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Wheelchair pushrim kinetics measurement: A method to cancel inaccuracies due to pushrim weight and wheel camber

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ABSTRACT

The commercially available SmartWheel™ is largely used in research and increasingly used in clinical practice to measure the forces and moments applied on the wheelchair pushrims by the user. However, in some situations (i.e. cambered wheels or increased pushrim weight), the recorded kinetics may include dynamic offsets that affect the accuracy of the measurements. In this work, an automatic method to identify and cancel these offsets is proposed and tested.

First, the method was tested on an experimental bench with different cambers and pushrim weights. Then, the method was generalized to wheelchair propulsion. Nine experienced wheelchair users propelled their own wheelchairs instrumented with two SmartWheels with anti-slip pushrim covers. The dynamic offsets were correctly identified using the propulsion acquisition, without needing a separate baseline acquisition. A kinetic analysis was performed with and without dynamic offset cancellation using the proposed method. The most altered kinetic variables during propulsion were the vertical and total forces, with errors of up to 9 N ($p < 0.001$, large effect size of 5).

This method is simple to implement, fully automatic and requires no further acquisitions. Therefore, we advise to use it systematically to enhance the accuracy of existing and future kinetic measurements.

1. Introduction

Wheelchair propulsion is a tedious task that leads to the development of upper limb secondary musculoskeletal impairments (SMI) over time in more than half of manual wheelchair users [1–4]. Extensive research was conducted in the last decade to reduce the high prevalence of SMI. One key innovation is the SmartWheel™ instrumented wheelchair wheel, developed by the Human Engineering Research Laboratory in Pittsburgh [5]. Since it became available, the SmartWheel allowed the recording of the three forces and three moments applied by the user on the pushrims during wheelchair propulsion, which strengthened the level of evidence on the impact of the wheelchair propulsion technique and positioning on the development of SMI [6–9]. This new evidence led the Consortium for Spinal Cord Medicine to formulate recommendations for clinicians to instruct users to minimize the force and the rise of force they apply on the pushrims [10]. As this force can be easily measured using an instrumented wheel, the SmartWheel has been implemented in a growing number of clinical sites since 2008 [11].

The SmartWheel is functionally identical to a gait force plate: pushrim kinetics is measured by a combination of six load cells and is reported into a global reference frame located at the wheel hub center. However, the load cells cannot be zeroed statically like a gait force plate because the wheel rotates relative to the gravity during manual wheelchair propulsion. Therefore, as the wheel turns, the weight of the handrim causes dynamic offsets in the load cell readings, as a function of the wheel angle.

Such dynamic offsets were observed previously in other work. In 1998, Wu et al. [12] presented an instrumented wheel and recorded the pushrim kinetics as the wheel turned with no external force applied on the pushrim. They showed that for all velocities, dynamic offsets were present on the F_x and F_y signals and were very well-modeled by sinusoidal signals. Woods et al. [13] also observed oscillating offsets on F_x and F_y, along with static offsets on the other forces and moments. They modeled the dynamic offsets as a combination of splines before subtracting them from subsequent recordings.

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Nomenclature

$\boldsymbol{A}$	3×6 dynamic offsets identification matrix
$\boldsymbol{b}$	6×1 calibration vector for the SmartWheel's regression equations
$\boldsymbol{c}$	force channels (6×1 vector)
$\boldsymbol{c}_0$	force channels at power-on (6×1 vector)
$\boldsymbol{f}$	real pushrim kinetics (6×1 vector)
$\boldsymbol{f}_{\mathrm{ofs}(\theta)}$	dynamic offsets (6×1 vector)
$\boldsymbol{f}_{\mathrm{SW}}$	measured pushrim kinetics (6×1 vector)
$\boldsymbol{J}_{\mathrm{c}(\theta)}$	6×6 matrix that translates force channels into the global reference frame
$\boldsymbol{J}_{\tau}$	6×6 matrix that translates load cell forces into pushrim kinetics
$\boldsymbol{M}$	6×6 calibration matrix for the SmartWheel's regression equations
$\boldsymbol{q}_{\theta}$	1×3 state vector for the dynamic offsets identification
$\boldsymbol{R}_{(\theta)}$	6×6 rotation matrix that translates the pushrim kinetics into the global reference frame
$\boldsymbol{S}$	6×6 diagonal sensitivity matrix that translates force channels into load cell forces
$\boldsymbol{w}$	pushrim weight (6×1 vector)
θ	rear wheel angle
$\boldsymbol{\tau}$	load cell forces (6×1 vector)

