Relationship Between Hand Contact Angle and Shoulder Loading During Manual Wheelchair Propulsion by Individuals with Paraplegia

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Background: Shoulder loading during manual wheelchair propulsion (WCP) contributes to the development of shoulder pain in individuals with spinal cord injury (SCI). **Objective:** To use regression analysis to investigate the relationships between the hand contact angle (location of the hand on the pushrim at initial contact and release during the push phase of the WCP cycle) with propulsion characteristics, pushrim forces, and shoulder kinetics during WCP in individuals with paraplegia. **Methods:** Biomechanical data were collected from 222 individuals (198 men and 24 women) with paraplegia from SCI during WCP on a stationary ergometer at a self-selected speed. The average age of participants was 34.7 years (±9.3), mean time since SCI was 9.3 years (±6.1), and average body weight was 74.4 kg (±15.9). The majority (n = 127; 56%) of participants had lower level paraplegia (T8 to L5) and 95 (42%) had high paraplegia (T2 to T7). **Results:** Increased push arc (mean = 75.3°) was associated with greater velocity (R = 0.384, P < .001) and cycle distance (R = 0.658, P < .001) and reduced cadence (R = -0.419, P < .001). Initial contact angle and hand release angles were equally associated with cycle distance and cadence, whereas a more anterior release angle was associated with greater velocity (R = 0.372, P < .001). When controlling for body weight, a more posterior initial contact angle was associated with greater posterior shoulder net joint force (R = 0.229, P = .001) and greater flexor net joint moment (R = 0.204, P = .002), whereas a more anterior hand release angle was significantly associated with increased vertical (R = 0.270, P < .001) and greater lateral (R = .293, P < .001) pushrim forces; greater shoulder net joint forces in all 3 planes — posterior (R = 0.164, P = .015), superior (R = 0.176, P = .009), and medial (R = 0.284, P < .001); and greater external rotator (R = 0.176, P = .009) and adductor (R = 0.259, P = .001) net joint moments. **Conclusions:** Current clinical practice guidelines recommend using long, smooth strokes during manual WCP to reduce peak shoulder forces and to prevent shoulder pain development. The position of the hand at both initial contact and hand release must be considered in WCP training. It is recommended that participants should reach back to initiate contact with the pushrim to maximize push arc but avoid a more anterior hand position at release, because this could increase shoulder load during the push phase of WCP. **Key words:** *biomechanics, manual wheelchair propulsion, paraplegia, shoulder, spinal cord injury*

The incidence of shoulder joint pain in individuals after spinal cord injury (SCI) is greater than that in the nondisabled population at every age and increases steadily with time post injury; it impacts up to 70% of individuals at 20 years post SCI.[1] Because persons with SCI are dependent on their arms for both functional mobility and activities of daily living (ADLs), shoulder joint pain can present a further loss of function[2] and independence[3] and decreased quality of life.[4] The high prevalence of upper extremity pain and injury among this population is likely influenced by the high physical demands of manual wheelchair propulsion (WCP),[5] as significant shoulder and scapular muscle activity is required to generate the mechanical power necessary to propel the wheelchair while maintaining joint stability.[6]

Although the exact relationship between the physical demands of WCP and the development of shoulder pathology is not yet fully understood, ergonomics studies consistently suggest that there is a link between highly repetitive tasks and the occurrence of upper extremity pain and injury.[7,8]

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WCP involves hundreds of repetitive hand contacts with the pushrim of the wheel during the course of a day. Generation of reaction forces at the hand–rim interface during WCP involves a significant workload for the upper limbs.[9] At initial contact of the hand with the pushrim, the position of extreme shoulder extension with internal rotation[10] can place the greater tubercle and supraspinatus tendon close to the acromion. As the limb is loaded during the subsequent early push phase, high forces and moments[11] are experienced by the shoulder joint. The repetitive mechanical loading imposed on the upper limbs causes muscle fatigue and can lead to reduction in scapular humeral and scapular thoracic muscular control, increasing the risk for subacromial impingement.[12] The resulting injury impairs an individual's ability to maintain ADLs.[1]

