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Effects of user's actions on rolling resistance and wheelchair stability during handrim wheelchair propulsion in the field

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ABSTRACT

Currently, rolling resistance and wheelchair stability during manual wheelchair propulsion can be assessed from the loads applied on the front and rear wheels, which are determined in a static condition. However, a user's actions on the wheelchair would change these loads during locomotion, which should affect both the rolling resistance and wheelchair stability. The goal of this study was to verify these assumptions and assess how much the rolling resistance and wheelchair stability are affected by the user's actions during propulsion. For that purpose, a mechanical model was developed using measurements of an instrumented wheelchair equipped with several six-component dynamometers. Experiments were performed by three subjects propelling the instrumented wheelchair over flat ground. The results showed variations over wide ranges of the fore-aft distribution of the total load, rolling resistance, wheelchair stability, wheelchair velocity and mechanical power dissipated by the rolling resistance during the propulsion cycle. In addition, the time courses of all these variables differed with the subject. Finally, this study demonstrated the possibility of assessing intra-cycle values of both rolling resistance and wheelchair stability during manual wheelchair displacements in the field, which provides a technical step towards evaluating a wheelchair user in his daily environment.

1. Introduction

Evaluating the biomechanical stresses sustained by manual wheelchair (MWC) users in their daily lives is an important area of field research for scientists and clinicians. For that purpose, it is necessary to assess the stress induced by the rolling resistance during propulsion in a user's actual environment. Indeed, rolling resistance is essential when studying manual wheelchair (MWC) locomotion because it dissipates a part of the energy produced by the user during propulsion. Thus, decreasing the rolling resistance increases the mobility and autonomy of a MWC user. Rolling resistance is also essential to assess the power output produced by a user, as well as the gross mechanical efficiency, which are useful data for clinicians.

Previous studies that focused on rolling resistance made it possible to clarify the effects of the types of front and rear wheels, tires pressure, rear wheel camber and floor type [1–7]. Models have been proposed to assess the subject-specific rolling resistance according to the loads applied to the front and rear wheels [7–14]. These models have shown the effect of the wheel radius on the rolling resistance, which explains the increase in rolling resistance that is noted when the mass is brought forward [11–16]. However, the loads applied to the front and rear wheels change with a user's posture in a MWC and evolve during the propulsion cycle [11,13,16]. As a consequence, exploratory studies have shown wide variations in the fore-aft distribution of the total load during a propulsion cycle performed in the field [11,13,16]. Hence, the mean rolling resistance during the propulsion cycle could be different from that assessed with loads measured in a static condition. Simultaneously, a change in the fore-aft distribution of the total load would change the rearward/forward stability of the MWC with some tipping hazards. However, one limitation of these preliminary studies was that the fore-aft distribution of the total load was only determined using a vertical projection of the global centre of mass (COM) [11] or the seat centre of pressure [16] between the

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front and rear wheels, neglecting the effects of internal actions at the interface between the user and MWC (*i.e.* fore-aft actions on the seat). In addition, the method used in [11] required measurements of the subject's movements with a motion capture system, which limited the study to the volume covered by the cameras' fields of view.

This study aimed at evaluating the intra-cycle variations in the loads applied on the front and rear wheels during propulsion in the field and their effects on both the rolling resistance and MWC rearward/forward stability. For that purpose, a method based on the mechanical modelling of the MWC propulsion was developed. The application of this method required the use of an instrumented MWC [17], which was equipped with several six-component dynamometers to measure all of the mechanical actions applied by the user to the MWC. Experiments were performed by three subjects propelling the instrumented MWC over level ground.

2. Materials and methods

2.1. Model of MWC rolling resistance

In order to assess the rolling resistance acting on an MWC during propulsion in the field, it was necessary to define a mechanical model of the MWC rolling resistance. For that purpose, the following equation, previously presented in [7,11–14] was used:

$$F_{roll} = -\left(\frac{\lambda_f}{r_f}R_{Nf} + \frac{\lambda_r}{r_r}R_{Nr}\right) \tag{1}$$

where: F_{roll} is the MWC rolling resistance [in N]; λ_f and λ_r are the specific rolling resistance parameters [in m] for the front and rear wheels on the studied surface, respectively; r_f and r_r are the front and rear wheels radii [in m], respectively; R_{Nf} and R_{Nr} are the normal components [in N] of the ground reaction forces applied to the front and rear wheels, respectively, and represent the loads applied to the front and rear wheels.

