PREDICTING THE SEQUENCE OF MEAN PROPULSION FORCES DURING INDOOR WHEELCHAIR SPORTS: A PROOF OF CONCEPT

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Monitoring the push force is an important asset during wheelchair (WC) sports training. However, current instrumented wheels cannot be used without significantly altering the WC-user dynamics. Moreover, the push force could not be estimated directly from the WC acceleration because of the strong influence of the upper body movement on the WC-user dynamics. In this paper, we present a new method to predict the progression of the mean push force using temporal information (grab/release times) and kinematic information (WC velocity changes). This method was validated at two velocities with 17 manual WC users who propelled their own standard manual WC in an indoor hallway. When summed over both sides, the root-mean-square prediction error was 15.7 N at a comfortable velocity and 35.9 N at the maximum velocity. These results have great implications for indoor WC sports training.

KEYWORDS: Wheelchair sport, force prediction, biomechanics, kinetics, wheelchairs.

INTRODUCTION: Wheelchair (WC) motion in adaptive sports is performed by applying push forces and moments on both rear wheels, which in turn transmit these forces and moments as push forces on the ground. Knowing the amount of force applied by the athlete to the wheels is a powerful indicator of his/her propulsion technique, endurance and ability to accelerate. The commercially available SmartWheel instrumented wheels can measure the push forces and moments when propelling a standard manual WC. However, using these wheels increases the inertia and rolling resistance, decreases the wheel rigidity and therefore affects propulsion dynamics, which could be a significant problem in WC sports. Using an accelerometer, the push force could be estimated by the second law of Newton ($\sum F = ma$). However, using such a simple 1-body model of the WC-user system neglects the fore-and-aft movement of the upper body (UB), which accounts for an important component of the WC acceleration (Sauret, Vaslin, Dabonneville, & Cid, 2008). In this paper, we present a method to predict the mean push force on each stroke, based on time information (grab/release times) and WC velocity variation, independently of the user movement.

METHODS: Data from 17 participants who participated in a previous study (Lalumière, Blouin, Chénier, Aissaoui, & Gagnon, 2014) were used in this study. The participants were adult manual WC users with a complete or incomplete spinal cord injury, who used a manual WC as their primary means of mobility. Potential participants were excluded if they had a history of pressure ulcers on the buttocks, or pain that could have altered their propulsion biomechanics. After giving their informed consent, the participants were weighed with their own WC instrumented bilaterally with two synchronized instrumented wheels (SmartWheel, Outfront LCC). These instrumented wheels measure the 3 forces and 3 moments applied on the pushrim by the user using 6 force transducers, and record the angular position of the wheel using an optical encoder (Asato, Cooper, Robertson, & Ster, 1993). These data are sampled at 240 Hz and sent wirelessly to a portable computer.

The participants underwent two propulsion trials on a straight, level ground, 20-meter long indoor hallway: a first trial at a self-selected comfortable velocity, then another trial at maximum velocity. All participants used at least 10 strokes to complete the trials.

The first 10 pushes of every participant were analysed for both conditions (comfortable and maximal velocity). For each stroke, the measured mean push force $\bar{F}_{(\text{push})}$ was defined as the sum of both measured push moments divided by the radius of the wheels, averaged over the length of the push phase (wheel grab to wheel release). The grab and release times were obtained based on a dual force threshold of 5 N (grab) and 2 N (release) on the resultant force applied on the left wheel.

