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The influence of speed and grade on wheelchair propulsion hand pattern

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ABSTRACT

Background: The hand pattern used during manual wheelchair propulsion (i.e., full-cycle hand path) can provide insight into an individual's propulsion technique. However, previous analyses of hand patterns have been limited by their focus on a single propulsion condition and reliance on subjective qualitative characterization methods. The purpose of this study was to develop a set of objective quantitative parameters to characterize hand patterns and determine the influence of propulsion speed and grade of incline on the patterns preferred by manual wheelchair users.

Methods: Kinematic and kinetic data were collected from 170 experienced manual wheelchair users on an ergometer during three conditions: level propulsion at their self-selected speed, level propulsion at their fastest comfortable speed and graded propulsion (8%) at their level self-selected speed. Hand patterns were quantified using a set of objective parameters, and differences across conditions were identified.

Findings: Increased propulsion speed resulted in a shift away from under-rim hand patterns. Increased grade of incline resulted in the hand remaining near the handrim throughout the cycle.

Interpretation: Manual wheelchair users change their hand pattern based on task-specific constraints and goals. Further work is needed to investigate how differences between hand patterns influence upper extremity demand and potentially lead to the development of overuse injuries and pain.

1. Introduction

The manual wheelchair propulsion cycle can be divided into contact and recovery phases (e.g., Kwarciak et al., 2009). During the contact phase, the user delivers mechanical power to the wheelchair via contact with the handrim and consequently the hand is constrained to the handrim. During the recovery phase, the user repositions the arm and hand in preparation for the next stroke. The hand is far less constrained during the recovery phase and can follow any number of paths in preparation for the next cycle. This relative freedom leads to a wide spectrum of possible hand patterns (i.e., full-cycle hand paths) that are frequently classified into four pattern types based on the shape of their projection onto the plane of the handrim: arcing (AR), single loop (SL), double loop (DL) and semicircular (SC) (Fig. 1, e.g., Boninger et al., 2002). DL and SC are sometimes grouped together and designated as under-rim patterns, which is a term describing the location of the hand just prior to initiation of contact with the handrim (Kwarciak et al., 2009). As the movement of the hand is closely linked with propulsion mechanics, the hand pattern is a clinically visible indicator that can provide insight into an individual's propulsion technique (e.g., Shimada et al., 1998).

Previous studies classifying hand patterns have primarily used subjective and qualitative methods (e.g., de Groot et al., 2008; Shimada et al., 1998). However, hybrid patterns occur and the lack of objective methods to classify them can lead to inconsistencies between studies (Koontz et al., 2009). Early studies relied on a single rater system (e.g., Boninger et al., 2002), but recent investigations have attempted to minimize the influence of subjectivity by using a multiple rater classification procedure (Koontz et al., 2009; Kwarciak et al., 2012). One study used a set of quantitative parameters and data clustering techniques to distinguish between pattern types (Aissaoui and Desroches, 2008). However, while their investigation revealed four distinct pattern types, three resembled variants of AR and the fourth resembled SL. None of their identified patterns resembled SC or DL, despite the prevalence of these patterns in other studies. A more recent study attempted to characterize hand patterns using a complex set of quantitative parameters such as maximum length and height (Stephens and Engsberg, 2010). However, they did not attempt to use these parameters to distinguish between pattern types, instead relying on subjective classification methods.

Most hand pattern studies have focused on level propulsion at a self-selected speed. However, daily living activities often require an individual to propel their wheelchair under more intense conditions (e.g., at a

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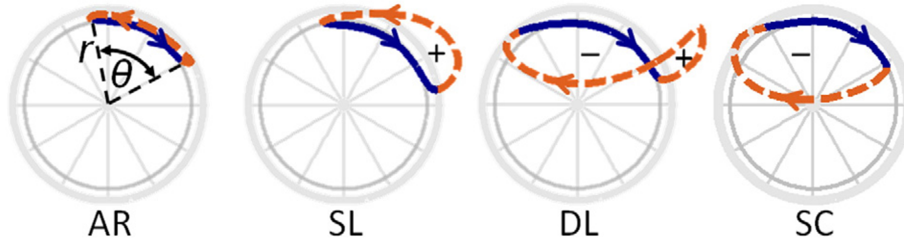