Propulsion technique is one aspect of wheelchair use that is believed to be associated with upper limb overuse injury.[13] Although WCP requires the application of a propulsive force to the pushrim during the push phase, individuals can choose a variety of kinematic paths to return the hand to the pushrim during the recovery phase[13] and can vary the timing and location of the hand at initial contact and release from the pushrim during the push phase.[14] Current clinical guidelines recommend using long, smooth strokes that maximize the hand contact time and impulse applied to the pushrim while minimizing the magnitude and rate of loading forces.[7,8] Current propulsion training instruction aims for maximizing the overall size of the contact angle or push arc to reduce the number of strokes needed to maintain the same speed[15]; this reduces the repetitive hand contacts and upper limb motions. The peak force transmitted to the shoulder joint is reduced by spreading out the force applied to the pushrim over a greater arc of contact.[11] The user can selectively maximize the push arc by initially contacting the pushrim further behind the top of the wheel, by releasing the pushrim later and further forward on the pushrim, or by combining these options.

Although we know from literature that maximizing the push arc results in favorable changes to stroke mechanics that may help prevent the development of upper limb pain and injury, it is unknown whether strategies for positioning the hand on the pushrim at initial contact and at hand release may stress the upper limbs differently. To date, a clinician would have little empirical evidence by which to offer a recommendation to support their reasoning for the optimal location of hand contacts used to propel a manual wheelchair. Knowledge of how the upper limbs are stressed differently in response to the user's technique for contacting and releasing the pushrim could serve to further refine the current clinical practice regarding optimal propulsion training techniques for mitigating the negative consequences of increased shoulder loads on the musculoskeletal system experienced by manual wheelchair users with SCI.

The purpose of this study was to determine the relationship between the hand contact angle at initial contact and hand release with propulsion characteristics, pushrim forces, and shoulder kinetics during self-selected manual WCP by individuals with paraplegia. Differences in initial contact and hand release are expected to change the relative location and push arc (contact angle) and be associated with changes in temporal propulsion characteristics (eg, velocity, cadence, cycle distance). A more forward rear wheel axle relative to the shoulder joint position has been demonstrated to reduce the superiorly directed shoulder force[16] and muscular demands,[17] possibly by shifting the arc of hand contact further back on the pushrim. Therefore, we hypothesize that differences in initial contact and hand release angles will be associated with changes in pushrim and shoulder kinetics components. Furthermore, we expect that increases in pushrim forces and shoulder joint kinetics will be associated more with increased anterior hand release angle compared to more posterior initial contact angles.

Methods

Participants

Participants were self-selected; they volunteered in response to flyers posted at outpatient clinics at Rancho Los Amigos National Rehabilitation Center (RLANRC). Informed consent was obtained and persons were screened to determine eligibility. Persons were candidates for inclusion into the study if they (a) had complete or incomplete paraplegia from SCI with a neurological level of injury according to the International Standards for the Neurological Classification of Spinal Cord Injury (ISNCSCI)[18,19] of T2 or lower, (b) had a duration of SCI from 2 to 20 years, (c) were age 18 years or older, (d) had absence of shoulder pain with a total score of 12 or less on the Wheelchair Users' Shoulder Pain Index (WUSPI),[20] (e) utilized a manual wheelchair for mobility at least 50% of the time, and (f) had the ability to understand the informed consent. They were not admitted into the study if any of the following exclusion criteria were present: (a) upper extremity fracture or surgery within the last year; (b) presence of rotator cuff tendinopathy, bicipital tendonitis, adhesive capsulitis, or cervical radiculopathy; (c) positive findings on any clinical tests for rotator cuff impingement or tear (Jobe's Empty Can test,[21,22] Codman's Drop Arm test,[23,24] Hawkins-Kennedy Impingement test,[25] and resisted external rotation[25]); (d) any serious medical conditions. We included only individuals with paraplegia, because we anticipated that upper extremity weakness from cervical level SCI would alter the relationships between the hand contact angles and kinetic variables differently than those for paraplegia.

Prior to data collection, participants read and signed an informed consent that had been approved by the RLANRC institutional review board.

