated in the occupational and ergonomics literature (Herbert, Gerr, & Dropkin, 2000; Keir, Bach, & Rempel, 1998; Pinkham, 1988; Rempel, Smutz, So, & Armstrong, 1994). In addition to modifying the task, alterations to tool design often are made to alleviate pain symptoms or reduce injury risk. Consistent with this approach, studies have shown that altering certain wheelchair handrim features influences propulsion performance and biomechanics. Traut and Schmauder tested the effect of 10 different handrims varying in cross-sectional shape, diameter, and surface texture on driving, braking, and maneuvering a wheelchair (Traut & Schmauder, 1993). They found that the larger diameter rim and contoured rim were subjectively ranked among the highest while the standard handrim design was ranked as one of the lowest. Van der Linden et al. investigated the effects on propulsion with two sizes of tube diameters (oval 25 × 30 mm and circular 18 mm diameter) (van der Linden, Valent, Veeger, & van der Woude, 1996). They found that gross mechanical efficiency was higher when using the larger tube diameter and that propulsion frequency decreased (although not significantly) with the larger diameter rims for all three speeds tested. Differences in grip and finger flexor activity (CTS-related factors) were hypothesized to account for the improved efficiency. Gaines and La tested a contoured, oval-shaped handrim of unspecified dimensions with 28 MWUs (Gaines & La, 1986). The majority of users preferred the contoured, oval rims to their standard rims and felt the new rim decreased the effort needed to propel. Incorporating a custom flexible interface between the handrim and the wheel has been found to minimize impact loading while at the same time increasing metabolic efficiency (Richter et al., 2000a, 2000b). Finally, research also indicates that adding a high-friction coating to the handrim improves grip and reduces forces necessary to stabilize the hand on the rim (Koontz, Boninger, Baldwin, Cooper, & O'Connor, 1998; Traut & Schmauder, 1993). Although the affects of altered handrim designs on enhancing mobility have been investigated, their efficacy as pain-relieving devices has never been demonstrated.

Extensive research provides evidence that the repetitive gripping of small objects (often referred to as "pinch gripping") not only contributes to the onset of CTS, but also exacerbates the pain associated with CTS (Keir et al., 1998; Rempel, Keir, Smutz, & Hargens, 1997). Thus, standard wheelchair handrims may exacerbate CTS because of the poor grip that they provide (e.g., the small tube

FIG. 1. Design features of the Natural-Fit.

requires a pinch grip). To compensate, many users grab the tire to enhance grip. And, although the standard handrim is used for both propulsion and braking, it has not been optimally designed for either one. In short, the poor ergonomic design of standard handrims does not provide the features and functions necessary to prevent, manage, or treat CTS.

The Natural-Fit™ is an ergonomic wheelchair handrim designed to provide an improved fit to the hand and relieve stress and pressure on the carpal tunnel. The Natural-Fit was introduced to market in 2003 by Three Rivers Holdings, Inc., in Mesa, ??3 Arizona. A U.S. patent for the handrim design was issued in 2001 (6,276,705, "Wheelchair hand rim," Baldwin et al.), and a second patent is pending. The commercial Natural-Fit is an assembly of two separate components, a smooth oval surface for the palm of the hand and a higher-friction contoured slot for the thumb. In addition to providing separate surfaces for propulsion and braking, the assembly of these two components creates an ergonomic grip for the hand that eliminates "pinch gripping" (Figs. 1–3).

The studies reported here were conducted to (1) compare propulsion biomechanical variables associated with median nerve injury between the Natural-Fit and standard handrims, and (2) determine if extended use of a Natural-Fit handrim reduces upper-extremity pain and improves func-

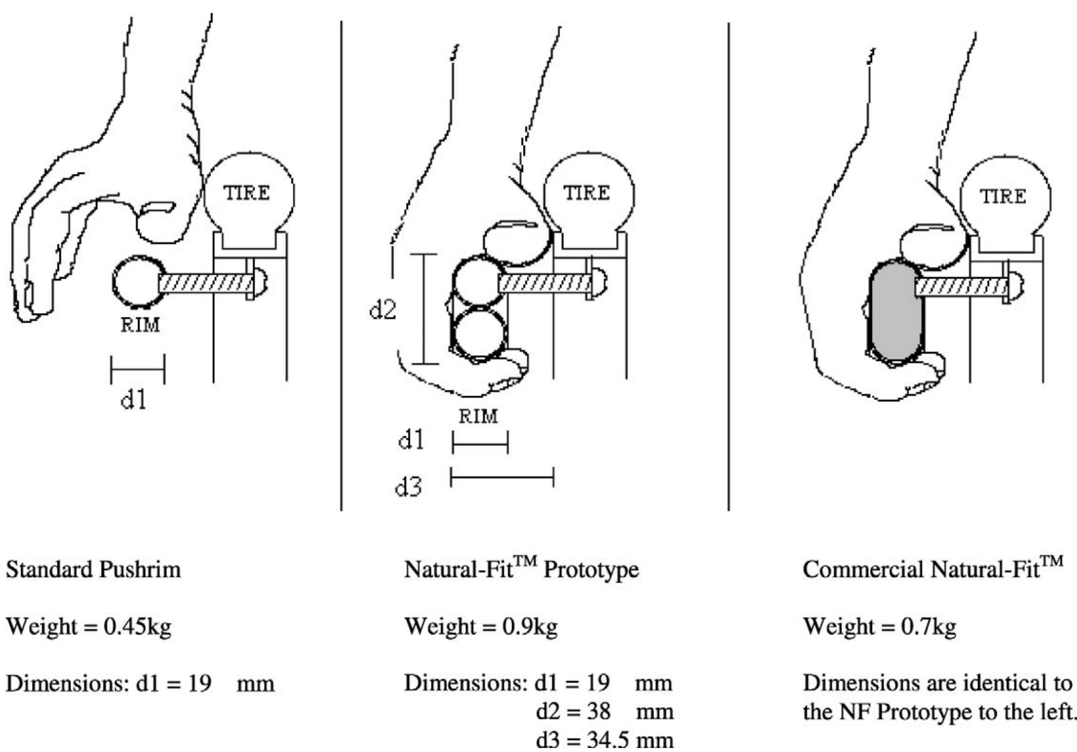

FIG. 2. Standard noncoated handrim (left); Natural-Fit prototype (middle); commercial Natural-Fit (right).

Pinch Grip with a Standard Handrim

Ergonomic Grip with the Natural-Fit

FIG. 3. Grip comparison between a standard handrim (left) and the Natural-Fit (right).

tional outcomes of manual wheelchair users. We hypothesized the following: (1) After a 2-week trial period, a biomechanical analysis would show decreased rate of loading and decreased peak forces for the Natural-Fit in comparison to the standard handrim design and (2) individuals who used the Natural-Fit for an extended time period (e.g., more than 2 weeks) would report decreased severity of CTS-related symptoms (e.g., less hand and wrist pain) and increased functional status compared to when they used a standard handrim.

Three studies were conducted to achieve these objectives. The methods and results of the biomechanical evaluation of the Natural-Fit (Study 1) are presented first, followed by the methods and results of the two retrospective studies of symptom severity and functional status following extended use with the Natural-Fit (Studies 2 and 3).

