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The Effect of External Power Output and Its Reliability on Propulsion Technique Variables in Wheelchair Users With Spinal Cord Injury

Sonja de Groot, Rachel E. Cowan, Megan K. MacGillivray, Marika T. Leving, and Bonita J. Sawatzky

***Abstract*— The purpose of this study was to assess 1) how treadmill slope variance affected external power output (PO) and propulsion technique reliability; and 2) how PO is associated with propulsion technique. Eighteen individuals with spinal cord injury performed two wheelchair treadmill exercise blocks (0% and 1% treadmill slope, standardized velocity) twice on two separate days. PO, velocity, and 14 propulsion technique variables were measured. In a follow-up study, N = 29 performed wheelchair treadmill drag tests. Target and actual slope were documented and PO, intraclass correlation coefficients (ICC) and smallest detectable differences (SDD) were calculated. Within and between visits, the reliability study ICCs were perfect for velocity (1.0), weak for PO (0.33-0.46), and acceptable (>0.70) for five (0% slope) and 10 (1% slope) propulsion technique variables, resulting in SDDs of 35-196%. Measured PO explained 56-90% of the variance in key propulsion technique variables. In the follow-up, PO ICCs were weak (0.43) and SDDs high. Bias between target and actual slope appeared random. In conclusion, PO variability accounts for 50-90% of the variability in propulsion technique variables when speed and wheelchair set-up are held constant. Therefore, small differences in PO between interventions could mask the effect of the interventions on propulsion technique.**

***Index Terms*— Exercise test, power output, spinal cord injuries, treadmill, wheelchairs.**

I. Introduction

A SIGNIFICANT amount of research has focused on how wheelchair propulsion technique, i.e., push-rim kinetics, is impacted by the user (e.g., learning, fitness) [1], wheelchair-user interface (e.g., rim size, seat height) [2], [3], and wheelchair (e.g., tyre pressure, mass) [4]–[6] variables. This approach can be useful to optimize the wheelchair, the interface, and to educate the user in establishing the best propulsion technique, to obtain and maintain mobility, an active lifestyle and prevent upper-extremity overuse injuries. The goal of this previous research was to identify the factors that have the greatest impact on propulsion technique and thus are important clinical intervention targets. Standardized submaximal wheelchair exercise tests are commonly used to evaluate interventions focussing on the user, wheelchair-user interface, or wheelchair.

When clinicians or researchers use submaximal exercise tests to evaluate an intervention, they need to know whether the change in propulsion technique is a 'real' change, i.e., is greater than measurement error, or within the range of measurement error. In that respect, it is important to know the reliability of propulsion technique outcomes and the magnitude of change that must occur in order to conclude that the intervention had a 'real' effect (i.e., a change larger than the measurement error). Moderate to high intraclass correlation coefficients have been reported for propulsion technique variables [7], [8] during submaximal wheelchair treadmill or ergometer exercise tests in non-disabled non-wheelchair users. However, variability within wheelchair users, such as those with a spinal cord injury (SCI), might be different due to their motor impairments or their experience with wheelchair propulsion. Reliability studies of overground propulsion technique at self-selected, non-standardized velocities have reported lower intra- and intersession reliability for propulsion technique variables in non-disabled, non-wheelchair users compared with experienced manual wheelchair users [9]. Thus, it is likely that the reliability results for standardized submaximal wheelchair exercise tests among non-wheelchair users are not valid for experienced wheelchair users. We therefore conducted a study

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This work involved human subjects in its research. Approval of all ethical and experimental procedures and protocols was granted by the Local Universities' Clinical Research Ethics Boards.

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to determine the reliability and smallest detectable difference of propulsion technique variables during submaximal wheelchair treadmill exercise tests.

Propulsion technique reliability outcomes from our reliability study were unexpectedly poor. Upon investigation with a follow-up study, we determined that the poor reliability of the propulsion technique variables was due to a high intra and intersession variation in external power output. On a wheelchair treadmill, if the wheelchair-user system is unchanged, external power output is only influenced by treadmill speed and treadmill slope. The original reliability study indicated treadmill speed was highly consistent across trials (ICC of 1.00), which suggested treadmill slope was the source of variation. Our follow-up study revealed the treadmill to have a random error between the actual and measured slope of the treadmill. While we knew from a previous study [10] that the actual velocity and slope could be different than the target velocity and slope, and differ across treadmills of the same manufacturer and specifications, we did not anticipate a random error across tests.

Although we did not achieve our original goal of assessing the reliability of wheelchair propulsion technique during standardized treadmill testing, our dataset provides a great example of the importance of real-time measures of slope and velocity in order to achieve standardized external power output for evaluation of a wheelchair intervention. Therefore, the purpose of this manuscript was to assess 1) how slope variance affected external PO and propulsion technique reliability; and 2) how external PO is associated with propulsion technique variables in wheelchair users.

From the original reliability study, we will present the propulsion technique and external power output reliability analysis and describe the relationship between external power output and propulsion technique variables. From the follow-up study, we will describe the relationship between external power output and treadmill slope and treadmill slope reliability.

II. Materials and Methods

A. Original Reliability Study

1) Participants: Eighteen adults at least 1-year post SCI were included at two locations (ICORD, Vancouver, Canada, and Miami Project to Cure Paralysis, Miami, USA). Inclusion criteria were 1) age 18-65 years; 2) diagnosed with spinal cord injury/disease; 3) use a manual wheelchair for at least 50% of their weekly mobility; 4) ability to complete study procedures in their personal manual wheelchair; 5) use a manual wheelchair with quick release axles. Exclusion criteria were: significant upper extremity pain (Wheelchair Users Shoulder Pain Index (WUSPI) > 60) [11], [12], cardiovascular disease where exercise is contraindicated, or inability to speak English. The study received approval from the local universities' clinical research ethics boards. All participants provided written informed consent.