Instrumentation

Data collection was performed in the participant's own wheelchair or in a rigid frame, lightweight Quickie GPV test wheelchair with either a 16-in. or 18-in. wide seat, depending on the size of the participant, as the wheelchair frame design of some participants could not be mounted onto our test ergometer. The rear axle position, height of the footrest, and seat and back of the test wheelchair were adjusted to match the participant's own wheelchair. Each participant used his or her own seat cushion. The wheelchair was positioned on a stationary ergometer (**Figure 1A**), consisting of a support frame and split rollers; this allowed separate rotation of each wheel. The rollers were coupled by means of a differential to an alternator and a modified Velodyne bicycle ergometer (Schwinn Bicycle Company, Chicago, IL) with computer-controlled resistance. To quantify the friction force between the tire and ergometer rollers, we used a coast-down test (from 182 m/min to 35 m/min) with the participant sitting in his or her wheelchair or the test wheelchair mounted on top of the ergometer. Removable flywheels proportional to the weight of both the person and the wheelchair were used to simulate the translational inertia of overground propulsion. Further details about

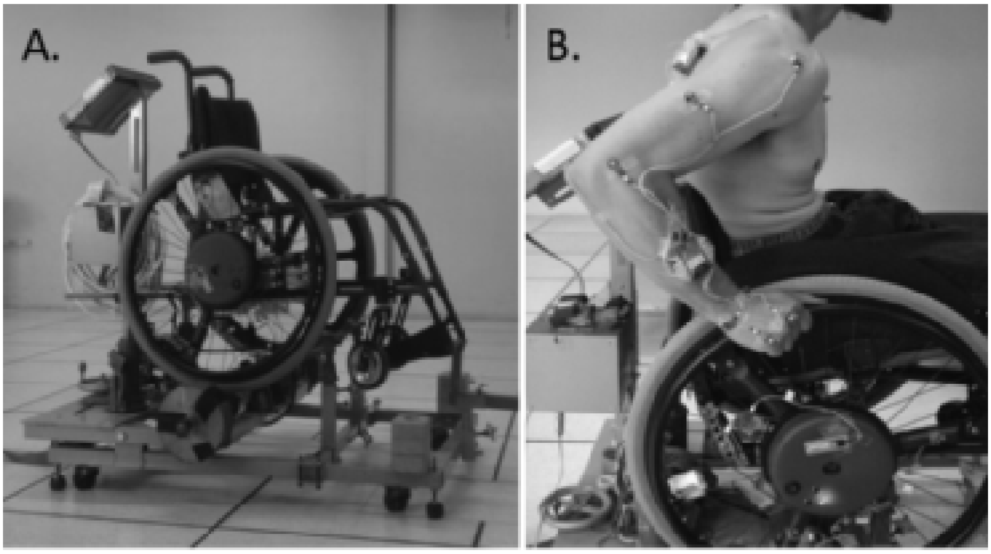

Figure 1. Experimental setup. (A) Manual wheelchair ergometer consisting of supporting frame, controlling computer, and split rollers. (B) Participant on ergometer with markers affixed to the body and wheel.

the ergometer instrumentation and calibration steps are described in a previous article.[26]

Three-dimensional trunk, upper extremity, and wheel kinematics were collected at 100 Hz using a CODA motion analysis system (Charnwood Dynamics Ltd., Leicestershire, UK). Thirteen active infrared markers were placed on the trunk at the manubrium, xiphoid process, spinous process of C7 and T7 vertebrae, greater tubercle of the humerus, lateral epicondyle, medial epicondyle, middle of the upper arm and forearm, radial styloid, ulnar styloid, head of the third metacarpal, and head of the fifth metacarpal. Three reflective markers were placed on each wheel. Bilateral 3-dimensional pushrim kinetics were collected at 100 Hz using instrumented wheels (SmartWheel; Three Rivers Holdings, Mesa, AZ) (**Figure 1B**).

Data collection

Prior to data collection, participants were asked to propel the wheelchair on the ergometer until they felt accustomed to the experimental conditions. Data were collected while participants performed wheelchair propulsion using their preferred propulsion technique at their customary speed with friction level set similar to overground (tile surface) propulsion.[27] Participants propelled the wheelchair for at least 30 seconds immediately before beginning the data collection to achieve near steady-state propulsion. Two 10-second trials (6-10 propulsion cycles/trial) of wheelchair propulsion were recorded.