STUDY 1: BIOMECHANICAL EVALUATION

Methods

This study took place at the Human Engineering Research Laboratories in Pittsburgh, Pennsylvania, and was approved by the local Pittsburgh VA Research and Development Committee, VA Human Studies Subcommittee, as well as the University of Pittsburgh Institutional Review Board.

Subjects

Ten manual wheelchair users (one woman and nine men) provided informed consent to participate in the study. The inclusion criteria for subjects were (1) use a manual wheelchair as their primary mode of mobility, (2) have a spinal cord injury, (3) be between the ages of 18 and 70 years, and (4) use a wheelchair that has quick release axles. Subjects were excluded from participating in the study if they reported a history of trauma to either upper extremity. The subjects who participated had a spinal cord injury between T4 and T12, and average age and years since injury were 40.20 ± 7.42 and 18.6 ± 7.50 years, respectively.

Experiment Protocol

For the biomechanical analysis, a prototype version of the Natural-Fit (NF) was used. The prototype differed from the commercial NF in that it had two 19 mm diameter anodized aluminum rims that were mounted, one on top of the other, to create a pseudo-oval shape (Fig. 2). The slot for the thumb on the NF prototype was powder-coated to provide a higher-friction surface than the oval tube's surface (a high-friction vinyl-like surface is available on the commercial NF). Subjects were tested in the lab on two different occasions: Initial Visit—first time use with the NF prototype, and Follow-Up Visit—after a 2-week practice period. At the end of the first visit, a set of NF handrims were mounted in place of subjects' own handrims. At the end of the 2-week practice run, the NF handrims were removed, and their own handrims were reinstalled on their chair.

During each visit, the subjects were asked to push their own wheelchairs on a dynamometer, which simulated propulsion over a level, smooth floor. Each wheelchair was secured to the dynamometer using a four-point tie-down arrangement. A 17-inch computer screen was positioned in front of the subjects to provide visual feedback on their real-time average and side-to-side speed. Subjects used their own standard (STD) handrim (either anodized or vinyl-coated depending on what they used on their everyday wheelchair) and the NF alternatively. Figure 2 shows the differences in weight and dimensions for the STD rim without coating and the NF prototype. The type of handrim (NF vs. STD) tested first was randomly assigned so as to control for any learning or order effects stemming from completing the same protocol twice.

Propulsion kinetics were obtained using a SmartWheel™, a three-dimensional force and torque-sensing handrim (Three Rivers Holdings, Mesa, AZ). Details concerning the system components, percent linearity, and precision of this device have been previously documented (Cooper, Robertson, VanSickel, Boninger, & Shimada, 1997; VanSickle, Cooper, & Robertson, 1995). The SmartWheel's coordinate system follows the right-hand rule with positive "x" forward, positive "y" up, and positive "z" pointing out of the wheel along the axle (see Robertson, Boninger, Cooper, Shimada, 1996, for a diagram of force directions). Kinetic data were collected via an infrared wireless transmitter at 240 Hz and afterwards filtered using an eighth-order Butterworth low-pass filter, zero-lag, and a 20 Hz cutoff frequency (Cooper, DiGiovine, Boninger, Shimada, & Robertson, 1998).

The SmartWheels were fitted with either a standard or vinyl-coated handrim (depending on the subject's current rim type) or the NF prototype. Whereas the commercial NF is flush against the wheel rim, the NF prototype had to be offset from the wheel rim about ⅛″ (0.32 cm) in order to record accurate forces and moments. The SmartWheels were attached directly to the subjects' own wheelchairs, and data were collected bilaterally. Two OPTO*TRAK* 3020 three-dimensional motion analysis cameras (Northern Digital Inc., Ontario, Canada) were synchronized with the SmartWheel data and used to record the positions of the third metacarpalphalangeal (MCP) joint (hand) and rear wheel hub at 60 Hz. The cameras were mounted on the side walls facing the right and left sides of the individual.

After an acclimation period, subjects were asked to push under three conditions: (1) constant 0.9 m/s (SLOW), (2) constant 1.8 m/s (FAST), and (3) accelerate from a rest position to maximum speed (ACC). Trials SLOW and FAST lasted about 1 minute with data collection occurring in the last 20 seconds of the trial. The ACC trial lasted 20 seconds. The three components of applied handrim force (F_x, F_y, and F_z), moment about the hub (M_z) and wheel position data from the SmartWheel and motion data were recorded for each trial.

Data Analysis

The selected biomechanical variables were resultant handrim force, rate of rise of resultant force, mechanical effective force, wheel torque (moment generated about the rear hub), grip moment, cadence, average velocity, and push angle. These variables are described in more detail in the following paragraphs.

Kinetic data were interpolated linearly to match the kinematic data collection rate of 60 Hz. The SmartWheel force components were mathematically combined to determine the resultant force (i.e., total force) on the handrim. Rate of rise of resultant force was computed by taking the derivative of the resultant force with respect to time and then determining the maximum value during the first third of the stroke to capture initial impact loading on the handrim. We chose to analyze resultant force and rate of rise of force because these variables have been related to wrist injury among wheelchair users (Boninger et al., 1999). Forces in the plane of the wheel, F_x, F_y, and the point-of-force application (PFA) were used to calculate tangential forces (F_t) (Cooper et al., 1996). The PFA is a point on the handrim that best represents the location where the force is being applied. The MCP joint position was assumed for the PFA because previous studies have shown that using kinematic estimates of the PFA is more accurate than kinetic estimates (Sabick, Zhao, & An, 2001). The F_t calculation requires the angle between the PFA and horizontal. This was found by constructing a vector between the location of the PFA (in the sagittal plane: *x, y*) and the marker on the hub and computing the arc tangent of the differences in their *y* and *x* positions. This was the same method used to determine the push angle, which was the PFA angle at the start of force application minus the PFA angle at the end of force application.

Grip moment was estimated by computing the difference between the measured M_z and moments generated about the axle by the applied F_t force calculated using the PFA (F_{tPFA}): ??11

$$M_{grip} = M_z - F_{PFA} \times R_{rim}$$

where R_{rim} = distance from hub to center of the handrim (0.267 m). Although grip moment, which is the force of the grip on the handrim (like a twisting force exerted on the pushrim by the hand), is difficult to measure directly, this calculation (subtracting the moment caused from the tangential force from the measured moment about the hub) represents an indirect measure of that force.

Mechanical effective force (MEF) is the proportion of force at the handrim that contributes to forward motion and is defined as:

TABLE 1. Propulsion variables for the standard and Natural-Fit handrims for the SLOW condition[a]

Propulsion variables	Initial visit		Follow-up visit	
	STD ($N = 9$)	NF ($N = 10$)	STD ($N = 10$)	NF ($N = 10$)
Average velocity (m/s)	0.96 (0.08)	0.98 (0.10)	1.03 (0.14)	1.00 (0.09)
Cadence (strokes/s)	0.98 (0.12)	1.03 (0.20)	1.00 (0.19)	0.98 (0.16)
Push angle (degrees)	79.2 (12.0)	77.1 (18.9)	85.0 (15.6)	83.0 (11.0)
Peak resultant force (N)	58.9 (11.6)	69.1 (18.3)	61.1 (18.0)	61.0 (17.6)
Peak force rate of rise (N/s)	942.7 (167.7)	1237.1 (784.8)	952.9 (422.3)	1017.0 (589.6)
Peak wheel torque (Nm)	14.0 (2.3)	14.6 (3.0)	15.0 (4.6)	14.2 (3.2)
Mechanical effective force	0.70 (0.23)	0.62 (0.24)	0.74 (0.24)	0.70 (0.26)
Grip moment (Nm)	2.13 (0.94)	1.74 (0.81)	1.76 (0.57)	1.51 (0.56)

[a]Group means and standard deviations are shown in parentheses.

$$MEF = \frac{1}{n}\sum_{i=1}^{n}\frac{F_i^{\,2}(i)}{F^2(i)},$$

where F_t in this equation ($F_{t\text{Wheel}}$) is the tangential force obtained by dividing the measured M_z by the radius of the handrim ($F_t = M_z/R_{rim}$) and F is the resultant force. We chose to use this calculation of F_t because the grip moment also can contribute to (or hinder) forward motion of the wheelchair. All the above variables were calculated over the push phase of the stroke only, which was determined by visual inspection of the wheel torque curves.