2) Design: Participants came to the research laboratory and were made familiar with the equipment. Any further questions regarding the study were answered before written informed consent was obtained. To screen for any significant upper extremity pain, the WUSPI [11], [12] was administered and evaluated. Personal data were collected, including age, level of injury, age at injury, body mass, and mass of the wheelchair.

Participants were tested on two separate days (visit 1 and 2). During each visit they had to perform two three-minute submaximal wheelchair exercise blocks twice. 3D torques and forces applied on the hand rim were measured at 240 HZ with a SmartWheel (Three Rivers Holdings, Mesa, AZ, USA) which was attached to the dominant hand side of the participant's wheelchair. The participants were instructed to propel the wheelchair by using the rims instead of the wheels.

3) Submaximal Exercise Test: Each participant performed the submaximal exercise tests in their own wheelchair on a treadmill (MaxMobility, Antioch, TN, USA). Participants were asked not to change their wheelchair set-up in between visits, were tested at the same time of day, and tyre pressure was inflated to the recommended pressure at each visit.

The protocol, regarding velocity, slope and test duration, was similar to the protocol that was used in previous studies to assess propulsion technique in people with SCI [13], [14]. Participants first practiced propulsion at 0.56, 0.83 and 1.11 $m\cdot s^{-1}$ to familiarize themselves with treadmill propulsion and to choose one of these speeds for testing. Two three-minute submaximal propulsion assessment blocks were conducted at the individual's preferred speed. During the first exercise block, participants propelled the wheelchair with the selected velocity and 0% target slope of the treadmill according to the treadmill user interface. After completion, participants rested for two minutes before starting with the second exercise block, which was performed at the same velocity and a 1% target slope according to the user interface of the treadmill. Propulsion kinetics were measured continuously during both exercise blocks. After these tests, participants rested for 30 min and then the tests were performed again with exactly the same protocol. This procedure was repeated on visit 2.

4) Data Analysis Propulsion Kinetics: The data from the SmartWheel were further analysed using custom-written Matlab routines [15]. The data file consisted of x, y and z components of force (N) and torque (Nm) as expressed by the wheels in their local coordinate systems, angle (rad), time (s) and sample number.

The last minute of each three-minute exercise block was analysed. Variables were calculated as the averaged mean values over the number of completed pushes of the last minute. The push was defined as the period that the hand exerted a positive torque (>1 Nm) on the hand rim. Fig. 1 shows an illustration of the definition of some of the variables.

Timing parameters were determined from the torque signal. Push time was defined as the time that the hand exerted a positive torque on the hand rim while the cycle time was defined as the time from the start of the push phase until the start of the next push phase. The push time was also expressed as a percentage of the cycle time (relative push time in %). Cycle frequency was defined as the number of complete pushes per minute.

The contact angle was the angle at the end of the push phase minus the angle at the start of the push phase. Force

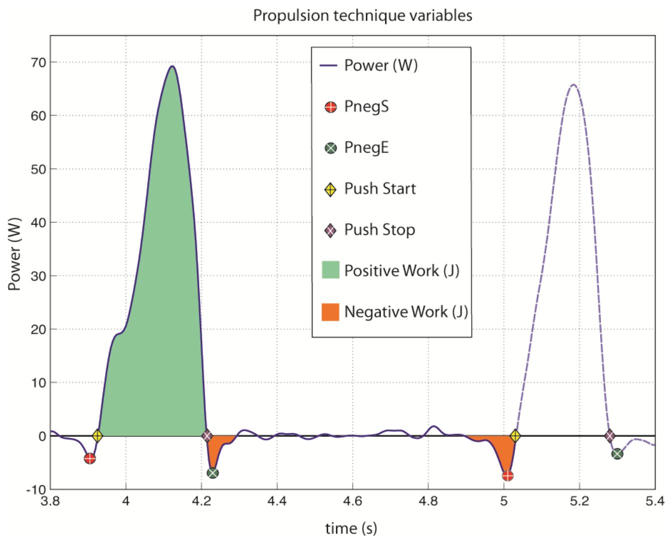

Fig. 1. Illustration of the definition of push time (from push start to push stop), cycle time (from push start to push start), and power loss before (PnegS) and after (PnegE) the push time [15].

parameters were calculated as mean and peak values over each of the pushes over the last minute of an exercise block. From force components Fx, Fy and Fz, the total force applied on the hand rim (Ftot) was calculated, according to:

$$\mathrm{Ftot} = \sqrt{}(\mathrm{Fx}^2 + \mathrm{Fy}^2 + \mathrm{Fz}^2)(\mathrm{N}) \quad (1)$$

The force component tangential to the hand rims, called the effective force (Fm), was calculated from torque (Mz) and hand rim radius (r_r) according to:

$$\mathrm{Fm} = \mathrm{Mz} \bullet r_r^{-1}(\mathrm{N}) \quad (2)$$

The fraction effective force on the hand rims (FEF) was calculated from the two equations above and expressed as a percentage:

$$\mathrm{FEF} = \mathrm{Fm} \bullet \mathrm{Ftot}^{-1} \bullet 100(\%) \quad (3)$$

The slope of the line between the start of the push and the peak force was determined to give an indication of how the peak force is built up over time.

