Proposing a new index to quantify instantaneous symmetry during manual wheelchair propulsion

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Abstract

Propelling a manual wheelchair (MWC) is a strenuous task that causes upper limb musculoskeletal disorders (MSD) in a large proportion of MWC users. Although most studies on MWC propulsion biomechanics assume that MWC propulsion is a relatively symmetric task, recent literature suggests that this is the case only when the assessed outcome measures are averaged over long periods of time, and not over short periods (i.e., instantaneously). No method is currently available to assess instantaneous symmetry. In this work, we present the Instantaneous Symmetry Index (ISI), a new method that quantifies how a variable has been instantaneously asymmetric during a selected time period. Thirteen experienced MWC users propelled on different cross slopes of 0%, 2%, 4%, 6% and 8%. As the cross slope is increased, the upper hand produced less propulsive moments and the lower hand produced more propulsive movements. This has been reflected in the ISI, which increased from 0.20 (0% slope) to 0.84 (8% slope) with a Spearman’s coefficient of 0.90. The ISI has great potential to evaluate the ability of a user to propel symmetrically and synchronously, and will be a relevant measure to include in future studies on the impact of MWC propulsion asymmetry on MSD risk.

1 Introduction

Individuals who rely on a manual wheelchair (MWC) for locomotion are prone to developing upper limb musculoskeletal disorders (MSD), especially at the shoulder (Gironda et al., 2004; Jain et al., 2010). A direct link between MSD and shoulder load has been established (Mercer et al., 2006). In most biomechanical studies on shoulder load during MWC propulsion, pushrim kinetics is assessed only on one side and perfect symmetry is assumed (Desroches et al., 2008; Bregman et al., 2009; Rankin et al., 2010; Munaretto et al., 2012). However, it is unclear whether MWC propulsion is a symmetric activity or not. Vegter et al. (2013) propose that pushrim kinetics is symmetric when the outcome variables are averaged over long periods of time. This is in accordance with Soltau et al. (2015), who also found symmetrical pushrim kinetics when averaging pushes over 10 seconds. In contrast, Hurd et al. (2008) confirmed asymmetric pushrim kinetics when averaging only three consecutive pushes. Vegter et al. (2013) explain this difference due to the bimanual control that must be exerted to keep steering the MWC in a straight direction. Thus, MWC propulsion symmetry should be interpreted differently depending on whether the interest is in average or instantaneous symmetry. Average symmetry means the assessed variable’s average is equal on both sides, whereas instantaneous symmetry means the variable is equal on both sides at one specific instant.

The following non-exhaustive manual MWC propulsion conditions are all known to generate instantaneous asymmetry to different extents:

(1) Uneven floor and cross slope: Richter et al. (2007) report that propelling on a cross slope increases the lower hand propulsive moments.

(2) Turning and steering: Lam (2002) report that performing turning maneuvres increases the load on all the upper body joints.

(3) Using an alternate (ALT) propulsion technique as opposed to a synchronous (SYN) propulsion technique: although the recommendations between both techniques are still

contradictory (Faupin et al., 2013; Glaser et al., 1980; Goosey-Tolfrey and Kirk, 2003; Lenton et al., 2013), ALT propulsion decreases the push angle and therefore was found to increase the pushrim forces and the rate of rise of forces compared to SYN propulsion (Lenton et al., 2013).

Based on this somewhat limited evidence, minimizing the instantaneous asymmetry could reduce the shoulder load. However, while Hurd et al. (2008) proposed an average symmetry index (SI) similar to the one used in previous gait studies (Patterson et al., 2010; Perttunen et al., 2004), no index currently assesses the instantaneous symmetry during MWC propulsion.

The main objective of this work is to develop and validate a new Instantaneous Symmetry Index (ISI) that measures the accumulation of instantaneous asymmetry over time. This ISI was tested during MWC propulsion on a cross slope to control the independent variable (% cross slope). We hypothesized that the propulsive moments' instantaneous asymmetry will increase as the cross slope is augmented, and that the ISI will capture this increase of instantaneous asymmetry.