Stroke cadence was determined by counting the number of strokes (or partial strokes) per second. Propulsion velocity was determined from the angular wheel position data. A 30-point moving average of the angular distance data was calculated before determining the instantaneous velocity for each stroke, which allowed for smoothing the velocity curve. An average velocity was calculated for each stroke.

Postprocessing of all variables was done in Matlab (Mathworks, Inc., Natick, MA). All variables were determined for 10 consecutive strokes for the SLOW and FAST trials. A prior study found that wheelchair speed approaches steady state after the third propulsion stroke (Koontz et al., 2005); therefore only the first two strokes were analyzed of the ACC trial. Data were averaged across strokes within the trial. Pierson r correlations were performed to assess similarities in the propulsion variables between the right and left sides. Since both right- and left-side data were highly correlated (minimum $r^2 = 0.775$; $p < 0.05$), the data were further collapsed by averaging across sides.

Statistical Analysis

Biomechanical data were analyzed using separate repeated-measures mixed models ($\alpha < 0.1$) for each propulsion condition and variable. The subjects were entered as the random factor, and the fixed factors were visit (initial, follow-up) and rim type (STD, NF). The statistical program SAS (SAS Institute Inc., Cary, NC) was used for the analysis. A mixed-model test (PROC MIXED) retains all subject data for cases where missing data for a trial are present. This is different than a traditional repeated-measures ANOVA test (PROC GLM), which omits all of the subject's data if he or she does not have complete data. There were two subject's trials in which we were unable to process the data and therefore were "missing." The mixed-model test is valid only if the data were missing at random. There were no systematic reasons for missing data in this study; therefore this assumption was met. A post hoc analysis consisting of paired comparisons with a Bonferroni adjustment was planned to examine interaction effects.

Results

The propulsion variables for all conditions (slow, fast, acceleration) were similar for both visits (initial and follow-up; see Tables 1–3). There was no significant interaction between rim type and visit for any of the conditions. We found statistical differences between the STD and NF rims for the ??4

TABLE 2. Propulsion variables for the standard and Natural-Fit handrims for the FAST condition[a]

Propulsion variables	Initial visit		Follow-up visit	
	STD ($N = 9$)	NF ($N = 10$)	STD ($N = 10$)	NF ($N = 10$)
Average velocity (m/s)	1.84 (0.22)	1.85 (0.23)	1.86 (0.09)	1.85 (0.08)
Cadence (strokes/s)	1.30 (0.18)	1.35 (0.20)	1.41 (0.23)	1.33 (0.26)
Push angle (degrees)	87.4 (14.0)	86.9 (14.2)	88.3 (16.4)	88.7 (14.5)
Peak resultant force (N)	94.3 (26.4)	107.9 (25.0)	88.6 (21.3)	102.6 (18.9)
Peak force rate of rise (N/s)	1782.6 (637.5)	2045.0 (887.9)	1654.5 (563.8)	2014.4 (693.8)
Peak wheel torque (Nm)	19.6 (5.4)	20.9 (6.8)	19.8 (4.9)	19.8 (4.4)
Mechanical effective force	0.53 (0.16)	0.46 (0.14)	0.63 (0.16)	0.54 (0.19)
Grip moment (Nm)	2.42 (1.19)	2.25 (1.20)	2.19 (0.73)	1.64 (0.23)

[a]Group means and standard deviations are shown in parentheses.

SLOW and FAST conditions when visits were statistically combined (e.g., main effect of handrim
??5 type) (Table 4). All findings with a $p < 0.1$ are shown.

Regardless of the rim type, subjects propelled with the same average velocity, stroke cadence, push angle, peak force rate of rise, and peak wheel torque. This was true for all three conditions. The SLOW speed condition showed reduced grip moments for the NF ($p = 0.0188$). Mean grip moments for this condition ranged from 1.76 to 2.13 Nm for the STD rims and 1.74 to 1.51 Nm for the NF rims. These moments constitute about 10.6% to 15.2% of the peak wheel torques. A similar pattern of reduced grip moments was found in the fast speed condition particularly at the follow-up visit (see the bottom row of Table 2), but these differences failed to reach conventional levels of significance ($p = 0.1237$), most likely because of the greater variance (see the bottom row of Tables 1 and 2) that resulted in the fast condition. Although a general interaction effect was not found with the mixed model design at this speed ($p = 0.2293$), a paired t test revealed that grip moments were significantly different between the NF and standard handrims at the follow-up visit ($p = 0.028$). During the FAST speed, subjects' peak resultant forces were 14 N higher ($p = 0.0211$) for the NF when data from both visits were averaged together.

Whereas the increased peak resultant forces are inconsistent with the hypothesized effects of the NF, evidence of reduced grip moments is consistent with the expected consequences of the ergonomic design of the NF. The ergonomic design, because it requires less effort to stabilize the hand on the rim, led to reduced grip moments. Although the absolute differences in grip moments are small (less than 1 Newton-meter), they are significant particularly in the context of repetitive tasks (such as propelling a wheelchair) in which small differences are magnified over the course of thousands of repetitions.

STUDY 2: SYMPTOM SEVERITY ASSESSMENT

To complement the biomechanical data reported above, a second study was conducted to obtain self-reports of CTS-related symptom severity (e.g., hand and wrist pain) after extended use of the NF. In this questionnaire, respondents were asked to compare retrospectively their current experience of symptoms since using the NF with their prior experience of symptoms when using standard handrims. Because the ergonomics of the NF are designed to reduce stress during propulsion and braking, reduce activation of the finger flexors, and reduce pressure on the carpal tunnel, we expected to find that prolonged use leads to reductions in symptom severity for wheelchair users. The objective of this retrospective questionnaire was to test this hypothesis.