Data processing

Kinematic and kinetic data were low-pass filtered with a fourth-order zero-lag Butterworth filter with cutoff frequencies of 8 Hz and 10 Hz, respectively, using Visual3D (C-Motion, Inc., Germantown, MD). Initial assessment of the right and left side kinematics and kinetics data revealed a high level of symmetry.[28] Therefore, all subsequent data analysis was completed for the right side only. Cycle duration, defined as the elapsed time between successive hand–pushrim contacts, was determined using pushrim force data. Initial contact was defined as the point when the resultant force on the wheel exceeded 5 N, and release was the point when the force was reduced to below 5 N. Push phase was defined as the time when the hand remained in contact with the pushrim. The recovery phase was defined as the interval between release and the next initial contact with the pushrim. Propulsion velocity, cadence, and cycle distance were calculated from the kinematics data for each propulsion cycle, which were then averaged across cycles. The third metacarpophalangeal joint (MCP3) center, which was located using a previously described method,[10] was used to determine the hand contact angle created by the line segment from the MCP3 and the top dead center of the wheel at pushrim initial contact and at hand release (**Figure 2**). Push arc was calculated from the distance between hand release angle and initial contact angle. Peak anterior, vertical, and lateral forces relative to the pushrim were calculated for each propulsion cycle and averaged across cycles for each participant.

Four segments were constructed based on the International Society of Biomechanics (ISB) standard definitions.[29] The thorax segment was defined using markers placed at the xiphoid, manubrium, and T7 and C7 vertebrae. The

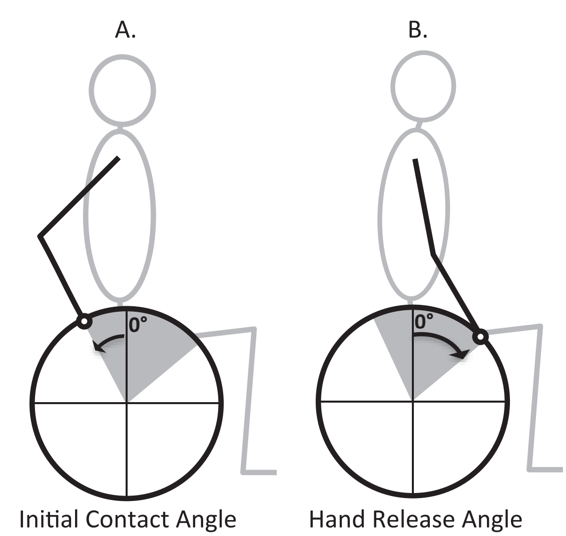

Figure 2. Initial contact angle (A) and hand release angle (B) during the push phase of manual wheelchair propulsion (WCP) measured from the top dead center of the wheel. The push arc starts from the initial contact to hand release. These angles are determined from the third metacarpophalangeal joint center (MCP3).

right upper arm segment was constructed with the marker at the humeral head, a noncollinear marker on the upper arm, and the lateral humeral epicondyle marker. The right forearm segment was created using the lateral humeral epicondyle marker, a noncollinear marker on the forearm, and the marker on the ulnar styloid. The right hand segment was created using the markers of the radial styloid, the ulnar styloid, and the head of the third metacarpal. The rear axle horizontal position was calculated from the difference between horizontal wheel center and shoulder joint center position. A negative rear axle horizontal position indicates that it is anterior to the shoulder joint and vice versa.

An inverse dynamics model was then implemented in Visual3D to calculate right upper extremity net joint forces and moments. In the joint kinetics model, the point of force application was located at the hand center of mass.[30] Net joint forces and internal net joint moments of the shoulder (glenohumeral) were calculated and expressed relative to the proximal segment (trunk) frame. The peak superiorly, posteriorly, and medially directed net joint forces and flexor, adductor, and external rotator net joint moments were calculated for each cycle and averaged across cycles for each participant.