2 Methods

2.1 Participants

Thirteen experienced MWC users with a spinal cord injury participated in this study (Table 1). Inclusion criteria were adult MWC users diagnosed with a spinal cord injury between C6 and L1, who use a MWC as their primary mean of mobility. Participants were excluded if they reported pain or a medical condition that could limit their performance during the experimental tasks. They attended a single data collection session at the Pathokinesiology Laboratory of the Centre for Interdisciplinary Research in Rehabilitation of Greater Montreal (CRIR), Centre intégré universitaire de santé et de services sociaux du Centre-Sud-de-l'Île-de-Montréal. The protocol was approved by the Research Ethics Committee of the CRIR. All participants approved and signed the information and consent form before the experiments.

Insert Table 1 here.

2.2 Materials and experimental tasks

The participants propelled their own MWC that was bilaterally equipped with instrumented wheels (SmartWheel, Outfront LCC) to record the forces and moments applied on the pushrim by the user at a sampling frequency of 240 Hz. Participants propelled on the full length of a 12-meter long, 1.07-meter wide platform at a self-selected speed. The platform was laterally inclined in five height/width ratios corresponding to 0%, 2%, 4%, 6% and 8% cross slopes in a random order. Four trials were completed, two in each direction for each cross slope. A picture of the experimental setup is presented in Figure 1.

2.3 Data processing

2.3.1 Definition of the ISI

The ISI is defined as the absolute area between both curves of the assessed variable, normalized by the sum of the absolute areas under both curves:

$$\mathrm{ISI} = \frac{\int_{t_1}^{t_2} |D - ND|\, dt}{\int_{t_1}^{t_2} |D|dt + \int_{t_1}^{t^2} |ND|\, dt} \quad (1)$$

where D and ND are the assessed variable on the dominant and non-dominant sides, respectively, and where t_1 and t_2 represent the start and the end of the time period during which the ISI is calculated. The ISI is comprised in an interval varying between 0 and 1. A value of 0 means that the variable was always instantaneously symmetric. A value of 1 means the contrary; at every instant, either one side was zero or both sides were of the opposite sign (e.g., one hand is pushing while the other is pulling).

Figures 2 and 3 show how the ISI increases from 0 to 1 as a function of the amplitude and phase differences imposed between both sides. These sample data were obtained from unilateral propulsive moments recorded on the 0% cross slope; the propulsive moments applied by the non-dominant hand were copied onto the dominant side, and then modulated in amplitude (Fig 2) or shifted in time (Fig 3) to demonstrate the capability of the ISI to detect such changes of instantaneous symmetry.

Insert Figure 2 here.

Insert Figure 3 here.

2.3.2 Processing of cross slope propulsion data

For each trial on the platform, the propulsive moments of both pushrims were synchronized and interpolated over a common time vector at 240 Hz. No other filtering was applied to the data.

The ISI was calculated continuously from the start of the third push until the start of the last push, using the bilateral propulsive moments. The four resulting ISI values were then averaged to one ISI for each participant/slope combination. The correlation between the cross slope and the ISI was verified using Spearman’s rank correlation coefficient.

The SI (Hurd et al., 2008) was calculated using the punctual values of mean propulsive moments during the push phases, averaged over the same pushes:

$$\mathrm{SI} = \left|1 - \frac{D}{ND}\right| \quad (2)$$

The SI was only calculated on level ground (0% cross slope), because this is the only condition where both propulsive moments’ curves are comparable: for many participants, the upper hand moments became erratic even for the lowest cross slope of 2%, which prevented the proper isolation of push phases and therefore prevented calculating the mean propulsive moments. For the level ground condition, the ISI and SI values were compared using Spearman’s rank correlation coefficient.

3 Results

Fig. 4 shows a sample of the bilateral propulsive moments as a function of the cross slope for one participant. Both propulsive moments are generally symmetric on the 0% slope. Then, as the cross slope increases, the lower hand propulsive moments gradually increase at the expense of a reduction in upper hand propulsive moments that also become increasingly variable. At an 8% cross slope, the upper hand applies very low moments and the lower hand applies about twice the moments compared to a 0% cross slope.