Fig. 1. Hand pattern and variable definitions. The four hand pattern types are arcing (AR), single loop (SL), double loop (DL) and semicircular (SC). The solid line denotes the contact phase, while the dashed line denotes the recovery phase. Also depicted are the radius of the handrim (r) and the angle of handrim contact (θ). The mathematical signs denote whether the signed area enclosed by each loop is positive (+) or negative (−).

higher speed or up a graded surface) that may place the upper extremity at a higher risk for injury. Both speed and grade have been shown to influence propulsion spatiotemporal characteristics (e.g., van der Woude et al., 1988), joint kinetics (Kulig et al., 1998) and muscle activity (e.g., Chow et al., 2009). However, studies investigating their influence on hand patterns have been limited. One study has suggested that an increase in propulsion speed may lead to fewer individuals selecting an under-rim hand pattern (Boninger et al., 2002). Others have suggested that individuals may be more likely to use AR when encountering a higher grade of incline (Richter et al., 2007), with the investigators attributing this preference to previous results suggesting that AR may be the most biomechanically efficient pattern (de Groot et al., 2004). However, as these studies specified hand pattern solely as a categorical variable, changes in patterns could only be quantified by the number of individuals that crossed a subjective threshold between patterns.

The purpose of this study was to develop a set of objective quantitative parameters to characterize hand patterns and determine the influence of propulsion speed and grade of incline on the patterns preferred by manual wheelchair users. Based on previous study observations, we hypothesized that (1) increased propulsion speed would result in a shift away from under-rim patterns (i.e., DL and SC), and (2) increased grade would result in a shift toward the AR pattern.

2. Methods

2.1. Subjects

Experimental data were collected from 170 individuals with complete motor paraplegia and free of shoulder pain (gender: 153 male, 17 female; age: mean = 34.9 years, SD = 9.1 years; time from injury: mean = 9.6 years, SD = 6.2 years; height: mean = 1.74 m, SD = 0.09 m; mass: mean = 75.0 kg, SD = 16.5 kg). Participants were recruited from outpatient clinics throughout the Rancho Los Amigos National Rehabilitation Center and provided informed written consent in accordance with the Institutional Review Board.

2.2. Data collection

Each participant propelled their own wheelchair on a stationary ergometer during 3 conditions: free, fast and graded (Fig. 2). For the free condition, subjects performed level propulsion at their self-selected free speed (mean = 1.04 m/s, SD = 0.30 m/s) with the resistance level set similar to overground propulsion over a tile surface (e.g., Raina et al., 2012). For the fast condition, subjects performed level propulsion at their fastest comfortable speed (mean = 1.90 m/s, SD = 0.46 m/s). For the graded condition, subjects performed inclined propulsion at their level self-selected speed (mean = 1.05 m/s, SD = 0.30 m/s) with the front end of the ergometer elevated and resistance level increased to simulate propulsion at an 8% incline (e.g., Lighthall-Haubert et al., 2009).

Subjects acclimated to each condition until they felt comfortable, and a 10-second trial (preceded by at least 30 s of propulsion to ensure near steady-state cycles) was recorded for each condition, with a 5-minute rest period between conditions. Trunk, right-side upper extremity and wheel kinematics were collected using a CODA motion analysis system (Charnwood Dynamics Ltd., Leicestershire, UK) with 15 active markers placed on landmarks on the body and right wheel. Three-dimensional right-side handrim kinetics were measured using an instrumented wheel (SmartWheel; Three Rivers Holdings, Mesa, AZ, USA).

2.3. 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, USA). A resultant handrim force threshold of 5 N was used to delineate between contact and recovery phases. Contact and recovery phase data for each cycle were time-normalized and averaged across propulsion cycles within each subject. Cadence, contact percentage (i.e., percentage of cycle time spent in the contact phase) and the average (F_{avg}) and peak

Fig. 2. Experimental setup used to collect propulsion mechanics on a custom-built wheelchair ergometer. A CODA motion analysis system (Charnwood Dynamics Ltd., Leicestershire, UK) was used to collect kinematic data, while a SmartWheel (Three Rivers Holdings, Mesa, AZ, USA) was used to measure handrim kinetics.

(F_{peak}) resultant handrim forces were calculated for each cycle and then averaged across cycles.