The mean power output (POmean), during a complete set of cycles during the last minute was calculated from the start of the first push until the start of the last push. The work per push cycle was calculated by integrating the power over the duration of the push.

The negative deflections or ‘dips’ just before and after the push phase, i.e., the negative power output, were calculated from the power output curve. The negative dips were defined as the most negative power output values respectively prior to and just after the push.

B. Follow-Up Study on Slope Reliability

After seeing the results of the reliability outcomes, extra tests were performed with the treadmill in Miami to investigate the reliability of the treadmill slope and the resulting impact on PO. Slope reliability was assessed by performing a drag test using a standardized set of target slopes (input using the treadmill control interface) in a standardized order (target slopes (%): 6, 5, 4, 3, 2, 1, 5.5, 4.5, 3.5, 2.5, 1.5). During the drag test the participant sat passively in the wheelchair while the wheelchair was connected to the force transducer with a rope (Fig. 2). The PO was calculated by multiplying the measured force at a particular slope with the treadmill velocity. The drag test was performed twice during one day and once during a second day on all participants (N = 29 manual wheelchair users with SCI) as part of the IRB approved protocol for a separate study [16]. During each drag test, the actual slope of the treadmill was measured at each of the standardized slopes using a digital inclinometer placed on the edge of the frame of the treadmill bed.

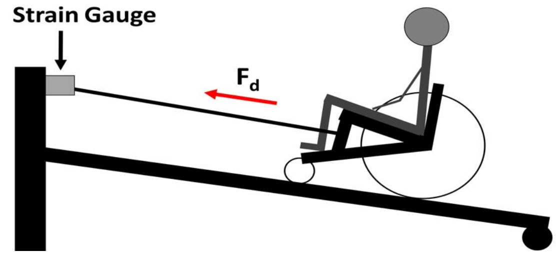

Fig. 2. Illustration of the setup to perform a drag test.

C. Statistics

1) Original Reliability Study: Reliability of velocity, external power output, and propulsion technique was assessed according to the Generalizability Theory, which is based on analysis of variance (ANOVA) [17]. Variance values were obtained from variance component analyses with a random-effects design and the method of restricted maximum likelihood. Four components of variance were estimated with this analysis, i.e. variance attributable to participants (var_p), visit (var_v), tests (var_t), and residual error (var_e). Intraclass correlation coefficients (ICC), standard errors of measurement (SEM) and the smallest detectable differences (SDD) were calculated with these variance components for the submaximal blocks (0% and 1% target slope) separately. ICCs greater than 0.70 were considered acceptable for discriminating between groups of individuals, while an ICC greater than 0.90 was considered acceptable for evaluating individual level change [18]. Finally, scatter plots were constructed to illustrate the individual agreement of velocity and power output between tests for each visit.

The relationship between PO and four key propulsion technique variables (mean force, push frequency, work per push and contact angle) was investigated with multi-level regression analysis (to correct for repeated measurements (target slope, test, visit) within participants) with data from the original reliability study.

2) Follow-Up Slope Reliability Study: The relationship between the actual slope and the PO was investigated via a multi-level regression analysis (to correct for repeated measurements within participants). Reliability was assessed for the 1% target slope using the same approach and variance components described above. Finally, scatter plots were constructed

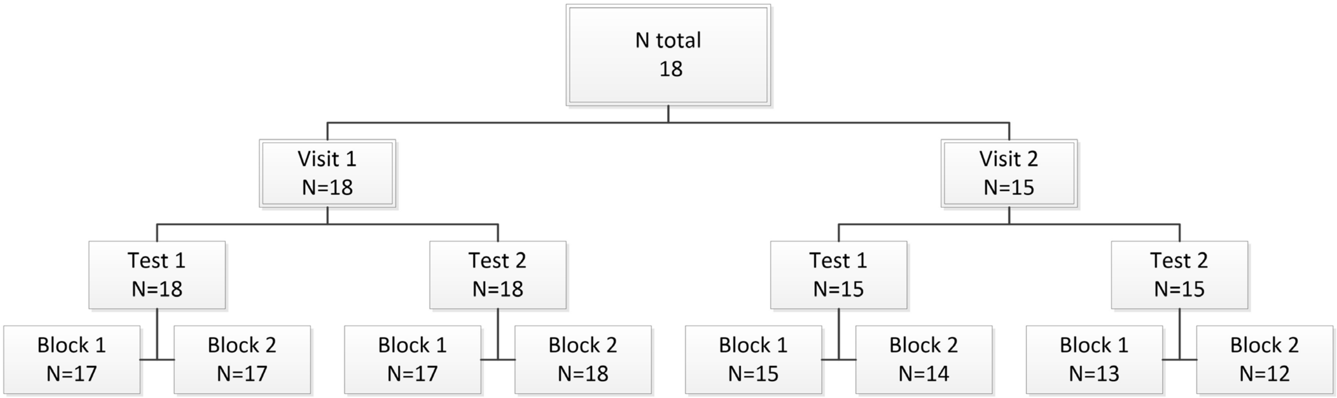

Fig. 3. Flow chart of the number of participants that performed the tests per visit, test and block (block 1 = 0% target slope; block 2 = 1% target slope).

to illustrate the difference in slope (in degrees) between two tests on the same day and between tests performed on two separate days.

Significance was set at $P < 0.05$ for all tests.