A similar method approach was proposed by Sauret et al. [14] and Dabonneville et al. [15], who modeled the dynamic offsets as Fourier polynomials. However, instead of subtracting these offsets from the pushrim kinetics, they subtracted them from the raw force channel data. Therefore, this approach requires (1) calibration information to convert the force channels into pushrim force and moments, and (2) raw force channel data, which may limit its application on past acquisitions where raw force channel data or calibration information may have been discarded.

For all these experimental prototypes, the existence of dynamic offsets and their cancellation method were well-documented. However, it seems that the commercial SmartWheel is not prone to such dynamic offsets. The reason for this resides in a different approach to convert the raw force channel data in pushrim kinetics. The SmartWheel does not require a baseline trial, but requires in-factory calibration values for a given pushrim weight and a given wheel camber. Using these calibration values, the dynamic offsets can be estimated as a function of the wheel angle, and are directly cancelled during propulsion. However, because calibration values are dependent on pushrim weight and wheel camber, the recorded kinetics may be inaccurate when wheel camber is modified or when weight is added to the pushrim. The first condition (cambered wheels) is encountered with users of an ultralight wheelchair who want the benefit of the wider base of support and seated stability, manoeuvrability and ergonomics provided by cambered wheels [16,17]. The second condition (increased pushrim weight) happens, for example, when using an anti-slip pushrim cover to optimize grip between the users' hand and the pushrim. As an example, the use of a commercial Q-Grip pushrim cover (Out-Front, Mesa, AZ, USA), a neoprene shell superposed to the existing pushrim and weighing about 570 g, facilitates manual wheelchair propulsion among persons with limited hand function. Since both conditions may arise in clinics, the validity of the measured kinetic variables under these conditions must be verified. Moreover, if corrections are required, then these corrections must not require additional manual processing, either in a clinical or research context.

The first part of this study aims to measure the effects of wheel camber and pushrim weight on kinetic measurements and to propose a method to cancel these effects. We hypothesized that (1) cambering the rear wheels camber and/or adding weight to the pushrims will introduce dynamic offsets larger than the reported SmartWheel measurements uncertainty [18], and (2) that identifying, then subtracting these offsets, will reduce the error below this uncertainty.

The second part of this study aims to generalize the proposed method to actual wheelchair propulsion data recorded at self-selected speed on level ground in a natural environment. We hypothesized that (1) the dynamic offsets introduced by pushrim weight or wheel camber will be identified directly from the propulsion acquisition, without needing a separate baseline acquisition, and (2) that correcting the recorded kinetics has a significant impact on typical outcome measurements such as the minimal, mean and maximal values of F_{x}, F_{y}, F_{z}, M_{x}, M_{y}, M_{z} and their vectorial sum F_{tot}, M_{tot}.

2. Methods – part 1 on an experimental bench

2.1. Material

A generic wheelchair (Astra, Orthofab Inc., Québec, QC, Canada) without wheel camber was instrumented with one 24-inch instrumented wheel (SmartWheel, Out-Front, Mesa, AZ, USA) such as the one presented in Fig. 1, on the right side. The wheelchair frame was fixed on a support so that the wheels did not touch the ground. One side of the support was installed on an elevator platform so that the wheelchair could be inclined at specific angles, thus simulating different wheel cambers (Fig. 2). The simulated camber α was calculated using the known width w of the support base and the height h of the elevator: $\alpha = \mathrm{asin}(h/w)$. During the acquisition, one trial was completed without added weight at the pushrim (i.e., no cover) and one trial was completed with an increased pushrim weight since a Q-Grip pushrim cover (Outfront, Mesa, AZ, USA) was used.

2.2. Data acquisition

The elevator platform was adjusted to reach three simulated camber angles:

- 0°: no camber;
- 10°: a typical maximal value with standard ultralight wheelchairs;
- 20°: typically used with sporting wheelchairs.

Fig. 1. The SmartWheel™ instrumented wheel.