2.4. Pattern characterization

The third metacarpophalangeal joint center (MCP3) was located using a previously described method (Rao et al., 1996), and the average MCP3 path was projected onto the plane of the handrim resulting in a closed curve (e.g., Fig. 1) to define the hand pattern. Next, a multiple rater system was used to classify each pattern into one of the four previously defined types (Fig. 1). Custom Matlab (Mathworks Inc., Natick, MA, USA) code displayed the individual hand patterns to the rater in a random order. Two raters that were familiar with the literature on propulsion hand patterns independently classified each hand pattern based solely on the displayed image of the hand pattern. In the case of a disagreement between raters, a third rater independently classified the hand pattern into one of the two hand pattern types chosen by the first two raters.

Each pattern was also objectively characterized using two newly developed parameters, net (linear sum) radial thickness, NRT (Eq. (1)), and total (absolute value sum) radial thickness, TRT (Eq. (2)) as follows:

$$NRT = \frac{\sum_{i=1}^{nloops} A_i}{r\theta} \quad (1)$$

$$TRT = \frac{\sum_{i=1}^{nloops} |A_i|}{r\theta} \quad (2)$$

where *nloops* is the number of loops in the curve, A_i is the signed area enclosed by the ith loop of the curve, r is the radius of the handrim, and θ is the angle of handrim contact (Fig. 1). The number of loops was calculated using custom Matlab code that determined the number of curve intersections.

The signed area was calculated using the surveyor's area formula, which is a special case of Green's theorem (e.g., Braden, 1986), such that counter-clockwise loops resulted in positive values and clockwise loops resulted in negative values (Fig. 1). Using this convention, positive NRT values denote hand patterns that are primarily over-rim (e.g., SL), while negative NRT values denote hand patterns that are primarily under-rim (e.g., SC). Meanwhile, small TRT values denote patterns in which the hand remains near the handrim (e.g., AR), while large TRT values denote patterns in which the hand moves farther away from the handrim (e.g., SL, SC, DL). As a result, on a two-dimensional plot with the vertical axis corresponding to TRT and the horizontal axis corresponding to either the ratio NRT/TRT (e.g., Fig. 3) or NRT (e.g., Fig. 4), a set of basic thresholds can divide the space into four regions that correspond to the four commonly observed hand pattern types. When used in coordination with TRT, the ratio NRT/TRT is helpful for pattern type classification and can improve figure clarity in the AR region. However, independently the NRT/TRT ratio is limited in its ability to differentiate between multiple patterns as it provides no information about pattern thickness. Therefore, NRT is more useful when comparing across conditions. To help validate the use of these new parameters to quantify hand patterns, the pattern type corresponding to the calculated parameters was compared with the pattern type identified by the multi-rater system.

2.5. Statistical analyses

To determine if propulsion condition affected the hand pattern, statistical analyses were performed using SPSS (IBM Corp., Armonk, NY, USA). Differences in the propulsion variables (NRT, TRT, θ, cadence, contact percentage, F_{avg} and F_{peak}) were assessed using a one-factor (propulsion condition) repeated measures ANOVA with three levels (free, fast and graded). When a significant main effect was found, pairwise comparisons were performed using paired t-tests with a Bonferroni adjustment for multiple comparisons. The unadjusted threshold for statistical significance for all analyses was set at $\alpha = 0.05$.

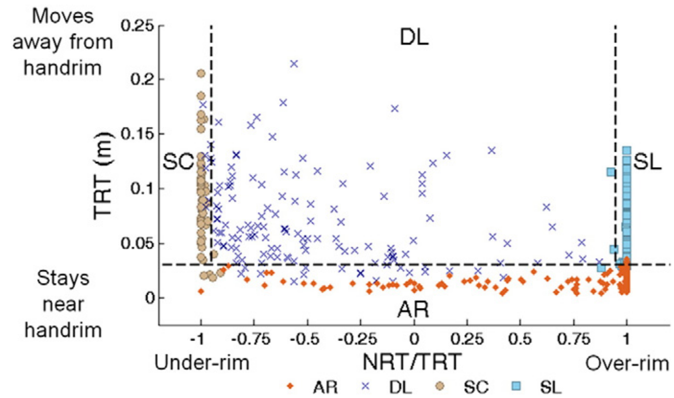

Fig. 3. Comparison of objective and subjective hand pattern classification results. The vertical axis corresponds to TRT and the horizontal axis corresponds to the ratio NRT/TRT. Thresholds for the objective classification are depicted with the dashed lines at TRT = 0.03 m, NRT/TRT = −0.95 and NRT/TRT = 0.95. Regions corresponding to each pattern type are labeled with the objective classification. Subjective classification is indicated with the following symbols: AR (◆), DL (×), SC (●) and SL (■). For figure clarity, NRT/TRT was selected as the horizontal axis variable instead of NRT.