The mean push force was also predicted. The following equation is the impulse-momentum equality during a period of one propulsion cycle:

$$\begin{aligned}\bar{F}_{(\text{push})}\Delta t_{(\text{push})} + \bar{F}_{(\text{recovery})}\Delta t_{(\text{recovery})} - \bar{R}\Delta t_{(\text{cycle})} \\ = m_{\text{wc+lb}}\Delta v_{\text{wc(cycle)}} + m_{\text{ub}}\Delta v_{\text{ub(cycle)}}\end{aligned} \tag{1}$$

where $\bar{F}_{(\text{push})}$ and $\bar{F}_{(\text{recovery})}$ are the mean push force during the push and recovery phases, respectively, $\Delta t_{(\text{push})}$ and $\Delta t_{(\text{recovery})}$ are the push length and recovery length, respectively, $\bar{R}$ is the rolling resistance force, $\Delta t_{(\text{cycle})}$ is the cycle length, $m_{\text{wc+lb}}$ is the mass of the WC and user's lower body, $\Delta v_{\text{wc(cycle)}}$ is the velocity gain of the WC during the cycle, m_{ub} is the mass of the user's UB, and $\Delta v_{\text{ub(cycle)}}$ is the velocity gain of the user's UB centre of mass during the cycle. As the UB movement is cyclic, its velocity gain over a complete cycle is equal to the velocity gain of the wheelchair: $\Delta v_{\text{ub(cycle)}} \approx \Delta v_{\text{wc(cycle)}}$. Moreover, the push force is null during the recovery phase: $\bar{F}_{(\text{recovery})} = 0$. Therefore, Eq. (1) simplifies to:

$$\bar{F}_{(\text{push})} \approx \frac{m_{\text{total}}\Delta v_{\text{wc(cycle)}} + \bar{R}\Delta t_{(\text{cycle})}}{\Delta t_{(\text{push})}} \tag{2}$$

where $m_{\text{total}} = m_{\text{wc}} + m_{\text{lb}} + m_{\text{ub}}$. To predict $\bar{F}_{(\text{push})}$ using Eq. (2), $\Delta v_{\text{wc(cycle)}}$ was calculated by filtering and deriving the angular position of the left wheel using a second-order Butterworth filter with a cut-off frequency of 6 Hz (Cooper et al., 2002). The mean rolling resistance $\bar{R}$ was estimated using $R = \mu N$, based on the normal ground force $N = m_{\text{total}}g$ and on the rolling resistance coefficient μ calculated in a previous study performed in similar conditions (Chénier, Bigras, & Aissaoui, 2015). The root-mean-square (RMS) absolute prediction error ϵ and relative prediction error $\epsilon_{\%}$ were calculated as:

$$\epsilon = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\text{predicted}\left(\bar{F}_{(\text{push})_i}\right) - \text{measured}\left(\bar{F}_{(\text{push})_i}\right))^2}$$

$$\epsilon_{\%} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{\text{predicted}\left(\bar{F}_{(\text{push})_i}\right) - \text{measured}\left(\bar{F}_{(\text{push})_i}\right)}{\text{measured}\left(\bar{F}_{(\text{push})_i}\right)}\right)^2} \times 100\%$$

where i correspond to one stroke among the n analysed strokes. No statistical analysis was performed for this exploratory proof of concept.

RESULTS: The RMS prediction error over all analysed strokes ($n = 170$) was $\epsilon = 15.7\ \text{N}$, $\epsilon_{\%} = 31\ \%$ at comfortable velocity, and $\epsilon = 35.9\ \text{N}$, $\epsilon_{\%} = 48\ \%$ at maximum velocity. Individual results are presented in Figures 1 and 2. As $\bar{F}_{(\text{push})}$ is directly proportional to the total mass of the wheelchair and user, m_{total} was also given for each participant.