III. Results

A. Original Reliability Study

Fig. 3 exhibits a flow chart of the number of participants that performed the tests per visit, test, and exercise block. The 18 participants (2 females), were on average 34 ± 10 years old, with a height of 1.74 ± 0.76m and body mass of 69.9 ± 13.6 kg. Most participants had paraplegia (N = 14) and motor complete lesion (N = 16) and their average time since injury was 9.3 ± 9.0 years (median: 5.5 years with interquartile range: 2.8-14.8).

1) Reliability of Velocity, External Power Output, and Propulsion Technique: Table I gives an overview of the outcomes for each exercise block (0% or 1% target slope), per test (first or second test of the day), and per visit (first or second visit).

Table II shows the reliability of the velocity, power output, and propulsion technique variables for both 0% and 1% target slope. Velocity had a perfect ICC of 1.0 for both target slopes. However, external power output showed a weak ICC (0.33-0.48) between tests and visits and a subsequently high SEM (2.9-3.3 W) and SDD (8.1-9.1 W) for both target slopes. Although the absolute mean difference in PO (W) between tests and visits, as shown in Table I, might seem small, the relative average difference (%) was large (ranging from −4 to −39% for the 0% target slope and from −5 to −72% for the 1% target slope).

The ICC was acceptable (>0.70) for measuring groups in only five of the 14 propulsion technique variables (relative push time, Fpeak, FEFmean, FEFpeak, and slope) during the 0% target slope (no treadmill slope). When using the 1% treadmill target slope the ICC for ten of 14 variables showed an acceptable ICC for comparing group results. However, none of the propulsion technique variables showed an ICC greater than 0.90, indicating that these variables would not be acceptable if measurements were to be used for evaluating individuals. A 'real' improvement in propulsion technique, expressed as SDD, was high for most variables (%SDD for 0% target slope: 46-196%; and 1% target slope: 35-196%).

Fig. 4 shows the agreement of velocity and power output during the 0% target slope (left graphs) and 1% target slope blocks (right graphs) at the first (x-axis) and second test (y-axis) during both visits (circle and triangle markers). In general, the plots show that the between test agreement of velocity was nearly perfect in contrast to the agreement of power output. Most power output values differed between visits by more than 10% (Fig. 4, dots outside of the 10% deviation lines).

External power output was significantly associated with all four key propulsion technique variables (Table III), with an explained variance ranging from 56% (contact angle) to 90% (work per push).

B. Follow-Up Treadmill Slope Reliability Study

Multi-level regression analysis showed a significant ($P < 0.0001$)) and strong ($R^2 = 97\%$) relationship between the actual treadmill slope and the measured external PO, leading to the formula with the following betas (standard errors):

$$\begin{aligned} \mathrm{PO(W)} &= 6.610(0.366) \\ &\quad + 11.121(0.316) \cdot \text{Actual Slope (degrees)} \end{aligned} \tag{4}$$

The reliability analysis of the 1% target treadmill slope showed results similar to the PO reliability analysis described in the previous paragraph, i.e., an ICC of 0.43 in the follow-up study vs. 0.48 in the reliability study and an SDD of 98% in the follow-up study vs. 100% in the reliability study (Table II). Fig. 5 shows the differences in actual slope (in degrees) between two tests on the same day (left upper graph) and two tests on two different days (right upper graph). From the 263 target slopes that were tested twice on one day, 153 (58%) actual slopes were exactly the same between tests. From the 285 target slopes that were tested twice on two different days, 166 (58%) actual slopes were exactly the same between tests. The difference between actual slopes on one day could go up to 100% and between days even up to 300% (i.e., 0.1 and 0.4 degrees). As can be seen in Fig. 5 (lower graphs)

TABLE I

DESCRIPTIVES OF THE PROPULSION TECHNIQUE VARIABLES FOR BLOCK WITH 0% AND 1% TARGET SLOPE DURING TEST 1 AND 2 FOR VISIT 1 AND 2