The progression of the ISI as a function of the cross slope is presented in Table 2 and in Fig. 5. The ISI increased progressively for all the participants across all the slopes and ranged from an average of 0.20 ± 0.09 to an average of 0.84 ± 0.09. The Spearman's rank correlation coefficient between cross slope and ISI was $r = 0.90$, indicating a very high correlation (Mukaka, 2012).

Insert Table 2 here.

Insert Figure 5 here.

The comparison between the SI and ISI on level ground is presented in Table 3. While both had an equal group average, the ISI was higher than the SI on a per-participant basis. The Spearman's rank correlation coefficient between both indices yielded $r = 0.51$, indicating a low to moderate correlation (Mukaka, 2012).

Insert Table 3 here.

4 Discussion

The present study defines the Instantaneous Symmetry Index (ISI) for the first time and confirms its validity. To this effect, as hypothesized, the ISI allowed the characterization of changes in terms of instantaneous propulsive moments' symmetry when propelling a MWC on different cross slopes. In fact, the progressively increasing ISI that accompanies the cross slope increments is a clear indicator of the propulsive moments' shift from one side to the other. Moreover, three participants had a near-to-one ISI on the 8% incline (#1, #5, #6), which indicates that the propulsive moments were always instantaneously asymmetric. In these cases, the upper hand did not contribute anymore to the forward propulsive moment during MWC propulsion, but instead generated negative propulsive moments in an effort to steer the MWC and continue to propel the MWC in a linear trajectory. This strengthens the results from Richter et al. (2007), who have observed that the lower hand generates greater moments as the cross slope increases.

The low to moderate correlation between the ISI and SI on level ground confirms the distinction between both indices: the SI expresses the symmetry by averaging the outcome variables as measured at the dominant and non-dominant hands over a specific number of pushes, while the ISI expresses it by accumulating the instantaneous asymmetry measured at each data point over a specific period of time. In the case of Fig. 3 (e), the average amplitude between both sides is equal and leads to an SI = 0 (average symmetry). In contrast, on an instantaneous basis, both propulsive moments are never equal and lead to an ISI = 1 (instantaneous asymmetry). Vegter et al. (2013) have proposed that MWC propulsion symmetry depends on the time scale and therefore on the research interest. Hence, if the research interest resides in instantaneous symmetry (e.g., motor control, steering capability, etc.), then the validity of the ISI appears superior to the SI.

Another key advantage of the ISI when being compared to the SI is that it can be calculated continuously over a time period, over the entire duration of the propulsion cycle. Conversely, the SI is typically computed only for the push phase of the propulsion cycle. In the context of the experimental tasks performed in the present study, calculating the SI using the propulsive moments became challenging and even impossible as the slope progressed, since it requires isolating each push phase at a time when the upper hand is almost constantly in contact with the wheel and predominantly used to steer the trajectory of the MWC by applying breaking moments of varying amplitudes. Hence, the ISI demonstrates a greater capability to adapt to various MWC propulsion conditions as compared to the SI (Fig. 4).

Investigating instantaneous asymmetry during MWC propulsion is relevant to gain a better understanding of the propulsion technique. As an example, minimal side-to-side natural variability is expected as individuals continuously correct their MWC orientation when traveling along a linear course (Vegter et al., 2013). This is supported by De Groot et al. (2005) who found that propelling on a track requires a higher metabolic cost than doing so on an ergometer because the users need to (1) steer the MWC and (2) stabilize their upper body segments according to the various MWC movement directions (i.e. inertial effects). Our results support these assertions since no participant propelled with continuously symmetric propulsive moments ($\mathrm{ISI} = 0$) even on level ground. It may be beneficial to minimize the steering moments so that the pushrim moments predominantly contribute to the linear displacement of the MWC and not to trajectory corrections. To this effect, the ISI could be used during MWC propulsion learning sessions as a dependent variable that should be minimized.