Methods

This study was coordinated by Three Rivers Holdings, the manufacturer of the Natural-Fit. It consisted of a questionnaire that was administered to individuals who had previously purchased the commercial NF handrims. Permission to report deidentified data from the questionnaires was

TABLE 3. Propulsion variables for the standard and Natural-Fit handrims for the ACC condition[a]

Propulsion variables	Initial visit		Follow-up visit	
	STD ($N = 10$)	NF ($N = 10$)	STD ($N = 9$)	NF ($N = 10$)
Average velocity (m/s)	1.19 (0.22)	1.18 (0.21)	1.17 (0.21)	1.19 (0.20)
Cadence (strokes/s)	1.07 (0.09)	1.09 (0.07)	1.12 (0.07)	1.12 (0.08)
Push angle (degrees)	70.8 (19.9)	72.9 (16.6)	61.0 (11.5)	66.5 (16.2)
Peak resultant force (N)	137.8 (39.6)	157.9 (33.6)	145.8 (48.2)	149.6 (32.6)
Peak force rate of rise (N/s)	1629.5 (755.3)	1857.5 (680.2)	1945.4 (877.8)	1828.4 (761.8)
Peak wheel torque (Nm)	32.9 (8.8)	34.3 (7.3)	35.2 (10.4)	33.8 (6.6)
Mechanical effective force	0.79 (0.27)	0.68 (0.22)	0.77 (0.23)	0.71 (0.19)
Grip moment (Nm)	3.83 (2.27)	3.65 (1.54)	3.27 (1.15)	3.10 (0.88)

[a]Group means and standard deviations are shown in parentheses.

granted by the University of Pittsburgh Institutional Review Board.

Subjects

The questionnaire was mailed to the homes of 90 wheelchair users who had previously purchased the NF handrims, had installed them on their wheelchairs in place of their standard handrims, and had been using them for at least 2 weeks.

Questionnaire

Questionnaires were mailed in late June 2004, and respondents were requested to return the questionnaire by July 12, 2004. In return for completing and mailing back the questionnaire, respondents were entered into a drawing to win one of three cash prizes: $150, $75, and $25. To ensure anonymity, they were told the following in a cover letter:

> Your responses to the survey will be completely anonymous. Please do not put your name on the survey. However, to insure your entry into the drawing for the cash prizes, each person has been assigned a code number (which is on the bottom of the second page of the survey). This code number will be removed from the survey upon receipt and placed separately in the drawing—leaving the survey without any identification.

Questions in the two-page questionnaire were on five-point scales and were asked in the context of comparing end users' propulsion experience with the NF to their experience with their prior standard handrims (see Appendix A for the complete questionnaire). Questions on pain, numbness, and tingling were adapted from the Symptom Severity Scale developed and validated by Levine and his colleagues (Levine et al., 1993). Specifically, Symptom Severity Scale questions that asked about respondents' current experience of pain were adapted for the present research by asking respondents to compare retrospectively their current experience of pain when using the NF to their prior experience of pain with their prior standard handrims. For example, questions from the Symptom Severity Scale on pain ("How often do you have pain hand or wrist pain during the day time?" or on numbness ("Do you have numbness in your hand?") were adapted to read:

TABLE 4. Summary statistics for main effect of handrim type

Trial	Variable	Adjusted mean difference	*P*-value	Direction[a]
SLOW	Mean grip moment	0.32 Nm	0.0188	NF < STD
FAST	Peak resultant force	13.8 N	0.0211	NF > STD
	Mechanical effective force	0.08	0.0624	NF < STD

[a]NF = Natural-Fit, STD = standard.

TABLE 5. Study 2—Effect of an ergonomic handrim on upper extremity pain, symptom severity questionnaire ($N = 46$)

Question paraphrase	Percentage of responses in each category: Much less	Somewhat less	About the same	Somewhat more	Much more	Overall mean (1 = less, 5 = more)
Is propelling more or less **comfortable** . . .	2.2	2.2	0.0	26.1	69.6	4.59
Is propelling more or less **fatiguing** . . .	52.2	32.6	8.7	6.5	0.0	1.69
Is propelling more or less **difficult** . . .	60.9	30.4	4.3	4.3	0.0	1.52
More or less **pain** in your hands . . .	60.9	23.9	13.0	0.0	2.2	1.59
More or less **pain** in your wrists . . .	52.2	28.3	17.4	0.0	2.2	1.72
More or less **pain** in your shoulders . . .	29.5	36.4	29.5	4.5	0.0	2.09
More or less **numbness** in your hands . . .	42.9	35.7	21.4	0.0	0.0	1.78
More or less **numbness** in your wrists . . .	38.1	23.8	38.1	0.0	0.0	2.00
More or less **numbness** in your shoulders . . .	33.3	19.0	47.6	0.0	0.0	2.14
More or less **tingling** in your hands . . .	46.3	34.1	19.5	0.0	0.0	1.73
More or less **tingling** in your wrists . . .	41.5	22.0	36.6	0.0	0.0	1.95
More or less **tingling** in yours shoulders . . .	29.3	24.4	43.9	2.4	0.0	2.19
Ease of **other** ADLs (more or less easy)	2.2	4.3	50.0	32.6	10.9	3.46
Opinion of the Natural-Fit (more or less favorable)	4.3	0.0	0.0	17.4	78.3	4.91

Do you feel more or less pain in your hands when using Natural-Fit Handrims than when using your prior handrims?

Do you feel more or less numbness in your hands when using Natural-Fit Handrims than when using your prior handrims?

Personal information about the respondent such as age, diagnosis, and years of wheelchair use was not documented.

Data Analysis

Data were analyzed using SPSS (SPSS, Inc., Chicago, IL). Means, medians, standard deviations, and frequency distributions were calculated for responses to the questionnaire. Because the comparison between the NF and respondents' prior handrim was self-contained within each question, descriptive analyses were used to examine these data.

Results

Forty-six questionnaires were returned from 37 males and 9 females, which resulted in a 51% response rate. Even with the incentive of the drawing, this is an unusually high response rate: Response rates to direct mail questionnaires can be as low as 2%–3%.

For the 46 respondents, average duration of use of the NF was 25 weeks, with a range of 2 to 64 weeks, and with 85% (39) of respondents at 10 weeks or more.

The results of the survey are summarized in Table 5. When asked to compare propelling with the NF to propelling with their prior handrims, 85% of respondents reported less pain in their hands with the NF than with their prior handrims, 80% reported less pain in their wrists, 66% reported less pain in their shoulders. As you can see in Table 5, a similar pattern of results was found for questions regarding tingling and numbness: Greater reductions were reported in the hand and wrist areas than in the shoulder area. On more general questions (those not directly assessing pain), 85% of respondents reported feeling less fatigue, 86% reported more comfort during propulsion, and 91% reported less difficulty during propulsion.

These results provide compelling evidence of self-reported reduction in pain in manual wheelchair users, particularly in the hands and wrists. This confirms the hypothesis that prolonged use (25 weeks/6 months average use) of the NF reduces pain in the hands and wrists of wheelchair users. Yet there are shortcomings in this study that warrant caution in interpreting these data. First, the questionnaire was administered by Three Rivers, the manufacturer of the NF. Although steps were taken to ensure anonymity and minimize bias, this remains a weakness of the current study. Second, for the pain-related questions, the questionnaire did not provide a "not applicable" (N/A) option for respondents who may have not been experiencing any pain at all with their prior handrims. These respondents may have felt compelled to respond anyway, in which case their responses would be invalid. Finally, this questionnaire explored only symptom severity and did not explore functional status, another critical outcome measure for people with CTS (Levine et al., 1993).

STUDY 3: SYMPTOM SEVERITY AND FUNCTIONAL STATUS ASSESSMENT

To address these shortcomings and to provide a replication and extension of Study 2, we conducted a third study. As in Study 2, respondents were asked to compare retrospectively their experiences with the NF to their prior experiences with standard handrims. However, in this study, changes in symptom severity *and* functional status were assessed (Levine et al., 1993). This study was also administered by researchers at the University of New Mexico, and the questionnaire included an "N/A" option for the symptom severity questions.