Propulsion technique	***Visit 1 – Test 1***		***Visit 1 – Test 2***		***Visit 2 – Test 1***		***Visit 2 – Test 2***	
BLOCK 0% target slope	***N***	***Mean ± SD***	***N***	***Mean ± SD***	***N***	***Mean ± SD***	***N***	***Mean ± SD***
Velocity, m/s	17	1.04±0.14	17	1.04±0.14	15	1.03±0.16	13	1.03±0.14
Power output 2-sided, W	17	7.3±3.5	17	8.8±4.3	15	6.3±2.5	13	7.5±2.1
Push time, s	17	0.38±0.08	17	0.38±0.10	15	0.39±0.10	13	0.42±0.13
Cycle time, s	17	1.64±1.16	17	1.51±0.92	15	1.73±1.08	13	1.63±0.73
Relative push time, %	17	29.1±10.4	17	30.6±8.6	15	28.3±8.5	13	29.4±11.5
Frequency, pushes/min	17	47.9±17.7	17	50.0±18.3	15	43.7±16.2	13	43.3±14.4
Contact angle, °	17	72.7±15.5	17	71.6±16.0	15	73.3±12.6	13	79.0±22.9
Fpeak, N	17	45.0±20.8	17	46.8±18.4	15	46.5±22.5	13	40.4±13.2
Fmean, N	17	31.3±14.3	17	32.0±12.0	15	32.7±15.6	13	26.7±8.7
FEFmean, %	17	55.9±19.6	17	59.1±21.4	15	55.5±28.9	13	67.2±30.0
FEFpeak, %	17	88.6±43.9	17	89.2±37.6	15	88.9±55.9	13	109.3±62.3
Slope, N/s	17	38.5±23.6	17	42.5±25.3	15	37.5±21.6	13	36.7±22.4
Negative dip before push phase, W	17	-1.23±1.47	17	-1.16±1.15	15	-1.25±1.34	13	-0.76±1.12
Negative dip after push phase, W	17	-1.62±1.46	17	-1.71±1.19	15	-1.62±1.61	13	-1.12±1.03
Work per push, J	17	5.8±3.5	17	6.2±3.0	15	6.0±3.8	13	6.2±2.8
BLOCK 1% target slope	***N***	***Mean ± SD***	***N***	***Mean ± SD***	***N***	***Mean ± SD***	***N***	***Mean ± SD***
Velocity, m/s	17	1.04±0.14	18	1.05±0.14	14	1.04±0.15	12	1.05±1.39
Power output 2-sided, W	17	8.5±4.3	18	10.3±5.1	14	8.3±3.4	12	9.3±3.3
Push time, s	17	0.39±0.08	18	0.40±0.10	14	0.39±0.08	12	0.40±0.09
Cycle time, s	17	1.44±0.74	18	1.39±0.83	14	1.63±0.95	12	1.54±0.68
Relative push time, %	17	31.5±8.6	18	33.1±9.7	14	29.9±9.1	12	30.0±9.8
Frequency, pushes/min	17	49.0±15.7	18	51.7±16.6	14	46.0±17.0	12	45.7±16.1
Contact angle, °	17	74.5±17.0	18	76.2±18.3	14	75.6±13.8	12	77.9±15.5
Fpeak, N	17	46.5±20.1	18	49.0±18.8	14	52.2±25.4	12	47.4±19.5
Fmean, N	17	32.2±14.0	18	33.7±12.2	14	36.3±17.2	12	30.8±11.5
FEFmean, %	17	57.0±22.9	18	58.1±22.5	14	54.8±23.8	12	68.9±32.0
FEFpeak, %	17	95.7±63.1	18	88.6±39.8	14	88.9±50.5	12	114.4±67.6
Slope, N/s	17	40.9±24.5	18	40.3±23.8	14	38.7±24.1	12	38.6±17.0
Negative dip before push phase, W	17	-1.14±1.46	18	-1.32±1.43	14	-1.15±1.21	12	-0.81±0.91
Negative dip after push phase, W	17	-1.66±1.65	18	-1.84±1.43	14	-1.82±1.83	12	-1.41±1.07
Work per push, J	17	6.2±3.4	18	7.0±3.7	14	7.1±4.4	12	7.4±3.7

the difference in the actual slope is more variable at the less steep slopes.

IV. DISCUSSION

A primary objective of manual wheelchair research is to understand what factors about the user, wheelchair, and wheelchair-user interface have the greatest impact on propulsion strain and technique, and are thus clinical intervention targets. The poor outcomes of our initial reliability study were due to measurement error, namely random error between the target and actual slope of the treadmill, identified during the follow-up study. This random error caused large variances in external power output between tests, which in turn resulted in a weak to moderate reliability for most propulsion technique variables. Since the velocity showed a high reliability, the difference in power output between tests was due to the difference in resistance (i.e., treadmill slope in this study). Our analyses illustrate the strong relationship between slope and external power output ($R^2 = 97\%$) and the moderate to strong relationship between external power output and propulsion technique ($R^2 = 56\text{-}90\%$).

The low to moderate ICCs (0.21-0.82) in our initial reliability study are in contrast to the moderate to high ICCs (ICC: 0.77-0.93 [8] and ICC: 0.72-0.99 [7]) reported by wheelchair studies on non-disabled (AB) non-wheelchair users [7], [8]. They also contrast Lui *et al.* [9] who reported overground propulsion at a self-selected speed on tile for a single trial produced intra-day ICCs of 0.69-0.90, inter-day ICCs of 0.25-0.74 for AB non-wheelchair users and 0.80-0.93 ICCs for both intra and inter-day sessions for manual wheelchair users. Based on the results of Lui *et al.* [9], we anticipated that our treadmill-based study would produce similar, if not higher ICCs since we were in theory using a highly controlled test environment and our target sample was wheelchair users with SCI. The two ‘test’ environment variables that should have been nearly identical within a participant across their test sessions were velocity and external PO. Velocity was tightly controlled, evidenced by perfect ICCs (1.00, Table II) and a smallest detectable difference of 3%. However, low ICCs (0.33 & 0.48) and high SDDs (108% & 100%) indicated external PO was poorly controlled.

Our follow-up study allowed us to determine that poor reliability of PO was due to a random error between the target and actual treadmill slope. On a wheelchair treadmill, PO is the product of velocity (v) and total drag force (N) [19]. Total drag force is influenced by rolling friction (Froll), air resistance (Fair), gravitational effects when going up/down a slope ($m \cdot g \cdot \sin\alpha$) and internal friction (Fint). The random error between target vs. actual slope can be explained by multiple equipment-based factors. First is the amount of tolerance

TABLE II

RELIABILITY PARAMETERS OF THE PROPULSION TECHNIQUE PARAMETERS FOR BLOCK WITH 0% AND 1% TARGET SLOPE AND THE RELIABILITY OF THE TREADMILL INCLINATION ANGLE (AT 1% TARGET SLOPE) OF THE EXTRA TESTS PERFORMED IN THE MIAMI LAB

