Effect of workload setting on propulsion technique in handrim wheelchair propulsion

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ARTICLE INFO

ABSTRACT

Objective: To investigate the influence of workload setting (speed at constant power, method to impose power) on the propulsion technique (i.e. force and timing characteristics) in handrim wheelchair propulsion.

Method: Twelve able-bodied men participated in this study. External forces were measured during handrim wheelchair propulsion on a motor driven treadmill at different velocities and constant power output (to test the forced effect of speed) and at power outputs imposed by incline vs. pulley system (to test the effect of method to impose power). Outcome measures were the force and timing variables of the propulsion technique.

Results: FEF and timing variables showed significant differences between the speed conditions when propelling at the same power output ($p < 0.01$). Push time was reduced while push angle increased. The method to impose power only showed slight differences in the timing variables, however not in the force variables.

Conclusions: Researchers and clinicians must be aware of testing and evaluation conditions that may differently affect propulsion technique parameters despite an overall constant power output.

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1. Introduction

Measuring propulsion forces and studying propulsion technique of handrim wheelchair propulsion are becoming common in research as well as in some rehabilitation practices [1]. Low mechanical efficiency can explain high physical [2] and mechanical strain [3,4] associated with wheelchair propulsion. However, our understanding of the mechanical load and the role of propulsion technique in handrim wheelchair propulsion is still limited. A propulsion technique with a long push time and a large push angle could increase the mechanical efficiency [5]. Such a propulsion technique can possibly increase performance, reduce the musculoskeletal load and has been associated with lower risk to develop musculoskeletal injuries [6]. With information on force characteristics, magnitude and direction, we could possibly identify the risk factors for overuse injuries [7,8]. It is also important to study propulsion technique when optimizing the wheelchair-user interface, such as seat position or testing new handrim features in manual wheelchair propulsion [9,10].

Over the last couple of years, with the availability of instrumented wheelchairs, considerable research has been done in wheelchair exercise testing concerning force application and propulsion characteristics [11–20]. Results were, however, not always consistent. This might be due to different measuring devices (ergometer vs. ambulant force sensing systems), test conditions (ergometer vs. wheelchair propulsion on a treadmill) or test protocols (time schedule and workload setting (i.e. power output, speed)).

Regarding experiments conducted on a treadmill, several strategies can be chosen to set the workload: by changing speed, changing the slope, or changing the resistance with the use of a pulley system. Researchers have studied the effects of increased speed [21,22] and incline [22,23] on the propulsion variables. The above-mentioned studies found that propelling at a higher speed or incline had an effect on the propulsion variables. However, these effects might not have been caused exclusively by speed or incline itself, since a change in speed or incline also results respectively in a changed power output and resistance, which in itself could have had an influence on the propulsion variables. Veeger et al. and de Groot et al. compared the propulsion variables at the same power output but with different speeds [24,25] and their results showed that some propulsion variables (FEF, propulsion moment) did not change with increased speed at the same power output [24].

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To be able to compare the results of various studies among each other, it is important to know the effect of different workload settings on propulsion technique variables. Where some studies investigated the chosen effect of a higher power output through increasing speed, this study will follow the line of Veeger et al. [24] and will investigate the forced effect of a higher speed (while maintaining constant power and thus by definition lowering the resisting force). This study will compare the forced effect of an incline to propelling on a level treadmill at the same power output. In the latter, the resistance is imposed by a pulley system. It is hypothesized that the effect of a higher speed at a given constant power output influences the propulsion technique variables, namely increases the push frequency and decreases the propulsion force. Further, it is hypothesized that propelling up an incline will lead to a different force application when compared to propelling against the resistance of the pulley system, resulting in the same power output.

2. Methods

2.1. Subjects

Twelve able-bodied men, all employees at the research department, participated in this study. Inclusion criteria were: male, no experience in wheelchair use and no shoulder pain or recent injuries to the upper extremities. The local ethics committee approved the study and all subjects gave their written informed consent.