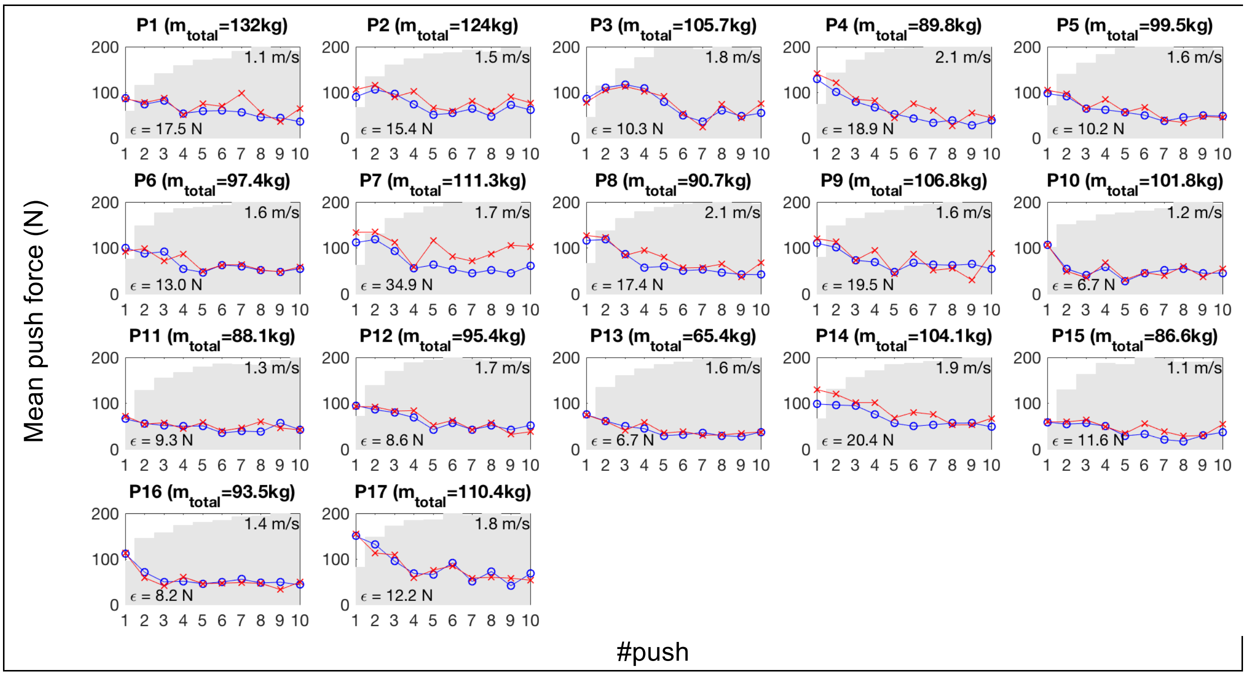

Figure 1: Comparison between the measured (o) and predicted (x) mean push force at comfortable velocity. The grey shading is the velocity (highest velocity in the top right corner).