	Block 0% target slope					Block 1% target slope				
Propulsion technique	**Mean**	**ICC**	**SEM**	**SDD**	**SDD%**	**Mean**	**ICC**	**SEM**	**SDD**	**SDD%**
Velocity, m/s	1.03	1.00	0.01	0.03	3	1.04	1.00	0.01	0.03	3
Power output 2-sided, W	7.5	0.33	2.9	8.1	108	9.1	0.48	3.3	9.1	100
Push time, s	0.39	0.40	0.08	0.22	56	0.40	0.62	0.06	0.17	43
Cycle time, s	1.62	0.65	0.62	1.72	106	1.49	0.75	0.43	1.19	80
Relative push time, %	29.4	0.75	4.9	13.6	46	31.3	0.76	4.7	12.9	41
Frequency, pushes/min	46.5	0.67	10.2	28.4	61	48.5	0.72	8.9	24.8	51
Contact angle, °	73.9	0.21	14.9	41.5	56	76.2	0.64	9.7	26.9	35
Fpeak, N	44.9	0.74	10.3	28.5	63	48.7	0.80	9.8	27.3	56
Fmean, N	30.9	0.62	8.4	23.3	75	33.3	0.73	7.4	20.6	62
FEFmean, %	59.1	0.75	12.1	33.5	57	59.2	0.77	11.6	32.2	54
FEFpeak, %	93.2	0.81	21.0	58.2	62	95.8	0.81	23.0	63.7	67
Slope, N/s	39.0	0.82	10.7	29.6	76	39.8	0.77	11.7	32.5	82
Negative dip before push phase, W	-1.12	0.61	0.79	2.19	-196	-1.13	0.62	0.80	2.22	-196
Negative dip after push phase, W	-1.54	0.67	0.77	2.13	-138	-1.70	0.72	0.82	2.27	-133
Work per push, J	6.0	0.49	2.5	6.8	113	6.9	0.78	1.8	5.1	74
Extra reliability analysis										
Actual treadmill slope, °						0.17	0.43	0.06	0.17	98

TABLE III

RELATIONSHIP BETWEEN EXTERNAL POWER OUTPUT (PO) AND FOUR PROPULSION TECHNIQUE VARIABLES

	Mean force (N)		**Frequency (pushes/min)**		**Work per push (J)**		**Contact angle (°)**	
	Beta (SE)	*p-value*	*Beta (SE)*	*p-value*	*Beta (SE)*	*p-value*	*Beta (SE)*	*p-value*
Constant	23.177 (2.727)		40.467 (3.298)		3.186 (0.705)		65.944 (3.361)	
PO (W)	1.066 (0.206)	<0.0001	0.773 (0.366)	0.03	0.386 (0.059)	<0.0001	1.089 (0.367)	0.002
R^2	84%		50%		90%		56%	

between the target and actual slope allowed by the equipment. When following up with the manufacturer they advised against narrowing the tolerance because the treadmill would constantly adjust and might never settle at any slope. Corollary to this was the low sensitivity of the sensor used to detect slope, which could result in a difference between the actual and sensed slope. Finally, the treadmill could not always achieve a 0% slope due to the way the mechanism that adjusted slope was mounted to the treadmill and interfaced with the floor. Because of these issues, there were small within and between day differences between the target and actual slope. Data from the follow-up study indicated that the actual treadmill slope explained 97% of the variance in power output. Data from the original reliability study (Table III) indicated that external PO variance accounts for between 56 to 90% of the variance in key propulsion technique outcomes. Together, these results provide strong causal evidence of the degree to which external PO and the determinants of external PO, e.g. slope and velocity, can influence propulsion technique.

The effect of external PO and determinants of external PO on propulsion technique has many implications. First, from a study design and execution perspective, it is critical that these factors are measured if not explicitly controlled during testing. A recent review of wheelchair propulsion assessment protocols by De Klerk *et al.* [20] provides guidance on what factors should be measured for various experimental set-ups. The poor outcomes of our initial reliability study illustrate the impact of not measuring a determinant of external PO. Had this been an investigation into the effects of user, wheelchair, and/or wheelchair-user variables on propulsion technique in a research or clinical setting, we would have likely concluded that the variable that was manipulated had no effect (i.e., Type II error). We may not have recognized that treadmill-induced variations in external PO was likely confounding any other effect we were trying to measure. One potential downstream effect of Type II errors in these studies is an inability of clinicians to justify the need for a particular wheelchair set-up, component, or other seating or propulsion technique intervention.

Second, from a clinical intervention perspective, the effect of external PO and determinants of external PO on propulsion technique highlight the importance of quantifying the degree to which characteristics of the wheelchair-user system influence external PO. Directional effects are known, but the magnitude