Methods

As in Study 2, this study employed a questionnaire that was administered to individuals who had previously purchased the commercial NF handrims. This study was approved by the Institutional Review Board at the University of New Mexico School of Medicine, and an informed consent letter for anonymous surveys was included with the questionnaire.

Subjects

Questionnaires were mailed to the homes of 210 manual wheelchair users who had purchased the NF handrims, had installed them on their wheelchairs in place of their standard handrims, and had been using them for at least 2 weeks.

Questionnaire

Questionnaires were mailed on December 8, 2005, and returns were requested by December 20, 2005. Anonymity was achieved by including a code number (used to ensure that the respondents were compensated) on each questionnaire that was removed on receipt. In return for completing and returning the questionnaire to the University of New Mexico, respondents were compensated $10.00.

The four-page questionnaire is contained in Appendix B. Two questions were included for initial screening: Respondents were asked whether or not they had completed a similar survey in the past (to ensure no overlap with the prior study) and how long they had been using the NF (to ensure that it was greater than 2 weeks). Demographic questions (e.g., gender, age), injury-related questions (e.g., level of injury, time in a wheelchair), and questions probing their experience with the NF also were included. Symptom severity questions on pain, numbness, and tingling were identical to those asked in Study 2 except that an "N/A" option was added. Following Levine et al. (1993), two additional symptom severity questions were included that probed the experience of hand and wrist pain—one assessing the presence of pain during the day and a second assessing the presence of pain during the night. ??6

To assess functional status, respondents were asked to report whether it was more or less difficult to complete eight different activities of daily living (ADLs) since they began using the NF. Following Levine et al. (1993), these activities included writing, buttoning of clothes, holding a book, gripping a telephone receiver, opening jars, household chores, carrying grocery bags, and bathing and dressing. Respondents were also asked, more generally, whether using the NF made their "daily tasks more or less work."

Data Analysis

As in Study 2, data were analyzed using SPSS. Means, medians, standard deviations, and frequency distributions were calculated for responses to the questionnaire. Because the comparison between the NF and respondents' prior handrim was

TABLE 6. Measures of symptom severity ($N = 82$)[a]

Question	Percentage of responses for each response option					Overall mean (1 = less, 5 = more)
	Much less	Somewhat less	About the same	Somewhat more	Much more	
More or less **pain** in your hands . . .	38.0	38.0	17.7	1.3	5.1	1.97
More or less **pain** in your wrists . . .	30.3	40.8	25.0	0.0	3.9	2.07
More or less **pain** in your shoulders . . .	20.5	39.7	35.6	4.1	0.0	2.23
More or less **numbness** in your hands . . .	29.0	27.4	37.1	4.8	1.6	2.23
More or less **numbness** in your wrists . . .	21.3	29.5	44.3	4.9	0.0	2.33
More or less **numbness** in your shoulders . . .	13.6	32.2	52.5	0.0	1.7	2.44
More or less **tingling** in your hands . . .	29.2	27.7	35.4	4.6	3.1	2.25
More or less **tingling** in your wrists . . .	25.0	26.7	45.0	1.7	1.7	2.28
More or less **tingling** in your shoulders . . .	18.6	28.8	52.5	0.0	0.0	2.34
More or less hand and wrist pain during the **day** . . .	26.4	41.7	26.4	2.8	2.8	2.14
More or less hand and wrist pain during the **night** . . .	16.9	32.4	45.1	2.8	2.8	2.42

[a]Sample size varied by question because of respondents who failed to answer a question or marked it N/A. In these cases, they were dropped from the analysis for that question.

self-contained within each question, descriptive analyses were again used to examine these data. *T* tests were also employed to compare respondents who had been using the NF for less than 1 year to those who had been using the NF for more than 1 year.

Results

Eighty-nine questionnaires (out of 210 mailed) were returned, a 42% response rate. Seven subjects could not be included in the analysis (e.g., because they did not use the NF for 2 weeks or because they had completed a prior survey). For the final sample of 82, 72 were males and 10 were females, average age was 46–50 (respondents marked an age range), and average time in a wheelchair was 10–15 years (respondents marked a time range). Average duration of use of the NF was 9 months (the mean response fell directly between the ranges of 6–9 months and 9 months to 1 year), with a range of 2 weeks to over 2 years.

If subjects failed to respond to a question or marked it N/A (for the symptom severity questions), they were dropped from these analyses. Across the 11 questions that assessed symptom severity, the average percentage of N/A or missing responses (both types of responses led to removal from the analysis) was 18%. Given that respondents' average time in a wheelchair was 10–15 years, the fact that an average of 82% did respond to these questions (indicating some experience of pain) is not surprising and is consistent with the high prevalence of upper limb pain among manual wheelchair users, particularly as time in a wheelchair increases (Gellman et al., 1988; Pentland & Twomey, 1991; Sie et al., 1992; Wylie & Chakera, 1988).

The results for symptom severity are displayed in Table 6. Consistent with the findings in Study 2, in this third study, 76% of respondents reported less pain in their hands with the NF than with their prior handrims, 71% reported less pain in their wrists, and 60% reported less pain in their shoulders. As illustrated in Table 6, a similar pattern of results was found for questions regarding tingling and numbness: Greater reductions were reported in the hand and wrist areas than in the shoulder area. When asked more generally about their experience of pain during the day and during the night, 68% of respondents reported experiencing less pain during the day, and 49% reported experiencing less pain during the night.

To assess functional status, respondents were asked to report whether it was more or less difficult to complete eight different ADLs since they began using the NF. As can be seen in Table 7, for each ADL, the mean fell below the midpoint of the scale—meaning that, on average, each of these tasks was perceived by respondents as less difficult since using the NF. Specifically, whereas only 1%–6% (percentages varied within this range across the eight activities) reported more difficulty in completing these tasks, 23%–40% of respondents (again depending on activity) reported less

TABLE 7. Measures of functional status ($N = 82$)[a]

Question	Percentage of responses for each response option: Much less	Somewhat less	About the same	Somewhat more	Much more	Overall mean (1 = less, 5 = more)
More or less difficult **writing** . . .	7.3	22.0	64.6	6.1	0.0	2.70
More or less difficult **buttoning clothes** . . .	4.9	18.5	71.6	4.9	0.0	2.77
More or less difficult **holding a book while reading** . . .	6.1	17.1	72.0	4.9	0.0	2.76
More or less difficult **gripping a telephone receiver** . . .	6.1	20.7	69.5	2.4	1.2	2.72
More or less difficult **opening jars** . . .	7.3	22.0	68.3	2.4	0.0	2.66
More or less difficult **doing household chores** . . .	11.1	29.6	58.0	1.2	0.0	2.49
More or less difficult **carrying grocery bags** . . .	6.2	23.5	69.1	1.2	0.0	2.65
More or less difficult **bathing and dressing** . . .	6.1	23.2	69.5	1.2	0.0	2.66
Overall: More or less work **doing daily tasks** . . .	22.0	45.1	28.0	3.7	1.2	2.17

[a]Sample size varied by question because of respondents who failed to answer a question. In these cases, they were dropped from the analysis for that question.

difficulty in completing these tasks, with the remaining respondents (58%–72%) reporting no change in difficulty. When asked whether the NF made "daily tasks more or less work," 67% of respondents reported less work.