Regarding upper body stability, while a SYN technique reduces the pushrim forces and rates of rise (Lenton et al., 2013), an ALT technique may be associated with increased trunk stability due to the absence of fore-and-aft trunk movement, which could benefit individuals with impaired trunk control (Glaser et al., 1980). It is increasingly supported that trunk stability is strongly related to upper limb demand, and therefore to musculoskeletal integrity (Gagnon et al., 2009). Further research is strongly needed on the effect of combinations of SYN and ALT techniques on trunk stability, where the ISI would be an independent variable used to identify both techniques.

The causes of MSD are very complex. While instantaneous symmetry relates to the distribution of joint loading during propulsion, other measures such as the push angle, push frequency, push time, recovery time and velocity also relate to MSD risk (Consortium for Spinal Cord Medicine, 2005). As the ISI is a validated measure of instantaneous symmetry, it may compliment these other variables in future studies. It may be useful as an independent variable to understand the effect of instantaneous symmetry on MWC propulsion, or as a dependent variable to understand the impact of an intervention on instantaneous symmetry.

One limit of this study is the small sample of participants (n=13) used to compute the ISI; it cannot be shown if the ISI follows a Gaussian distribution, which is important for statistical analyses. Moreover, the interactions between ISI and common outcome variables (i.e. push angle, push frequency, push time, recovery time, velocity) need to be explored in future studies. Nonetheless, the present study appears sufficient to demonstrate the potential value added by the ISI in the context of MWC propulsion.

5 Conclusion

In this work, we have developed an Instantaneous Symmetry Index (ISI) that allows the measurement of the accumulation of instantaneous asymmetry of MWC propulsion during a selected time period. The ISI of the propulsive moments increased as the cross slope was augmented, confirming a progressive instantaneous asymmetry from the upper hand to the lower hand. The ISI may become a relevant outcome measure in future studies focusing on MWC propulsion.

Conflict of interest

The authors declare that this work is free of any conflict of interest.

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5.1 Table 1 – Participants' demographics

Participant	Sex	Age	Years using MWC	SCI Level	ASIA	Dominant side
1	M	47	13	T7	A	Right
2	M	28	0	T5	B	Right
3	M	63	2	T10	A	Right
4	M	42	14	C6	A	Right
5	M	25	4	T9	A	Right
6	M	68	3	T11	A	Right
7	M	38	12	T12	A	Right
8	M	31	13	T12	A	Right
9	F	34	14	T6	A	Right
10	M	59	26	T12	A	Right
11	M	54	9	T3	A	Right
12	F	31	31	T12	A	Right
13	M	19	2	C6	A	Right
Av		41±16	11±9			

5.2 Table 2 – Mean and s.d. of ISI values as a function of cross slope

	Cross slope				
	0%	2%	4%	6%	8%
Av	0.20	0.34	0.59	0.73	0.84
SD	0.09	0.09	0.14	0.13	0.09

5.3 Table 3 – Comparison between SI and ISI on a 0% cross-slope

	SI	ISI	ISI – SI
Av	0.20	0.20	0.13
SD	0.26	0.09	0.09

Figure 1 – A photograph of the experimental setup, with the platform inclined at 6%