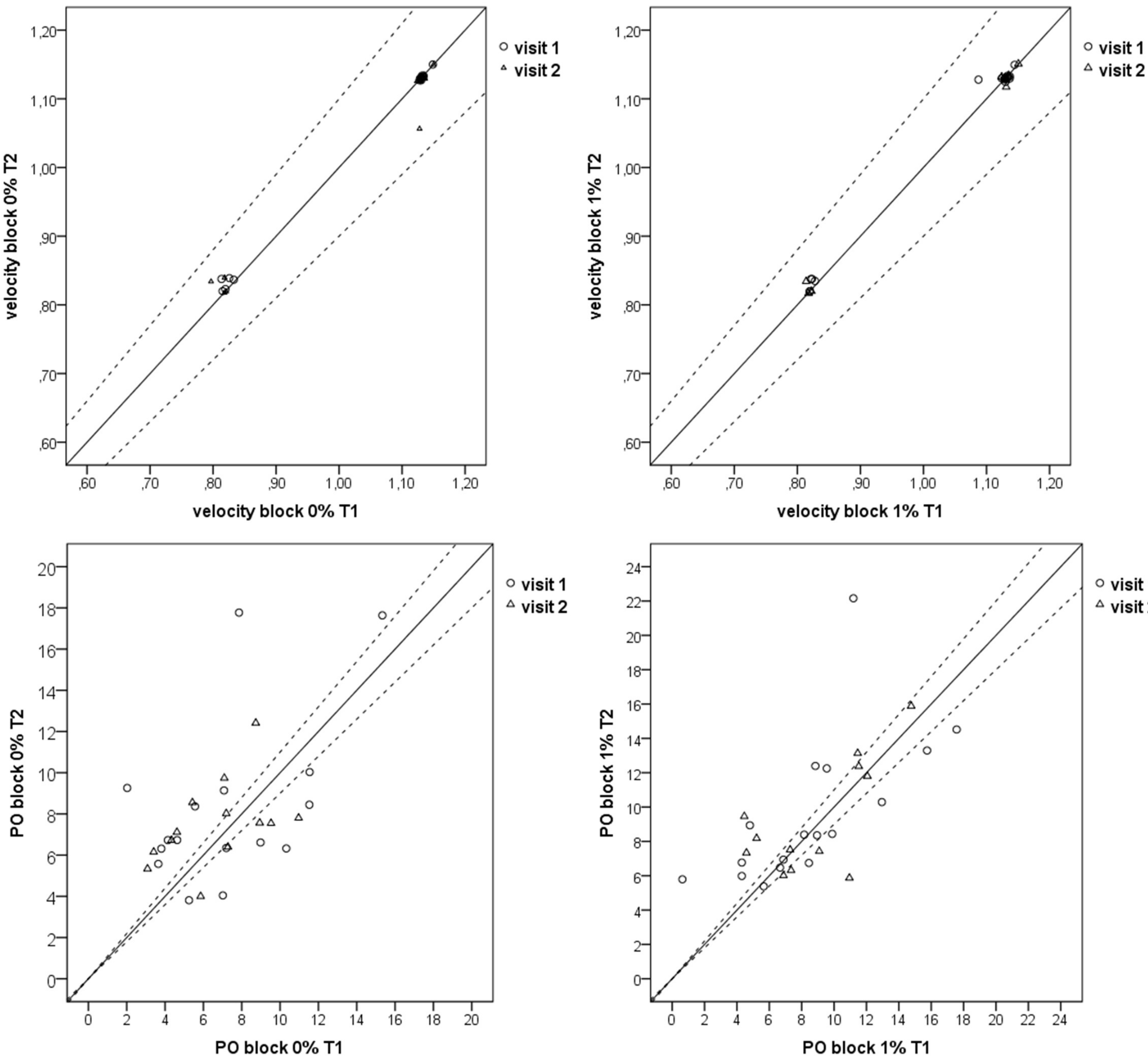

Fig. 4. Scatter plots representing the absolute agreement between the velocity (upper graphs) and external power output (PO, lower graphs) during the first (T1) and second (T2) test for visit 1 and 2 for exercise block with 0% target slope (left graphs) and 1% target slope (right graphs). The solid line is the line of identity, when a marker lies on this line it means that the T1 value is exactly the same as the T2 value. The dashed lines indicate 10% deviation boundaries. Each circle represents a participant.

of effects in isolation and combination are unknown. For example, it is known that increasing wheelchair-user system mass [4], [5] and using solid tires (vs. pneumatic) [5], [6] increases external PO. But because the focus has been on how mass and solid tires affect propulsion technique, researchers not always have quantified their effect on external PO, which might be the mechanism by which they affect propulsion technique. As a research community, in our desire to link clinical intervention options directly to propulsion technique outcomes, we have paid insufficient attention to characterizing the underlying relationship between external PO and propulsion technique, which is one of the pathways that clinical intervention options exert their influence on propulsion technique variables. Furthermore, based on the PO-propulsion technique relationship, measurement of external PO during each trial would better enable direct comparison to data collected on other treadmills and could be used to adjust for center effects when conducting multi-center trials.

Finally, because the underlying relationship between external PO and propulsion technique is poorly defined, it is not yet possible to establish objective thresholds for what constitutes ‘acceptable’ levels of external PO variance between trials, i.e. the amount of external PO variance that does not meaningfully alter propulsion technique. Our results suggest that such thresholds would be dependent on the primary outcomes of interest, as external PO accounted for more than 80% of the variance in mean external force and work per push (Table III) but only 40-50% of the variance in push frequency and contact angle (Table III). Ideally, such thresholds would be linked to the minimally clinical important difference (MCID) of each