To test the hypothesis that the impact of the NF will become more pronounced after more prolonged periods of use, we conducted a *t* test comparing respondents who had been using the NF for less than 1 year (49% of the respondents) to those who had been using the NF for more than 1 year. Significant differences were found consistent with this hypothesis.

1. For symptom severity, in comparison to the Under 1 Year group, those in the Over 1 Year group reported the following:

- Greater decreases in pain in the hands (M = 1.76, SD = 0.86 vs. M = 2.21, SD = 1.16), $t(77) = 1.98$, $p = .05$
- Greater decreases in pain in the wrists (M = 1.85, SD = 0.71 vs. M = 2.30, SD = 1.12), $t(74) = 2.10$, $p = .04$
- Greater decreases in shoulder pain (M = 2.03, SD = 0.88 vs. M = 2.43, SD = 0.73), $t(71) = 2.15$, $p = .04$
- Greater decreases in tingling in the shoulder (M = 2.13, SD = 0.81 vs. M = 2.57, SD = 0.69), $t(57) = 2.15$, $p = .03$.

2. For general functional status, respondents in the Over 1 Year group reported that daily tasks had become less work (M = 1.98, SD = 0.75) more so than those in the Under 1 Year group (M = 2.38, SD = 0.92), $t(80) = 2.15$, $p = .03$. There were no other significant differences.

DISCUSSION

An ergonomic handrim was evaluated for its potential to alter propulsion biomechanics positively and reduce upper limb pain and improve functional status in manual wheelchair users. Although occupational studies have proven that modifying a tool to optimize the fit to the worker can reduce upper limb pain and injury (Feldman, Travers, Chirico-Post, & Keyserling, 1987; Keir et al., 1998; Pinkham, 1988), no studies have investigated the impact of an ergonomic handrim on reducing pain. For manual wheelchair users, investigations into alternative propulsion devices and/or techniques will facilitate efforts to reduce pain in the upper extremities, enhance quality of life, avoid medical costs associated with the treatment of pain and injury, and extend the ability to remain in a manual wheelchair, which also avoids costs associated with the prescription of a power wheelchair.

Biomechanical Consequences

The first study revealed reduced grip moments for the NF for the slow speed condition and a similar, although not significant, pattern in the fast speed condition, particularly at the second visit. Sustained muscle contraction during gripping has been shown to increase the intracarpal tunnel pressure, which could cause potential injuries to the median nerve (Viikari-Juntura & Silverstein, 1999). Thus, reduction of the gripping force with the NF may have contributed to the reduction of self-reported pain noted by respondents in Studies 2 and 3. As we noted earlier, although the absolute differences in grip moments are small, they are not only statistically significant, but also clinically significant in the context of repetitive tasks (such as propelling a wheelchair) in which small differences are magnified over the course of thousands of repetitions.

The grip moment is difficult to measure directly but was indirectly determined by subtracting the moment caused from the tangential force from the measured moment about the hub. This calculation has been shown to be susceptible to errors based on the estimated location of the PFA (Impink, Boninger, Yang, & Cooper, 2005). However, the error was controlled for by using a repeated-measures design and using a marker on the hand, which has been shown to be more reliable than using kinetic data to estimate the PFA (Sabick et al., 2001). Although we acknowledge the susceptibility to error in this measure, it is unlikely that measurement error would account for the systematic differences between conditions found in Study 1. In fact, the noise created by error of this sort would make it more difficult to find the kind of systematic, statistically significant differences that were found. Nevertheless, we encourage continued investigation into grip forces to further bolster confidence in these findings.

The biomechanical evaluation also revealed that at the fast propulsion speed peak resultant forces were higher for the NF. One possible explanation for the higher peak forces is that it was easier for users to apply forces, possibly because of the reduced grip moment and enlarged surface area. Average resultant forces (although not reported in this paper) followed a similar trend as the peaks with greater force being used with the NF handrim. Based on the questionnaire findings, we expected the biomechanical analyses to have shown reduced stroke frequency, force, and rate of loading. There are several possible reasons for this inconsistency. The prototype NF, because of the concentric tube design (see Fig. 2), weighed two times more than the standard uncoated rim and 28% more than the commercial NF used by survey respondents. The manual wheelchair users in the first study were long-time STD handrim users (18.6 years on average) and may have needed extensive practice with the NF before any substantial technique adaptations could occur. The practice time between visits for the biomechanical study was only 2 weeks. The average time of NF handrim use by the questionnaire respondents was 6 months in Study 2 and 9 months in Study 3, which indicates that it may take this long after using the STD to accommodate and benefit from the ergonomic handrim design. The duration of usage and periods between data collection is something that should be studied in the future to determine rates of adaptation.

Early indications of adaptation are present in the biomechanical data. For example, at the slow propulsion speed, mean peak resultant forces and peak resultant force rate of rise decreased between visits with the NF handrim, while these same variables increased slightly with the standard handrim. Similar trends can be seen for the other propulsion conditions. For all conditions, the mean grip moments decreased between visits one and two regardless of which rim was used. It may be that subjects, after using the NF for 2 weeks, adopted an alternative gripping style that they used when being retested with the standard rim.

Consequences for Symptom Severity and Functional Status

The results of Studies 2 and 3 demonstrate that, after extended use of the NF handrim, improved outcomes are evident, both in terms of reduced severity of CTS-related symptoms (Study 2 and 3) and in terms of improved function in activities of daily living (Study 3). These improvements over time are particularly compelling given that research on CTS among wheelchair users clearly indicates that CTS typically progresses over time and becomes more prevalent as one continues to use a wheelchair (Aljure, Eltorai, Bradley, Lin, & Johnson, 1985; Gellman et al., 1988; Sie et al. 1992). Therefore, all things being equal, we would expect symptoms to worsen and tasks to become more difficult as time passes since switching to the NF. Yet, the exact opposite pattern was found: CTS-related symptoms were reduced for the majority of respondents (see Tables 5 and 6) and functional status improved or remained unchanged for the majority of respondents (see Table 7). And, importantly, analyses indicated that the impact of the NF becomes more pronounced after more prolonged periods of use.

These data are based on self-reports, and subjects were asked to assess retrospectively their experience of CTS-related pain and functional status when using the NF compared to when using their prior handrims. Although it is important to complement these self-report data with objective measures of impairment, the self-report data are a meaningful and highly significant indicator of the positive outcome that using an ergonomic handrim can have on the pain associated with CTS. As a testament to the importance of self-report data, Katz and colleagues (Katz, Gelberman, Wright, Lew, & Liang, 1994) note that "Self-administered symptom severity and functional status scales are much more responsive to clinical improvement than measures of neuromuscular impairment and should serve as primary outcomes in clinical studies of therapy for carpal tunnel syndrome." There are also many strengths of this retrospective method of research including: (1) subjects experience the NF in their own natural settings, (2) subjects serve as their own controls, and (3) it affords assessment of clinical outcomes after prolonged use.

However, there are some alternative explanations for the questionnaire results. Because the survey is not based on a random sample, one may argue that only those with favorable outcomes decided to respond. Although this is an important alternative explanation, it is unlikely that it accounts for these results. First, both studies offered incentives to complete and return the questionnaire. Offering incentives should reduce the likelihood that only those who are satisfied with the handrim would respond. Second, because responses were clearly made to be anonymous, it is unlikely that respondents thought that they had to be "positive."