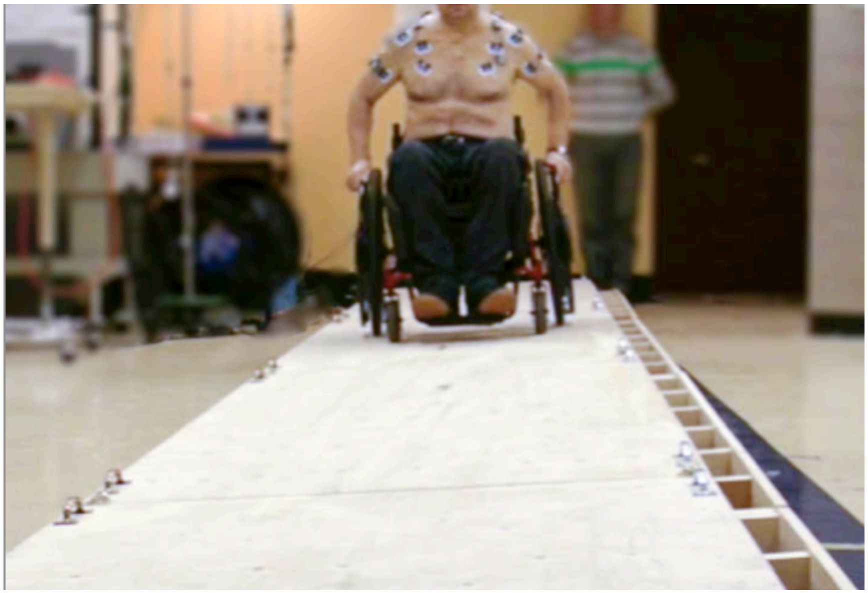

Figure 2 – The effect of moment amplitude symmetry on the ISI.

On the left (a), the propulsive moments have the same amplitude and phase, therefore ISI= 0, meaning that the moments are always instantaneously symmetric. Starting from between (c) and (d), the dominant hand stops pushing and evens starts pulling the wheels, which maximizes the ISI to one, meaning the moments are always instantaneously asymmetric.

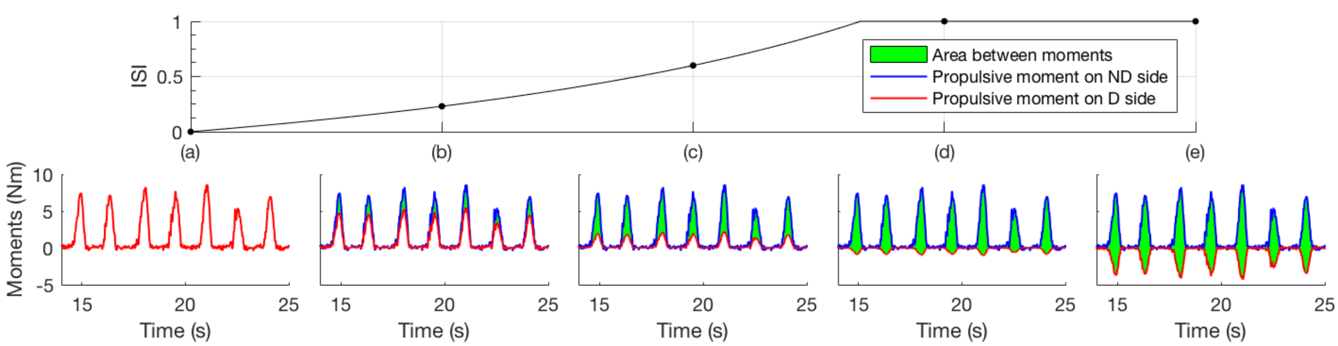

Figure 3 – The effect of moment phase symmetry on the ISI.

On the left (a), the propulsive moments have the same amplitude and phase, therefore ISI= 0, meaning the moments are always instantaneously symmetric. Starting from (d), the gap between the pushes disappears, which can be considered ALT propulsion. Therefore, although the moments are symmetric in average, they are always instantaneously asymmetric, thus $\mathrm{ISI} \approx 1$.