3. Results

With pattern type thresholds set at TRT = 0.03 m, NRT/TRT = −0.95 and NRT/TRT = +0.95, the objective pattern classification method and the subjective multi-rater method produced the same results 90% of the time (Fig. 3).

All variables were found to have a significant propulsion condition main effect ($P < 0.001$). The pairwise comparisons showed that compared to the free condition, the fast condition resulted in significantly higher NRT, θ, cadence, F_{avg} and F_{peak} and significantly lower contact percentage (Table 1, $P < 0.001$). The fast condition also resulted in significantly higher TRT ($P = 0.006$). Compared to the free condition, the graded condition resulted in significantly lower TRT and significantly higher NRT, θ, cadence, contact percentage, F_{avg}, and F_{peak} ($P < 0.001$). Compared to the fast condition, the graded condition resulted in significantly lower TRT and significantly higher θ, contact percentage, F_{avg} and F_{peak}. The propulsion pattern changes across conditions were also

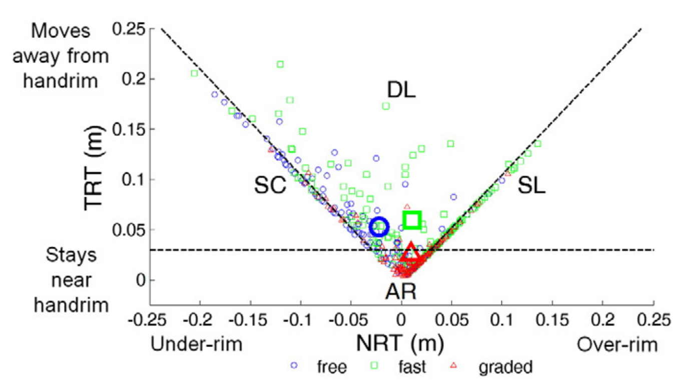

Fig. 4. Hand pattern parameter values across conditions. The vertical axis corresponds to TRT and the horizontal axis corresponds to NRT. Thresholds for the objective classification are depicted with the dashed lines at TRT = 0.03 m, NRT/TRT = −0.95 and NRT/TRT = 0.95. Regions corresponding with each pattern type are labeled with the objective classification. Propulsion condition is indicated as follows: free (○), fast (□) and graded (△). The across-subject mean values are indicated with a larger version of the same symbols. For comparisons across conditions, NRT was selected as the horizontal axis variable instead of NRT/TRT.

Table 1
Mean (standard deviation) values of the propulsion variables for each condition.

	Propulsion condition			Significant comparisons [$\alpha = 0.05$]
	Free	Fast	Graded	
NRT [m]	−0.0219 (0.0555)	0.0103 (0.0585)	0.0095 (0.0309)	□ ▒
TRT [m]	0.0529 (0.0401)	0.0601 (0.0418)	0.0261 (0.0224)	□ ▒ ■
θ [deg]	78.3 (15.7)	83.7 (14.2)	88.1 (14.2)	□ ▒ ■
Cadence [Hz]	0.890 (0.218)	1.312 (0.318)	1.258 (0.269)	□ ▒
Contact percentage [% cycle]	37.6 (7.6)	34.0 (7.2)	60.0 (6.8)	□ ▒ ■
F_{avg} [N]	29.7 (8.0)	42.8 (13.0)	74.0 (18.0)	□ ▒ ■
F_{peak} [N]	46.2 (15.3)	79.3 (29.6)	124.5 (32.3)	□ ▒ ■

□ denotes a significant free to fast pairwise comparison.
▒ denotes a significant free to graded pairwise comparison.
■ denotes a significant fast to graded pairwise comparison.

evident in a plot of TRT vs. NRT (Fig. 4) as well as the number of wheelchair users corresponding to each propulsion type (Table 2).