Data analysis

The Shapiro-Wilk statistical test for normality of distribution identified a normal distribution of the hand contact angles, propulsion characteristics, and kinetic variables. Body weight was explored as a potential covariate to the dependent variables (temporal spatial characteristics, pushrim forces, and shoulder joint kinetics). Body weight demonstrated a statistically significant correlation with all but one of the pushrim force and shoulder joint kinetic variables but not with any of the temporal spatial characteristics. The relationships between hand contact angles and propulsion characteristics were examined using correlation coefficients. Specifically, Pearson's product-moment correlations were calculated between push arc and the initial contact angle and hand release angle and propulsion velocity, cadence, cycle distance, and rear axle horizontal position. Rear axle position was also examined as a potential covariate for pushrim and shoulder kinetic variables but was only significantly related to one variable (anterior pushrim force). We used a multivariate linear regression analysis to examine the association between the initial contact and hand release angles and peak pushrim and shoulder joint kinetic variables, after controlling for body weight and rear axle horizontal position where appropriate. Specifically, 9 models were examined with each kinetic measure, as the dependent variable (pushrim forces, shoulder forces, and shoulder moments) and the independent variables were entered in 2 stages. Body weight was entered in the first block, with the exception of the model for shoulder adductor moment where body weight was not a significant covariate. Rear axle horizontal position was a significant covariate only for anterior pushrim force model and was also entered in the first block. After controlling for body weight (and rear axle position), initial contact angle and hand release angle were entered using a stepwise procedure. Because push arc is highly dependent on both initial contact and hand release angles and our premise that a longer push arc is desirable, we were interested in the independent effects of the initial contact and hand release angles. Partial correlations were calculated to compare the strength of relationships between initial contact angle and hand release angle with pushrim forces and peak push phase shoulder net joint forces and net joint moments. The threshold for statistical significance for all analyses was set at $\alpha = 0.05$. IBM SPSS 19.0 (IBM Corp., Armonk, NY) was used to analyze the data.

Results

Biomechanical data were collected from 222 individuals (198 men and 24 women) with paraplegia from SCI during WCP on a stationary ergometer performed at a self-selected speed. The average age of participants was 34.7 (±9.3) years, mean time since SCI was 9.3 (±6.0) years, and average body weight was 74.4 (±15.9) kg. The majority (n = 127; 56%) of participants had lower level paraplegia (T8 to L5) and 95 (42%) had high level paraplegia (T2 to T7) (**Table 1**).

Table 1. Demographic characteristics of the participants with paraplegia

Variable	Mean	*SD*	Minimum	Maximum
Age	34.7	9.3	18	64
Time since SCI, years	9.3	6.0	2.0	21.3
Body weight, kg	74.4	15.9	39.6	122.9
Height, m	1.7	0.1	1.5	2.0
Neurological level of SCI			T2-L5	
High paraplegia/ Low paraplegia			127/95	
Male/Female			198/24	

Shown are the mean, standard deviation (±*SD*), and ranges (minimum and maximum) for the hand angles, rear axle horizontal position, propulsion characteristics (**Table 2**), and peak pushrim and shoulder joint kinetics variables (**Table 3**). The majority (153; 69%) of the participants had rear axle position in front (mean = -2.5 cm [±5.1 cm]) of the shoulder joint. The vast majority (219; 99%) of participants reached back with an initial contact angle posterior to the wheel axle (25.9° [±10.0 °]). The largest shoulder joint force occurred in the posterior direction (mean = 32.8 N [±13.2 N]), which was greater than the superiorly (mean = -3.9 N [±12.1 N]) and medially directed (mean = 9.9 N [±6.9 N]) forces, indicating the relatively large horizontally directed load applied to the shoulder. For the self-selected free propulsion condition tested here, the vertical pushrim force was lower than the gravitational force of the arm weight resulting in negative and inferiorly directed (distraction) net shoulder joint force. The largest net joint moment was the flexor moment (mean = 11.0 Nm [±4.7 Nm]), which was greater than the external rotator (mean = 7.1 Nm [±3.3 Nm]) and adductor (mean = 3.6 Nm [±3.4 Nm]) net joint moments, indicating that the relatively large contribution of the flexor muscle group was required to maintain speed during WCP.

Table 2. Propulsion characteristics variables

Variable	Mean	*SD*	Minimum	Maximum
Push arc, degrees	75.3	13.8	42.9	116.1
Initial contact angle, degrees	25.9	10.0	-5.8	56.2
Release angle, degrees	49.5	10.4	15.0	73.5
Rear axle horizontal position, cm	-2.5	5.1	-16.6	8.8
Velocity, m/min	61.6	18.4	25.2	122.7
Cadence, cycle/min	54	13	31	97
Cycle distance, m	1.2	0.4	0.5	2.7

Propulsion characteristics

Larger push arc (mean = 75.3° [±13.8°]) was associated with increased velocity and longer cycle distance ($R = 0.384$, $R = 0.658$, respectively; $P < .01$) and slower cadence ($R = -0.419$, $P < .001$) (**Table 4**). As expected, a more forward rear axle horizontal position was correlated with more posterior initial contact angle ($R = -0.269$, $P < .001$). A more posterior initial contact angle was associated with a slower cadence ($R = -0.247$, $P < .001$), longer cycle distance ($R = 0.294$, $P < .001$), and increased velocity ($R = 0.139$, $P = .039$). A more anterior release angle was associated with slower cadence ($R = -0.314$, $P < .001$), longer cycle distance ($R = 0.584$, $P < .001$), and increased velocity ($R = 0.372$, $P < .001$).