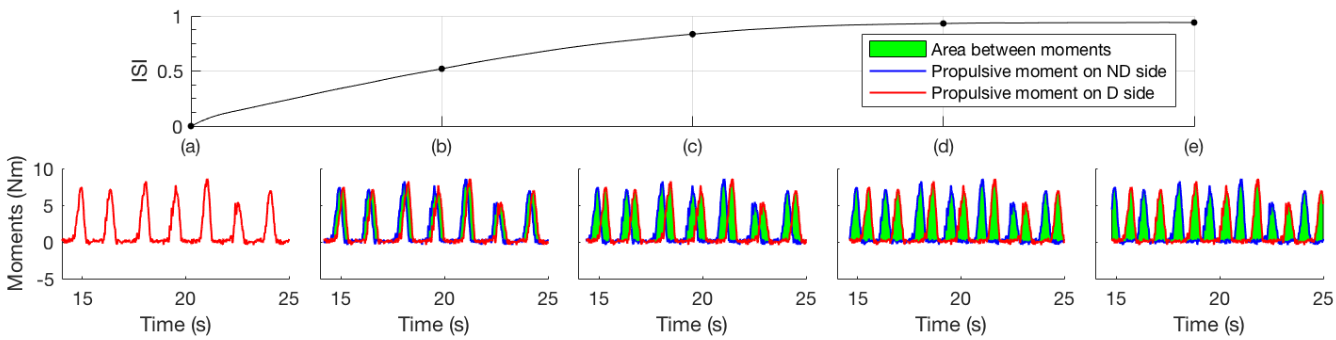

Figure 4 – A sample of bilateral propulsive moments as a function of the cross slope, with the right side at the bottom

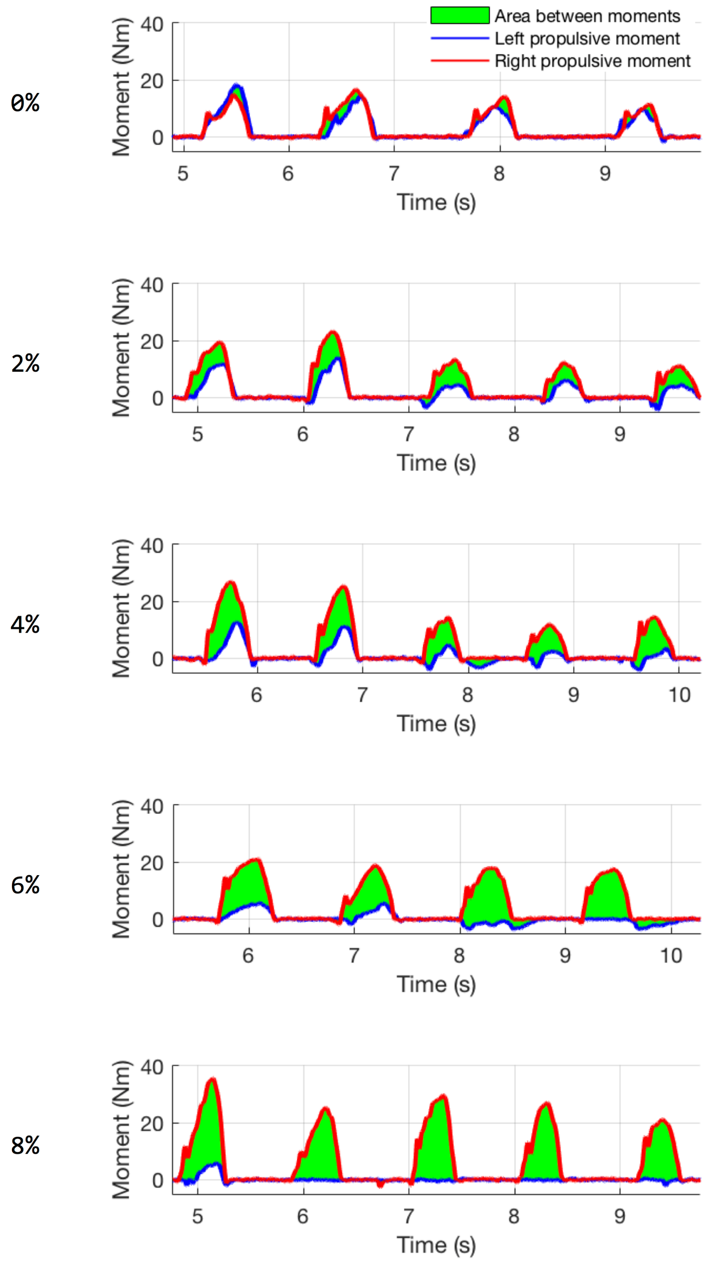

Figure 5 – ISI progression as a function of the cross slope