4. Discussion

Manual wheelchair users encounter a variety of propulsion conditions throughout their daily living activities that require modifications to their propulsion technique. The hand pattern used is a clinically observable indicator that can provide insight into an individual's propulsion technique, but studies analyzing the influence of propulsion condition on hand patterns have been limited. The present study used a set of objective quantitative parameters to assess the influence of speed and grade of incline on the preferred hand patterns used by manual wheelchair users.

The finding that NRT was significantly larger in the fast condition than during the free condition supports the hypothesis that increased propulsion speed would result in a shift away from under-rim patterns and is consistent with previous research showing a decrease in the number of under-rim patterns used with increasing speed (Boninger et al., 2002). This increase in NRT may be a result of the increased momentum of the arm at the end of the contact phase due to its increased velocity during the contact phase. At the beginning of the recovery phase, shoulder motion transitions from flexion to extension (e.g., Rao et al., 1996). Thus, the increased momentum during fast propulsion would prolong the transition unless there was an offsetting increase in the extensor moment at the shoulder (which would increase energy demands). A delayed transition would result in additional shoulder flexion and encourage the hand to move above the handrim during this period. This initial movement would likely lead to increases in both NRT and TRT, which is consistent with our results. The prolonged transition would also require an increase in the percentage of cycle time spent in the recovery phase, which is consistent with the significant decrease in contact percentage we observed.

In order to increase power output to the handrim, either θ, cadence and/or handrim force must increase. When increasing propulsion speed on level ground, users increased all of these parameters (Table 1). While there was a small increase in θ (6.9%), there were much larger increases in cadence, F_{avg} and F_{peak} (47.4%, 44.1%, and 71.6%, respectively). These results are consistent with previous studies suggesting that an increase in speed leads to an increase in cadence and force, but a decrease in contact percentage (e.g., Boninger et al., 2002; Chow et al., 2009). While only one study found a statistically significant increase in θ (Gil-Agudo et al., 2010), others have shown increases in θ similar to those in the present study (e.g., Boninger et al., 2002; Koontz et al., 2002). Since most of these studies used a limited number of subjects, it is possible that they would have found statistical significance with a larger sample size.

The finding that TRT was significantly smaller in the graded condition compared to the free condition supports the hypothesis that increased grade would result in a shift toward the AR pattern. This result is consistent with a previous study showing an increase in number of AR patterns with increasing grade of incline (Richter et al., 2007). Propulsion in the graded condition required increased contact percentage (and decreased recovery percentage). This may encourage the selection of a shorter recovery hand path, contributing to the decrease in TRT. Furthermore, individuals must keep the hand near the handrim in order to prevent the wheelchair from rolling backward while on the incline. In addition to the decrease in TRT, there was also an increase in NRT with increased grade of incline, which appears to be related to the decrease in the number of under-rim patterns and corresponding increase in the number of AR patterns (Table 2). While under-rim patterns have negative NRT values, AR patterns on average have small but positive NRT values due to the large quantity of AR patterns in which the hand never drops below the handrim (i.e., along the right-most edge of the AR regions in Figs. 2 and 3). This concentration may be explained by examining the ergonomics of the standard handrim grip. The thumb is placed along the top surface while the rest of the hand wraps laterally around the rim such that the fingers contact the bottom surface (e.g., Koontz et al., 2006). When the fingers are opened slightly to relax the grip, the hand can disengage from the handrim with either an upward or lateral movement, but the placement of the thumb prevents an initial downward movement. As there is minimal movement away from the handrim during the AR pattern, this initial constraint may encourage the hand to move slightly above the handrim instead of slightly below.

To achieve the substantial power increase between the free and graded conditions, users increased θ, cadence and force, which showed a similarity to the changes observed when moving between the free and fast conditions. Similarly, the smallest increase was in θ (12.5%). However, while the increase in cadence was similar to that seen with increased speed (41.3%), there was a much larger increase in the handrim force (F_{avg}: 149.2%, F_{peak}: 169.5%). These results are similar to studies showing an increased grade results in increases in both contact percentage (e.g., van der Woude et al., 1988) and handrim force (e.g., Gagnon et al., 2014; Richter et al., 2007). However, there is disagreement between studies on the influence of grade on cadence. While some studies agree with the present results suggesting that cadence increases with grade (Gagnon et al., 2014; van der Woude et al., 1988), others have found that cadence decreases with grade (Richter et al., 2007). This discrepancy is likely due to differences in the study protocols. Richter et al. (2007) allowed their subjects to reduce their speed with grade, while

Table 2
Number of wheelchair users (percentage) using each hand pattern type across conditions using the objective classification method.