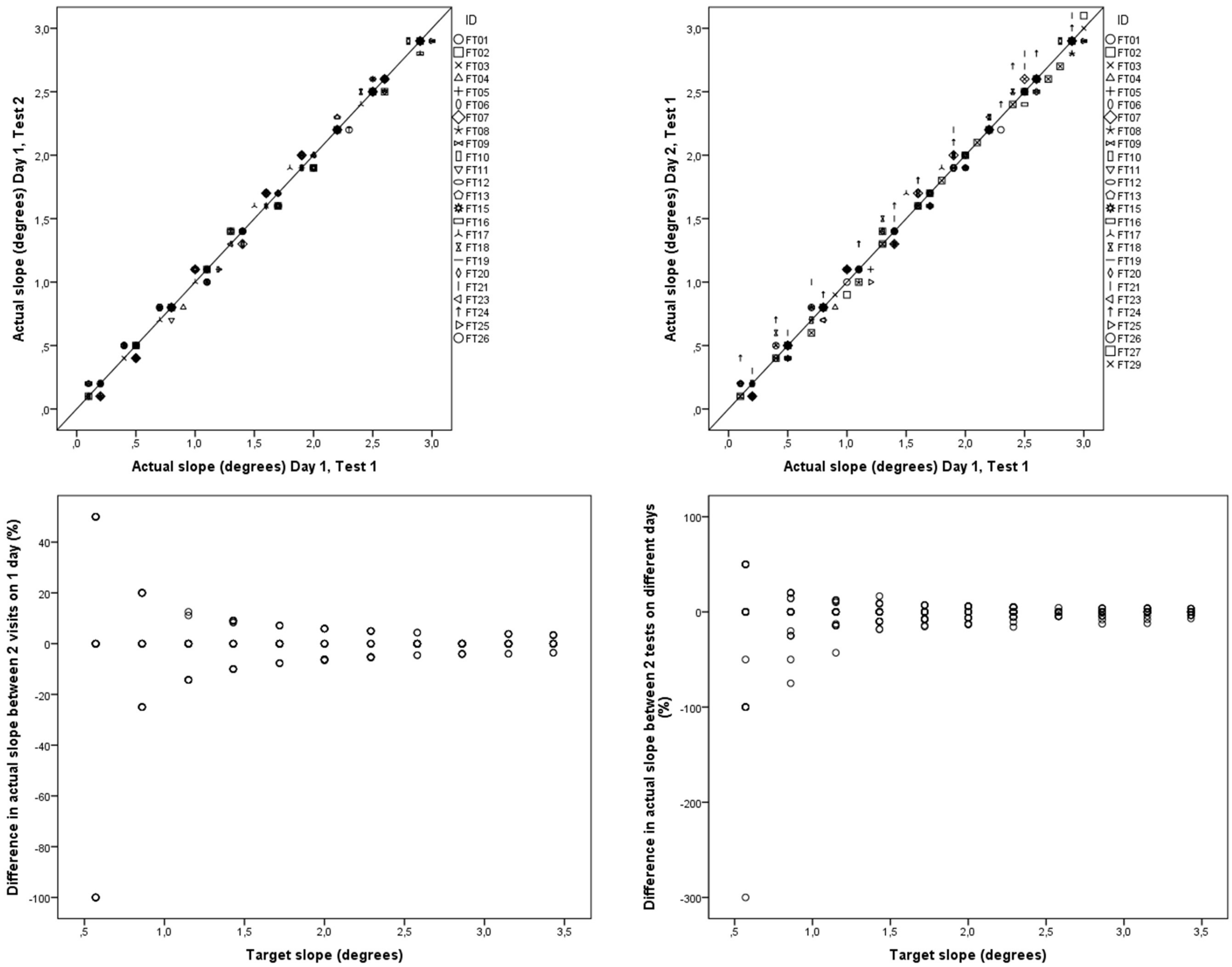

Fig. 5. Scatter plots representing the absolute agreement between the actual measured slope between two tests on 1 day (upper left) and between two tests on separate days (upper right) for different participants (see ID). The solid line is the line of identity, when a marker lies on this line it means that the actual measured slope is exactly the same during the two tests. The lower graphs present the difference (y-axis, in %) between the first and second test on the same day (left) and on two separate days (right) for the different target slopes (x-axis).

propulsion technique variable. However, propulsion technique MCIDs have not been established. Based on the relationship between external PO and propulsion technique in our original reliability study (Table III), each one Watt variation in external PO can alter mean push force by 0.7-1.5 N, work per push by 0.38-0.50 J, push frequency by 0.7-1.5 pushes/min, and contact angle by 1.0-1.7°. Additional work is required to characterize the complex relationship among speed, slope, surface softness and texture, external PO, propulsion technique, user, wheelchair, and wheelchair-user variables. A more refined understanding will better enable identification of interventions that meaningfully improve propulsion technique.

A limitation of the present study might be the sample size. In reliability studies large samples are needed, together with many visits and tests, to attain more stable estimates of variance components and subsequently of the total error variance [21]. However, it is difficult to include many more participants when working with a specific clinical population (wheelchair users with SCI who fulfill the inclusion criteria) who have to perform several submaximal exercise tests and have to come to a lab on separate days. That said, from a theoretical viewpoint more participants would have been better but from a practical viewpoint this was not feasible.

To know what the SDD is for each propulsion technique variable is important when evaluating an intervention for clinical practice or research. Future research should study the reliability of the propulsion technique variables again in wheelchair users with SCI, after checking the variability of the PO (i.e., velocity and slope/resistance of the test system).

Besides this SDD, MCID which is defined as the smallest change that a clinician or patient can perceive and identifies as important [17], is another important clinimetric property of test outcomes. In future, the MCID of propulsion demand for persons with SCI should be investigated as well. SCI researchers can use the MCID to determine if a tested intervention achieves a meaningful change in propulsion demand regardless of statistical significance. It also can be used to plan appropriately powered studies. This in turn supports SCI clinicians by helping them choose the intervention which most strongly decreases propulsion demand.

V. Conclusion

External PO variability accounts for 50-90% of the variability in propulsion technique variables when speed and wheelchair set-up are held constant. Researchers and clinicians should be aware that small differences in external PO between interventions of interest could mask the effect of the interventions on propulsion technique variables.

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