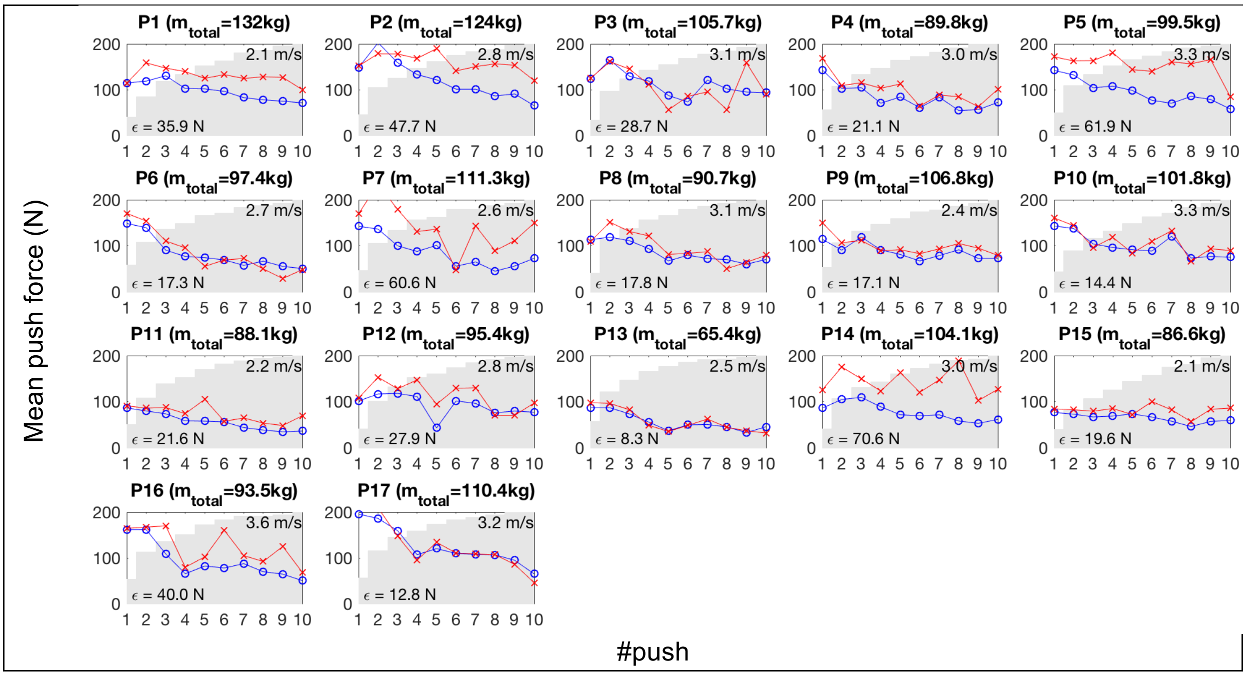

Figure 2: Comparison between the measured (o) and predicted (x) mean push force at maximal velocity. The grey shading is the velocity (highest velocity in the top right corner).

DISCUSSION: We observe in both figures that the predicted curves tend to follow the measured ones, particularly with participants 3 and 10 at a comfortable velocity. This supports that this method can estimate not only the mean push force during a complete trial, but also its progression during a sequence of strokes. The majority of the participants had an error lower than 15 N, which is less than the rolling resistance forces of about 15 to 25 N calculated from coast down tests (Chénier et al., 2015; Sauret et al., 2012). For other participants (7, 14), larger errors were observed in both velocity conditions. These higher errors, which seem to be participant specific, may be explained by a couple of reasons:
First, we assumed that the UB's velocity variation is equal to the WC's velocity variation over a cycle. Even if the UB's movement is cyclic, the user may grab or release the wheel at

different times from one stroke to another, which would desynchronize the push cycle and the UB's movement cycle. Second, push detection was based on the left wheel only. This implicit assumption of symmetry may not hold if the user propels with an alternate pattern or if he/she performs turning manoeuvres.

Despite the low to moderate absolute error found in our results, the relative prediction error $\epsilon_{\%}$ was high when normalized by the real push force. As sports propulsion generally implies higher accelerations than standard overground propulsion, we expect the relative error to decrease using sports data, as the push forces will be higher. This however remains to be confirmed, since in our data, the prediction error was generally larger at maximal velocity, possibly due to a different position of the user that may affect the rolling resistance force (Sauret et al., 2012).

Among the limitations of this study, the mean resistance force was considered constant during the entire trial, which may not be true for outdoor sports where external conditions may be inconsistent (e.g., air drag, different ground materials). However, we believe it is a realistic assertion for most indoor court sports since the floor surface is usually uniform and there is no wind. Finally, the force prediction was still based on data from instrumented wheels (grab times, release times, velocity changes); alternate ways to measure these spatiotemporal data, such as video analysis or inertial units (Mason, Rhodes & Goosey-Tolfrey, 2014) should be investigated.

CONCLUSION: In this paper, we presented a method to predict the progression of the mean push force during WC propulsion, based on temporal information (grab times, release times) and kinematic information (WC velocity changes). This proof of concept was verified indoors with 17 manual WC users who propelled at comfortable and maximum velocities and yielded absolute prediction errors of 15.7 N and 35.9 N, respectively. This method could have important applications in WC sports training, since monitoring the push forces applied to the wheels by the athlete is a strong indicator of his/her force, endurance, and WC motion abilities.

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