2.2. Model of MWC stability

The MWC stability tends to express the rearward or forward tipping hazard. In the literature, the static stability of a MWC has been assessed using an inclined platform [18–20]. However, this method cannot be used to assess the dynamic stability of a MWC. Therefore, the MWC stability was assessed using the ratio between the load applied on the front wheels and the total load, which is close to the method used by [21]:

$$MWC_{stability}(\%) = \frac{R_{Nf}}{R_{Nr} + R_{Nf}} \times 100 \tag{2}$$

Using this definition, $MWC_{stability} = 0\%$ is the critical threshold for a rearward tilting hazard, whereas $MWC_{stability} = 100\%$ is the critical threshold for the hazard of forward tilting. The maximum stability in both the forward and backward directions is reached when $MWC_{stability} = 50\%$.

2.3. Model of loads applied on front and rear wheels

In order to calculate both the rolling resistance and MWC stability, it was necessary to know the loads applied to the front (R_{Nf}) and rear wheels (R_{Nr}) within the propulsion cycle. Thus, a mechanical model of the MWC propulsion in the field was developed (see details in Appendix A). This model takes into account the mechanical actions exerted by the user on both the handrims and MWC frame (seat, backrest and footrest). After simplifications (Appendix B), the loads applied to the front and rear wheels can be well approximated using the following equations:

$$R_{Nf} = -\frac{(x_{A_S}F_{Sy} - y_{A_S}F_{Sx} + T_{Sz}) + x_G W_{WC}}{w_b} \tag{3}$$

$$R_{Nr} = -(W_{WC} + F_{Sy} + F_{HRy} + R_{Nf}) \tag{4}$$

where: x_G is the fore-aft position [in m] of the MWC's centre of mass with respect to the centre of the rear wheels; x_{A_S} and y_{A_S} are the fore-aft and vertical positions [in m] of the chosen point of reduction of the actions exerted by the user on the frame (seat, backrest and footrest) with respect to the rear wheels axle, respectively; w_b is the wheelbase [in m], which is the fore-aft distance between the front and rear wheel axles; W_{WC} is the MWC's weight [in N]; F_{Sx} and F_{Sy} are the fore-aft and vertical components [in N] of the resulting force applied by the user to the MWC frame (seat, backrest and footrest); T_{Sz} is the transversal torque [in Nm] applied at the chosen point of reduction of the user's actions on the MWC frame (A_S); F_{HRx} and F_{HRy} are the fore-aft and vertical components of the forces [in N] applied to the handrims.

2.4. Instrumented MWC

To measure the mechanical actions applied by the user on the MWC, an instrumented MWC (FRET-1) [13,16,17,23] was used. It was equipped with a 3-D accelerometer (FA3506, FGP, France) attached to the MWC frame; a six-component dynamometer (TSR-mesures, France [24]) attached between the frame and a rigid system that included the seat, backrest and footrest; two additional six-component dynamometers (TSR-mesures, France) on the handrims; and two angular potentiometers (Spectrol 601-1045, Vishay, USA) linked to the rear wheel axles. In addition, the handrims dynamometers were zeroed out following the instructions detailed in [25,26]. Thereby, the seat dynamometer made it possible to measure the six components (F_{Sx}, F_{Sy}, F_{Sz}, T_{Sx}, T_{Sy}, T_{Sz}) of the user's mechanical actions on the {seat + backrest + footrest} system at the origin, A_S (x_{A_S}, y_{A_S}, z_{A_S}), of the dynamometer. The handrim dynamometers made it possible to measure the six components (F_{HRx}, F_{HRy}, F_{HRz}, T_{HRx}, T_{HRy}, T_{HRz} with $T_{HRz} = T_{prop}$) of the subject's actions on the handrims, which were expressed at the centres of the rear wheels. The MWC's velocity was computed using a time differentiation of the angular positions measured by the angular potentiometers, assuming that the MWC rolled without slipping on the floor.

Data were sampled at a 200-Hz frequency using a 16-bit A/D conversion card (DAQCard-6036E, National Instruments, USA) plugged into an embedded mini-computer (TC1100, Hewlett-Packard, USA) fixed under the seat. The data were transmitted in real time using the IEEE 802.11b and TCP/IP wireless transfer protocols to a remote computer (M5200 N, ASUS, Taiwan), where they were recorded.

The instrumented MWC was equipped with standard front casters and pneumatic rear wheels inflated to 58 psi. The radii of the front (r_f) and rear wheels (r_r) were 0.07 and 0.30 m, respectively, and the wheelbase (w_b) was 0.33 m. The fore-aft and vertical coordinates of the seat dynamometer origin were measured ($x_{A_S} = 0.017$ m and $y_{A_S} = 0.155$ m) and those of the MWC centre of mass were computed from a 3-D geometrical model that included the embedded instrumentation ($x_G = 0.141$ m and $y_G = 0.060$ m) [13]. Equipped with all of the sensors and embedded electronics, the mass of the instrumented MWC was 38.5 kg.

2.5. Determination of rolling resistance parameters

Before the experiments with the subjects, the rolling resistance parameters of the front (λ_f) and rear wheels (λ_r) of the