	Condition		
	Free	Fast	Graded
AR	63 (37.1%)	46 (27.1%)	125 (73.5%)
SL	24 (14.1%)	61 (35.9%)	26 (15.3%)
DL	49 (28.8%)	55 (32.4%)	12 (7.1%)
SC	34 (20.0%)	8 (4.7%)	7 (4.1%)

the other studies had their subjects maintain their level ground speed. There is also little consensus regarding the influence of grade on θ. While one study found a significant decrease in θ with increased grade (Richter et al., 2007), others suggest that there may not be a consistent trend across a full range of typical incline grades (Chow et al., 2009; Gagnon et al., 2014; van der Woude et al., 1988). These differences may also be due to differences in study methods and numbers of subjects analyzed.

The results of the present study suggest that speed and grade significantly influence preferred hand patterns and related parameters. While differences in individual anthropometrics, strength and functional capacity among wheelchair users may prevent the identification of a single optimal hand pattern for all subjects (Raina et al., 2012), task-specific constraints and required upper extremity demand likely preclude the existence of a single optimal hand pattern for all tasks (Richter et al., 2007).

The hand pattern characterization method presented in this study has a number of advantages over previously used methods. The method can be used not only to classify hand patterns as one of the four commonly described pattern types but also to characterize patterns using quantitative parameters that can differentiate between patterns of the same type, which can be challenging using subjective methods. This quantitative data also enables statistical analyses (e.g., Table 1) and clear illustrations of trends (e.g., Fig. 4). The output can also help a clinician gain a greater understanding of an individual's propulsion technique across conditions or in different wheelchair configurations. The method could therefore be adapted into an algorithm that could assist a clinician by suggesting beneficial alterations to configuration and/or technique as part of a wheelchair fitting and propulsion training program. The method can also be adapted for a clinical or real-world setting easily, because although we used SmartWheel data to separate individual cycles, simple geometric limits could be used instead. Thus, data collection could be simplified to a single camera recording hand motion in the sagittal plane.

The method has many advantages but is not without limitations. While the method provides a detailed description of the hand pattern that an individual uses during manual propulsion, this description by itself cannot explain why these kinematics were selected over other options. While outside the scope of the current study, future investigations could explore this question through detailed modeling and simulation analyses.

Another potential limitation is that the experimental data was not collected overground but instead on a calibrated wheelchair ergometer. Although ergometers are unable to replicate every aspect of overground propulsion, they have been shown to produce steady-state propulsion mechanics that are consistent with overground data while also providing precise control over the experimental conditions (e.g., Koontz et al., 2012). In addition, while differences between overground and simulated propulsion may induce small changes to hand patterns (Stephens and Engsberg, 2010), this study examined relative differences between propulsion conditions and the same ergometer was used throughout the data collection. Thus, the use of an ergometer likely did not influence the study conclusions.

A final potential limitation is related to the thresholds used to delineate between pattern types based on their NRT and TRT values. These thresholds were selected in an attempt to reproduce the subjective classifications and are therefore effectively a quantification of the subjective opinions of the individual raters. While the success rate for the current data set could have been increased by further optimizing the thresholds and increasing their precision (e.g., adding decimal places), it is unlikely that the increased precision would result in consistently increased success rates across studies with different raters and their own subjective assessments. However, the primary purpose behind the development of the hand pattern characterization method was to provide an objective quantification of individual patterns (i.e., TRT and NRT values) that could be statistically analyzed, which is unaffected by the uncertainty in the threshold selection.

5. Conclusions

This study identified the influence of both speed and grade on hand patterns during wheelchair propulsion. The results suggest that the specific goals and constraints of the propulsion task can significantly influence preferred hand pattern selection. While hand pattern parameters can provide insight into propulsion technique, current understanding of the advantages and disadvantages of different hand pattern types is centered on large-scale biomechanical measures (e.g., θ and cadence). Further work is needed to identify the relationships between hand patterns and upper extremity demand. These relationships could then be used to help design rehabilitation programs and wheeled mobility devices aimed at minimizing the development of overuse injuries and pain in manual wheelchair users.

Conflict of interest statement

The authors have no conflict of interest to declare.

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