Pushrim and shoulder kinetics variables

A more posterior initial contact angle was associated with greater posterior shoulder net joint forces ($R = 0.229$, $P = .001$) than hand angle at release after controlling for body weight ($R = 0.164$, $P = .015$) (**Table 5**). Hand release angle also entered the model after initial contact angle, indicating that more posterior initial contact and more anterior release angles were both associated with increased horizontally directed forces on the shoulder (**Table 6**). In contrast, a more anterior hand release angle was associated with increased peak vertical and lateral forces on the pushrim, as well as increased peak superior and medial shoulder forces (partial correlations ranging from 0.176 to 0.293), whereas initial contact angle was not statistically significantly associated with those variables (partial correlations ranging from 0.000 to 0.091) after controlling for body weight. After hand release angle was entered into the models, initial contact angle did not add any further prediction and was not included in the model for these variables.

Table 3. Peak pushrim and shoulder joint kinetics variables

Variable	Mean	*SD*	Minimum	Maximum
Pushrim kinetics				
Anterior pushrim force, N	30.0	10.2	12.6	64.9
Vertical pushrim force, N	34.4	13.0	2.4	84.3
Lateral pushrim force, N	8.8	5.4	-0.2	30.2
Shoulder joint kinetics				
Posterior force, N	32.8	13.2	5.3	82.4
Superior force, N	-3.9	12.1	-34.4	36.4
Medial force, N	9.9	6.9	-6.2	36.2
Flexor moment, Nm	11.0	4.7	2.4	26.4
Adductor moment, Nm	3.6	3.4	-5.5	17.3
External rotator moment, Nm	7.1	3.3	1.9	27.0

Table 4. Pearson's product-moment correlations for hand contact angles and propulsion characteristics

	Push arc		Initial contact angle		Release angle	
Variable	*R*	*P*	*R*	*P*	*R*	*P*
Velocity, m/s	0.384**	<.001	0.139*	.039	0.372**	<.001
Cadence, cycle/min	-0.419**	<.001	-0.247**	<.001	-0.314**	<.001
Cycle distance, m	0.658**	<.001	0.294**	<.001	0.584**	<.001
Rear axle horizontal position, cm	-0.137*	.042	0.269**	<.001	0.078	.249

*Significant at P =.05 level (2-tailed).
**Significant at P = .001 level (2-tailed).

More posterior initial contact angle also was significantly associated with greater shoulder joint flexor moment (R = 0.204, P = .002) after controlling for body weight (**Table 5**). Hand release angle did not add any further prediction and was not included in the model for this variable (**Table 6**). In contrast, only hand release angle was significantly associated with the adductor and external rotator moments (R = 0.259, P = .001, and R = 0.176, P = .009, respectively). Body weight was not a significant predictor for adductor moment and, thus, was not included as a covariate. Initial contact angle did not add any further prediction and was not included in either model.

Discussion

This study examined the relationship between hand contact angle, an aspect of propulsion technique that can be easily modified, and the kinetic consequences. Our results demonstrated that releasing the hand later at a more anterior position on the pushrim was associated with increased peak shoulder forces in all directions and 2 of 3 shoulder joint moments. In contrast, reaching further back for initial hand contact was only associated with higher posteriorly directed shoulder force and flexor shoulder moments. The knowledge gained from this analysis can help refine the current clinical guidelines for optimal wheelchair propulsion.