2.2. Experimental design and data collection

The experiment was performed on a treadmill ("Mill" treadmill, Forcelink B.V., Culemborg, The Netherlands) in a Küschall wheelchair (Küschall K-Series, Küschall AG, Witterswil, Switzerland) with a camber of $6°$. The wheelchair had a standard configuration and was not adjusted to the user's body size. The wheelchair was fitted with a SmartWheel (Three Rivers Holdings LLC, Mesa, AZ, USA) on the left side and a dummy wheel on the right side [21].

Kinematics of the hand were measured with a 6-camera infrared camera system (Oqus, Qualisys AB, Gothenburg, Sweden). Kinematic data collection was synchronized with the SmartWheel at 100 Hz.

Before testing, the subjects were allowed to become accustomed to the wheelchair and the experimental setup. However, they were not instructed how to propel the wheelchair. After the familiarization period, the individual rolling resistance was determined in a separate drag test [26]. This technology was a special purpose development of the Engineering department of the Faculty of Human Movement Sciences of the VU University, Amsterdam, The Netherlands [27]. Based on the rolling resistance, external power output could be regulated with an additional external force, acting via a pulley system on the wheelchair-user combination (Fig. 1). External power output ($PO_{external}$) was calculated as: $(F_{drag} + F_{additional}) \cdot v_{belt}$ [28].

To evaluate the effect of speed, the subjects propelled at a constant power output (25 W) with three belt velocities ($v_{belt} = 0.83$, 1.11, 1.38 ms^{-1}) in combination with additional force acting via the pulley system ($(F_{drag} + F_{additional}) \cdot v_{belt} = 25$ W).

To evaluate the effect of the method to impose the external power, the subjects first propelled with a constant velocity of 1.11 ms^{-1} and increasing inclines (1%, 2.5% and 4%). Subsequently, the same external PO was evaluated through a simulation of the resistance of the three inclines via the pulley system, while the treadmill remained horizontal (Fig. 1).

Fig. 1. Overview of the test setup where the subject is propelling against extra resistance generated by a pulley system.

All test conditions were 1-min exercise bouts during which data were collected during the last 30 s.

2.3. Data analysis

From the 30 s recorded during each exercise bout, only complete pushes were used for data analysis. Cadence (number of pushes per minute) was calculated on the basis of the duration and number of the complete pushes in these 30 s by use of a Matlab program (The MathWorks Inc, Natick, MA, USA).

The SmartWheel recorded forces and moments in three dimensions [29] at 100 Hz, these forces were corrected for camber and analyzed in the following global coordinate system: $F_x = F_{lat}$: horizontally inward (the SmartWheel was fitted on the left side of the chair), F_y: vertically upward and F_z: horizontally backward. Via the inclination angle of the treadmill, forces were transformed to the global coordinate system. The total force (F_{tot}) acting on the push rim was calculated as the norm of the three force components.

The effective force component F_{tan}, which is tangential to the rim, as well as the radial force component (F_{rad}) was calculated from the global force components (F_y and F_z) and the hand position in relation to the wheelchair axis [29]. It was assumed that the second metacarpal was the point of force application onto the rim [24,30]. For all force variables the mean values over the push phases were calculated.

Over each push phase, the fraction of effective force (FEF) was calculated as the ratio between the mean propulsion moment around the wheel axle (M_{wheel}) divided by rim radius (r_{rim}) and the mean F_{tot} (FEF = $(M_{wheel} \cdot r^{-1}) \cdot F_{tot}^{-1}$) [24].

Performed power output ($PO_{performed}$) was calculated under the assumption that equal mean power was produced on the left and the right wheel over time [31]. Therefore power output was calculated as the product of the measured torque and the angular velocity times two ($PO_{performed} = (M_{wheel} \cdot \omega) \cdot 2$) [32]. From the mean $PO_{performed}$ and the cadence (f) in Hertz, the average work per cycle (W_{cycle}) was calculated ($W_{cycle} = PO_{performed} \cdot f^{-1}$) [33].

Push time was defined as the time period where the hand exerted a positive torque on the handrim [34]. Cycle time was defined as the period of time from the onset of one push phase to the onset of the next, recovery time as the difference between cycle time and push time. Push time was also expressed as the percentage of cycle time (PTpC). Push angle represents the angle over which positive torque was applied.