Another alternative explanation is based on the "placebo effect"—that is, just because respondents had a new ergonomic handrim on their chair, they were more likely to report improvements. Although placebo effects have been shown to account for self-reported improvements in up to 30%–40% of respondents (Price, 1984), this is nowhere near the percentages reported here (e.g., 70%–80% of respondents reported reductions in pain). Importantly, not all responses were positive: Respondents showed clear discrimination among the questions, as can be seen in Tables 5, 6, and 7. And, importantly, neither one of these alternative explanations can account for the finding that the impact of the NF became more pronounced after more prolonged periods of use.

CONCLUSION

The results reported here are bolstered by considerable converging evidence reviewed at the outset of this paper. This includes evidence of the effectiveness of similar ergonomic modifications in workplace settings (Herbert et al., 2000; Keir et al., 1998; Pinkham, 1988; Rempel et al., 1994), *and* evidence of the importance of changes in wheelchair handrim design (Traut & Schmauder, 1993; van der Linden et al., 1996; Gaines & La, 1986). This converging evidence is compelling and strengthens confidence in the evidence presented here of improved outcomes resulting from use of the NF handrim.

However, some aspects of the biomechanics findings were not consistent with the questionnaire data. This inconsistency may be accounted for by the difficulty in adapting to the NF in just 2 weeks after many years of using a standard handrim. It is also possible that the propulsion protocol followed did not evaluate the types of tasks in which the advantages of the NF over the STD may be most apparent. These tasks may include pushing up and coasting down a ramp, traversing carpeting or other difficult surfaces, curb ascents/descents, wheelie maneuvers, quick turning, and the like. A repeat study examining the biomechanics of various propulsion tasks after several months of use with the NF may provide objective evidence that complements the self-reported data.

CTS-related pain among manual wheelchair users that is left untreated will worsen, reduce quality of life, and eventually lead to surgery and/or transition to a power chair. The data reported here, and their consistency with the extensive ergonomics literature on the treatment of CTS in the workplace, provide evidence to suggest that ergonomic handrims may be an important addition to the short list of conservative, "first line of defense" options for the treatment and prevention of CTS.

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APPENDIX A. Study 2 Questionnaire

The Natural-Fit Handrim Feedback Survey

Please tell it like it is – we want your honest opinion of the Natural-Fit Handrim. Only through your forthright responses can we make it better.

As you know, fatigue and pain in the hand, wrist, and shoulder are sometimes common among people using manual wheelchairs. The purpose of this survey is to get an idea of **your** comfort, fatigue and pain **before** and **after** using *Natural-Fit Handrims*. We will also ask several questions about your overall opinion of the *Natural-Fit Handrim*.

1) Have the *Natural-Fit Handrims* made propelling your wheelchair more or less comfortable than when using your prior handrims?

☐ Much Less Comfortable ☐ Somewhat Less Comfortable ☐ About the same ☐ Somewhat More Comfortable ☐ Much More Comfortable

2) Is propelling your wheelchair more or less fatiguing when using *Natural-Fit Handrims* than when using your prior handrims?

☐ Much Less Fatiguing ☐ Somewhat Less Fatiguing ☐ About the same ☐ Somewhat More Fatiguing ☐ Much More Fatiguing

3) Do you think *Natural-Fit Handrims* make it more or less difficult to propel your wheelchair?

☐ Much Less Difficult ☐ Somewhat Less Difficult ☐ About the same ☐ Somewhat More Difficult ☐ Much More Difficult

4) Please rate each of the questions below by **circling one number** that best describes your experience or opinion. The scale to use is as follows:

1 = Much less 2 = Somewhat less 3 = About the same 4 = Somewhat more 5 = Much more

Do you feel more or less pain in your **hands** when using *Natural-Fit Handrims* than when using your prior handrims?	1	2	3	4	5
Do you feel more or less pain in your **wrists** when using *Natural-Fit Handrims* than when using your prior handrims?	1	2	3	4	5
Do you feel more or less pain in your **shoulders** when using *Natural-Fit Handrims* than when using your prior handrims?	1	2	3	4	5
Do you feel more or less numbness in your **hands** when using *Natural-Fit Handrims* than when using your prior handrims?	1	2	3	4	5
Do you feel more or less numbness in your **wrists** when using *Natural-Fit Handrims* than when using your prior handrims?	1	2	3	4	5
Do you feel more or less numbness in your **shoulders** when using *Natural-Fit Handrims* than when using your prior handrims?	1	2	3	4	5
Do you feel more or less tingling in your **hands** when using *Natural-Fit Handrims* than when using your prior handrims?	1	2	3	4	5
Do you feel more or less tingling in your **wrists** when using *Natural-Fit Handrims* than when using your prior handrims?	1	2	3	4	5
Do you feel more or less tingling in your **shoulders** when using *Natural-Fit Handrims* than when using your prior handrims?	1	2	3	4	5

5) How your hands, wrists, and shoulders feel may impact other activities you do on a daily basis. Have daily activities (e.g. writing, bathing and dressing) become harder or easier since using *Natural-Fit Handrims*?

☐ Definitely Not Easier ☐ Probably Not Easier ☐ About the same ☐ Easier ☐ Much Easier

6) The Natural-Fit Handrim has a variety of features. We are interested in how important each of these features is to you personally. Please rate each of the features below by **circling one number** that best describes your experience or opinion. The scale to use is as follows:

1 = Not at all important 2 = Not very important 3 = About the same 4 = Somewhat important 5 = Very important

Ergonomic fit to the hand	1	2	3	4	5
Larger smooth surface for braking	1	2	3	4	5
Added grip provided by coating of the thumb piece	1	2	3	4	5
Thumb piece for a larger propulsion surface	1	2	3	4	5
No gap between the rim and wheel	1	2	3	4	5
Removes the need to push on the wheelchair tires	1	2	3	4	5
Hygiene of hands improved	1	2	3	4	5
Retrofits to existing wheels of wheelchair	1	2	3	4	5

7) What is your overall opinion of the *Natural-Fit Handrim*?

☐ Very Unfavorable ☐ Somewhat Unfavorable ☐ Neutral ☐ Somewhat Favorable ☐ Very Favorable

8) Do you think that the *Natural-Fit* is better or worse than a standard wheelchair handrim?

☐ Much Worse ☐ Somewhat Worse ☐ Neutral ☐ Somewhat Better ☐ Much Better

9) If someone were to offer you money to switch back from *Natural-Fit Handrims* to standard wheelchair handrims, how much money would it take?

☐ $1 ☐ $100 ☐ $200 ☐ $300 ☐ $400 ☐ $500 ☐ I would never switch back

10) Who installed your *Natural-Fit Handrims*?

☐ I did ☐ A dealer ☐ A clinic ☐ A friend or family member

11) How easy or difficult was the installation of your *Natural-Fit Handrims*?

☐ Extremely Easy ☐ Somewhat Easy ☐ Neutral ☐ Somewhat Difficult ☐ Extremely Difficult

12) Is there anything about the *Natural-Fit* that you would change if you could? Please explain your answer.

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13) What are the features of the *Natural-Fit* that you like best? Please explain your answer.

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Thank you very much for your time!! Now please return the survey in the addressed, stamped envelope so that we can enter you in the cash prize drawing.

Your code is [[Survey #]]!!