The finding that increasing the push arc increases velocity and reduces pushing frequency is consistent with previous studies. Boninger et al[16] also showed that moving the horizontal axle position forward relative to the shoulder joint was significantly correlated with the push frequency, rate of rise of the pushrim force, and push angle. Rice et al[31] performed a propulsion training study that showed that maximizing contact angle (push arc) similarly resulted in reduced cadence and

Table 5. Partial correlations for hand contact angles and peak pushrim forces and shoulder joint kinetic variables

	Initial contact angle		Hand release angle	
Variable	***R***	***P***	***R***	***P***
Pushrim forces				
Anterior[a], N	0.125	.065	0.134	.048
Vertical, N	0.008	.909	0.270**	<.001
Lateral, N	0.056	.406	0.293**	<.001
Shoulder joint kinetics				
Posterior force, N	0.229**	.001	0.164*	.015
Superior force, N	0.091	.177	0.176*	.009
Medial force, N	0.000	.999	0.284**	<.001
Flexor moment, Nm	0.204*	.002	0.087	.198
Adductor moment[b], Nm	0.035	.609	0.259[A]	.001
External rotator moment, Nm	0.101	.135	0.176*	.009

[a]Rear axle horizontal position and body weight were significant predictors for anterior pushrim force and were entered as covariates.

[b]Body weight was not a significant predictor for adductor moment and was removed as a covariate. Pearson's product-moment correlations coefficient is reported for the adductor moment.

*Significant at P =.05 level (2-tailed).

**Significant at P = .001 level (2-tailed).

peak pushrim kinetics. De Groot et al[32] performed a WCP training study including persons with new injuries as well as novice wheelchair users and found that changing propulsion technique by increasing push arc and reducing stroke frequency improved mechanical efficiency that was attributed to the changes in propulsion technique.

Our study further enhances the understanding of the contribution of propulsion technique to biomechanics by examining the location of the hand at initial contact and release. In this study, both initial contact and hand release angles had similar correlations to cadence, but hand release angle was more strongly correlated with increased cycle distance and velocity of propulsion than initial contact angle.

The consequences of hand contact angle on musculoskeletal loading can be examined in terms of the changes in joint forces and moments experienced during WCP. Maximizing the push arc is a recommended technique for efficient propulsion mechanics; but where this arc of motion initiates and ends, relative to the pushrim, also impacts the loads experienced by the shoulder. In this study, we showed that reaching back in preparation for the push cycle (ie, more posterior initial contact angle) and releasing the hand later in the push phase (more anterior hand release angle) were associated with greater posterior shoulder joint force, but the correlations between increases in pushrim and net shoulder forces were stronger with anterior hand release angles. Only more posterior initial contact angle was associated with increased flexor net joint moments. In contrast, the more anterior hand release angle was strongly associated with increased adductor and external rotator shoulder net joint moments. These results show that a more posterior initial hand contact increases demands to the shoulder flexor muscle groups and releasing the hand later from the pushrim additionally increases the demands to the adductor and internal rotator muscle groups. The results also suggest that reaching backward can actually create the mechanical advantage for greater flexor moments for forward propulsion, in contrast to additional increases in less propulsive (ie, does not directly contribute to forward propulsion) moments associated with releasing at a later time (more anterior hand release angle). The relationship between a posterior initial hand contact and the posterior shoulder joint forces also was identified in an earlier study of the effects of an anterior rear wheel axle position.[16]

Table 6. Summary of final model of regression analysis for significant hand contact angle variables and pushrim and shoulder joint kinetics with body weight as a covariate

Variable	Predictor	*β*	*P*	*R*	Adjusted R^2	ANOVA	*P*
Pushrim force							
Anterior[a], N							
	Body weight	0.224	.001	0.336	0.097	$F(4, 216) = 6.9$	<.001
	Rear axle horizontal position	0.133	.049				
	Initial contact angle	0.139	.045				
	Hand release angle	0.140	.033				
Vertical, N							
	Body weight	0.252	<.001	0.371	0.129	$F(2, 218) = 17.3$	<.001
	Hand release angle	0.261	<.001				
Lateral, N							
	Body weight	0.149	.021	0.332	0.102	$F(2, 218) = 13.5$	<.001
	Hand release angle	0.290	<.001				
Shoulder joint kinetics							
Posterior force, N							
	Body weight	0.174	.009	0.318	0.089	$F(3, 217) = 8.1$	<.001
	Initial contact angle	0.250	<.001				
	Hand release angle	0.184	.005				
Superior force, N							
	Body weight	-0.297	<.001	0.335	0.104	$F(2, 218) = 13.7$	<.001
	Hand release angle	0.169	.009				
Medial force, N							
	Body weight	0.187	.004	0.342	0.109	$F(2, 218) = 14.5$	<.001
	Hand release angle	0.278	<.001				
Flexor moment, Nm							
	Body weight	0.207	.002	0.258	0.058	$F(2, 218) = 7.8$	.001
	Initial contact angle	0.207	.002				
Adductor moment[b], Nm							
	Hand release angle	0.259	<.001	0.259	0.063	$F(1, 219) = 15.7$	<.001
External rotator moment, Nm							
	Body weight	0.198	.003	0.268	0.063	$F(2, 218) = 8.4$	<.001
	Hand release angle	0.172	.009				

Note: ANOVA = analysis of variance.

[a]Rear axle horizontal position and body weight were significant predictors for anterior pushrim force and were entered as covariates.

[b]Body weight was not a significant predictor for adductor moment and was removed as a covariate.

In free and fast WCP with an anterior wheel axle (and posterior seat position), superior shoulder forces were reduced while posterior forces were unchanged. Posterior forces at the shoulder were increased with an anterior wheel axle only during the most demanding condition of graded WCP.

To relate the clinical implications of shoulder loads and wheelchair propulsion, Mercer et al[33] examined the association between the biomechanics of wheelchair propulsion and shoulder pathology in manual wheelchair users with paraplegia. Shoulder pathology was evaluated using physical exam and MRI. They determined that individuals who experienced higher net posterior or lateral shoulder joint forces or net extension shoulder joint moment during propulsion were more likely to exhibit coracoacromial ligament edema. Those who had larger lateral net joint forces or abduction net joint moments were more likely to have coracoacromial ligament thickening. Higher superior forces (compressive) and internal rotation joint moments were associated with increased signs of shoulder pathology during the physical exam. More of these kinetic variables found to be associated with shoulder pathology by Mercer and colleagues were more strongly related to the hand angle at release than to hand angle at initial contact in our study.

R-squared values of all of the models were relatively low, with hand angle explaining between 5% and 13% of the variance in the pushrim and shoulder joint kinetic variables (**Table 6**). This indicates that other independent biomechanical variables explain the variance in the pushrim and shoulder joint kinetic variables. Body weight is a significant factor that influences the musculoskeletal loading experienced by wheelchair users,[34] but muscle strength for a given body weight determines whether an individual gets shoulder pain. Mulroy et al[35] examined which factors were most influential in shoulder pain development and determined that participants who developed shoulder pain had decreased muscle strength, particularly in the shoulder adductors, and lower levels of physical activity prior to the onset of shoulder pain. Future studies are therefore needed to determine whether aspects of propulsion techniques are predictors of shoulder pain development.

Our study is limited, as we examined only free propulsion on a wheelchair ergometer. Although wheelchair users are exposed to varying propulsion conditions that affect the propulsion biomechanics, we wanted to examine a condition in which participants were not constrained by speed requirements and resistance level. We also wanted to analyze multiple propulsion cycles of a consistent propulsion pattern for each participant. Moreover, the participants in this study propelled in their own manual wheelchair or used a test wheelchair that was matched to their own chair, including their rear axle horizontal position. It is expected that each individual propelled using his or her own propulsion technique. We examined individuals with paraplegia with full upper extremity function but varying levels of strength in the abdominals and trunk extensor muscles. Participants with lower levels of injury were capable of controlling their push arc and had the capacity to initiate hand contact by reaching back as well as prolong the push arc by leaning forward to release at a more anterior position. Future analysis will examine the relationships between level of trunk control and propulsion techniques, including hand contact angles.

Conclusion

Current clinical guidelines recommend a propulsion technique of long, smooth strokes that maximize the contact time and impulse applied to the pushrim while minimizing the rapid rate of loading and impacts (short duration, large magnitude forces). More posterior initial contact and more anterior hand release angles decrease cadence and increase cycle distance and velocity, but they also influence the reaction forces and upper extremity demands; these effects must be considered when providing wheelchair propulsion training. In situations where maximizing propulsion speed is not a primary goal, the recommendation, based on our results, is to maximize the push arc by reaching back to contact the pushrim more posteriorly instead of using a more anterior hand position at pushrim release during the push phase of WCP.

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