APPENDIX B. Study 3 Questionnaire

STUDY TITLE

Does the use of contoured manual wheelchair rims impact upper extremity pain, comfort and efficiency?

Fatigue and pain in the hand, wrist, and shoulders are common problems among manual wheelchair users. The purpose of the survey is to get an idea of your comfort, fatigue, and pain before and after using Natural-Fit Contoured Handrims.

Some of you may have filled out a similar survey in the past, if you have please check here: ____

1. ☐ Male ☐ Female

2. How much do you exercise?

☐ None ☐ 1 – 3 times per week ☐ 4 – 5 times per week ☐ 6 – 7 times per week

3. Age (years)

☐ 18 – 25 ☐ 26 – 30 ☐ 31 – 35 ☐ 36 – 40 ☐ 41 – 45 ☐ 46 – 50 ☐ 51 – 55

☐ 56 – 60 ☐ 61 – 65 ☐ 66 – 70 ☐ 71 – 75 ☐ 76 – 80 ☐ > 80

4. How long have you been using a wheelchair?

☐ < 1 year ☐ 1 – 3 years ☐ 3 – 5 years ☐ 5 – 10 years ☐ 10 – 15 years ☐ 15 – 20 years

☐ 20 – 25 years ☐ > 25 years

5. What is your level of injury?

☐ $C_4 – C_6$ ☐ $C_7 – C_8$ ☐ $T_1 – T_3$ ☐ $T_4 – T_6$ ☐ $T_7 – T_9$

☐ $T_{10} – T_{12}$ ☐ $L_1 – L_3$ ☐ $L_4 – L_5$ ☐ $S_1 – S_3$

6. Have the contoured handrims made propelling your wheelchair more or less comfortable than when using your prior handrims?

☐ Much less Comfortable ☐ Somewhat less Comfortable ☐ About the same ☐ Somewhat more Comfortable ☐ Much more Comfortable

7. How long have you been using contoured handrims?

☐ < 1month ☐ 1 – 3 months ☐ 3 – 6 months ☐ 6 – 9 months

☐ 9 months – 1 year ☐ 1 – 2 years ☐ > 2 years

8. Why did you purchase or request to use contoured handrims?

☐ Reduce shoulder pain ☐ Reduce elbow pain ☐ Reduce wrist & hand pain

☐ Increase comfort while pushing ☐ Increase pushing efficiency ☐ Looks

☐ Cleanliness of hands while pushing ☐ To stop pushing on the tire

9. Are you still using your contoured handrims? ☐ Yes ☐ No

If you answered "NO", then please answer the next two questions. Otherwise, please skip to question 12.

10. Please explain why you have stopped using the contoured handrims?

☐ Did not reduce shoulder pain ☐ Did not reduce elbow pain ☐ Did not reduce wrist pain

☐ Decreased pushing efficiency ☐ Looks ☐ Did not keep hands cleaner while pushing

☐ Seemed to add weight to chair

11. How long did you use contoured handrims before you stopped?

☐ < 1 week ☐ 1 – 2 weeks ☐ 3 – 5 weeks ☐ 6 – 8 weeks ☐ 2 – 6 months

☐ 6 – 12 months ☐ > 1 year

12. Is propelling your wheelchair more or less fatiguing when using contoured handrims?

☐ Much less Fatiguing ☐ Somewhat less Fatiguing ☐ About the same ☐ Somewhat more Fatiguing ☐ Much more Fatiguing

13. Do you think contoured handrims make it more or less difficult to propel your wheelchair?

☐ Much less Difficult ☐ Somewhat less Difficult ☐ About the same ☐ Somewhat more Difficult ☐ Much more Difficult

14. Do you think that propelling your wheelchair with contoured handrims is more or less efficient?

☐ Much less Efficient ☐ Somewhat less Efficient ☐ About the same ☐ Somewhat more Efficient ☐ Much more Efficient

15. Did using contoured handrims make your daily tasks more or less work?

☐ Much less Work ☐ Somewhat less Work ☐ About the same ☐ Somewhat more Work ☐ Much more Work

16. Please rate each of the questions below by circling one number that best describes your experience or opinion. The scale to use is as follows:

1 = much less 2 = somewhat less 3 = About the same 4 = Somewhat more 5 = Much more

Do you feel more or less pain in your hands when using contoured handrims than when using your prior handrims?	1	2	3	4	5	N/A
Do you feel more or less pain in your wrists when using contoured handrims than when using your prior handrims?	1	2	3	4	5	N/A
Do you feel more or less pain in your shoulders when using contoured handrims than when using your prior handrims?	1	2	3	4	5	N/A
Do you feel more or less numbness in your hands when using contoured handrims than when using your prior handrims?	1	2	3	4	5	N/A
Do you feel more or less numbness in your wrists when using contoured handrims than when using your prior handrims?	1	2	3	4	5	N/A
Do you feel more or less numbness in your shoulders when using contoured handrims than when using your prior handrims?	1	2	3	4	5	N/A
Do you feel more or less tingling in your hands when using contoured handrims than when using your prior handrims?	1	2	3	4	5	N/A
Do you feel more or less tingling in your wrists when using contoured handrims than when using your prior handrims?	1	2	3	4	5	N/A
Do you feel more or less tingling in your shoulders when using contoured handrims than when using your prior handrims?	1	2	3	4	5	N/A

17. If you have pain, does hand or wrist pain bother you more or less during the <u>day</u> when using the contoured handrims than when using your prior handrims?

☐ Much less Pain ☐ Somewhat less Pain ☐ About the same ☐ Somewhat more Pain ☐ Much more Pain

18. If you have pain, does hand or wrist pain bother you more or less during the <u>night</u> when using the contoured handrims than when using your prior hand rims?

☐ Much less Pain ☐ Somewhat less Pain ☐ About the same ☐ Somewhat more Pain ☐ Much more Pain

19. Did the use of contoured handrims make attending social activities (i.e. church, group meetings, going out to eat) more or less trouble-free?

☐ Much less ☐ Somewhat less ☐ About the same ☐ Somewhat more ☐ Much more

20. How your hands and wrists feel may impact other activities you do on a daily basis. For each of the activities listed below, please circle the one number that best describes whether these activities have become more or less difficult since you have been using the contoured handrims.

Activity	Much Less Difficult	Somewhat Less Difficult	About the Same	Somewhat More Difficult	Much More Difficult
Writing	1	2	3	4	5
Buttoning of clothes	1	2	3	4	5
Holding a book while reading	1	2	3	4	5
Gripping of a telephone receiver	1	2	3	4	5
Opening of jars	1	2	3	4	5
Household chores	1	2	3	4	5
Carrying of grocery bags	1	2	3	4	5
Bathing and dressing	1	2	3	4	5

Adapted from Levine et al. A self-administered questionnaire for the assessment of severity of symptoms and functional status in carpal tunnel syndrome. *J Bone J Surg* 1993, 75-A:1585-1592.

21. Do you think that the contoured handrims are better or worse than a standard wheelchair handrim?

☐ Much Worse ☐ Somewhat Worse ☐ Neutral ☐ Somewhat Better ☐ Much Better

22. Do you have any comments regarding the contoured handrims?

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Thank you very much for your time! Now please return the survey by the deadline in the enclosed, addressed, stamped envelope so that we can send you your $10.00.

Your code is [[Survey #]]!