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Cardio-respiratory and subjective strains sustained by paraplegic subjects, when travelling on a cross slope in a manual wheelchair (MWC)

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ABSTRACT

The aim of this study was to quantify cardiac, energetic and subjective strains during manual wheelchair (MWC) travel on cross slopes (Cs). 25 paraplegics achieved eight 300 m propulsion tests combining 4 Cs (0, 2, 8 and 12%) and 2 velocities (Vi = 0.97 m s^{-1}, Vc "comfortable"). Heart rate and oxygen uptake were recorded continuously. Subjective rating (RPE) was made on completion of each test. Vc exceeds Vi for all Cs. Cardiac and energetic strains at Vc also exceed those at Vi ($p < 0.01$). Mean cardiac cost (in bpm) at Vc is 34 (SD = 13) bpm for a 0/2% Cs and 55 (18) bpm for a 12% Cs. Mean energetic cost (in J m^{-1} kg^{-1}) is 1.20 (0.38) and 2.76 (0.97) for respectively 0/2% and 12% Cs at Vi and, at Vc 1.50 (0.43) and 3.37 (1.43) for 0/2% and 12% Cs respectively. Subjective rating was considered as moderate for a 12% Cs. MWC users with high level injuries travel faster as those with low level injuries. Strain increase is linear for Cs from 0% to 12%. The results suggest that 2% Cs is generally acceptable, while 8% would be a critical threshold.

1. Introduction

In France, nearly 200,000 disabled persons use a manual wheelchair (MWC) and live at home (Vignier et al., 2008). Travelling difficulties are one of the determining factors in non-integration or occupational exclusion of persons in MWC (Lidal et al., 2007; Van Velzen et al., 2009). Environmental unsuitability amplifies an MWC's initial constraints and requires greater cardio-respiratory and muscular exertion on behalf of persons in relation to their physiological capacities (Collins et al., 2012, Meyers et al., 2002). Although the peak oxygen uptakes of MWC sportsmen may exceed 35 ml kg^{-1} min^{-1} (Bhambhani, 2002; Haisma et al., 2006; Huonker et al., 1998; Van der Woude et al., 2001), these capacities are less than 20, even 15 ml kg^{-1} min^{-1} for many users (Figoni, 1984; Haisma et al., 2006; Tahamont et al., 1986). Additional constraints like cross slope (Cs) which is the slope that is perpendicular to the direction of travel, can thus degrade MWC user social life and state of health by increasing musculo-skeletal disorders (Burnham and Steadward, 1994; Mercer et al., 2006; Van Drongelen et al., 2006). Indeed, Cs causes gyratory action of the chair's front wheels, which generate a force that tends to pull the "subject-wheelchair" combination to the lower side and requires users to fight against this force in order to keep a straight course (Cooper, 1990; Van der Woude et al., 2001).

A 2% Cs limit is regulatory in many countries (McMillen et al., 1999), but this may not always be respected. Furthermore, no result really prompts justification of this 2% established Cs limit. In fact few studies have focused on MWC movements on a Cs. A recent review by Cooper et al. (2011) only lists five such studies. Three were mainly directed towards the biomechanical aspects of wheelchair propulsion (Brubaker et al., 1986; Chesney and Axelson, 1996; Richter et al., 2007). The other two addressed the problems of travelling on varied surfaces, some with a Cs, experienced by populations suffering from various pathologies (Longmuir et al., 2003; Kockelman et al., 2001). Only the Brubaker et al. (1986) and the Kockelman et al. (2001) studies included physiological measurements. Despite the disparity in these studies an overview reveals that Cs limits of between 16 and 20% for short distances (Chesney and Axelson, 1996) and for longer journeys, a 4% Cs is acceptable for all users and a more critical 10% limit should never be exceeded (Kockelman et al., 2001). These values are very far from the 2% regulatory limit (McMillen et al., 1999).

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With a view to proposing a rationalised allowable Cs, the present study sets out to determine the cardio-respiratory and subjective strains involved in MWC travel under real propulsion conditions on different Cs and at two travelling velocities for a large number of regular MWC users.

2. Equipment and methods

The study was conducted in the occupational physiology laboratory at the Institut National de Recherche et de Sécurité (INRS) jointly with the Institut Régional de médecine physique et de Réadaptation (IRR) both located in Nancy in the eastern part of France.

2.1. Subjects

The 25 volunteer subjects were recruited from patients monitored at the IRR, based on the following inclusion criteria: men, paraplegic, adult and of working age (18–65 years old), travelling independently and regularly in an MWC for more than 6 months. Injury level was defined as "high" for injuries at or higher than the 6th thoracic vertebra, and as "low" for injuries of the 7th thoracic vertebra or lower who have functional abdominal muscles. Subjects have no contraindication (cardiovascular, pulmonary, muscular, skin and/or developing general pathologies). They were informed of the study protocol and gave their written consent. The study received approval from the local ethical committee.

2.2. Protocol

Two tests were performed: a test involving sub-maximal exertion on an arm ergocycle and a propulsion track test. The arm cranking test was conducted on a first half-day dedicated to the study inclusion medical examination. A second full-day was dedicated to the track propulsion testing. At least two rest days separated the two test sessions to eliminate fatigue from the cranking test. Both tests were conducted under medical surveillance.

2.2.1. Cranking test

The sub-maximal arm cranking test was conducted on an arm ergocycle fitted with a magnetic induction braking system ensuring power control (Upper Body Cycle, Kardiomed®). This test allowed to estimate the peak oxygen uptake (VO_2max) of the subjects through extrapolating the relationship between HR and VO_2 to their HRmax (Paré et al., 1993). The test started with a 2-min, 25 W warm-up step before continuing in 2-min steps with an increase of 10 W per step. Pedalling frequency was 50 rotations per minute. The test was stopped when the subjects reached 85% of their theoretical maximum heart rate (HRmax = 220 − age in years) (Wilmore and Costill, 2004).

2.2.2. Propulsion test

The propulsion test was performed on a 50 m long test track specially designed for the study. Two opposite straights were each 24 m long and the subjects travelled back and forth on these. The track was 1.2 m wide in compliance with wheelchair route minimum width. The wooden track was covered with surfacing material (Tarasafe super, Gerflor®) with a dynamic friction coefficient of 0.4 (ua) close to that of an average asphalt pavement (0.38 u.a.). The track Cs was mechanically adjusted and checked using an electronic level (Laser Cross Liner Novipro, Bosch®).

The subjects were submitted to 8 experimental conditions combining 4 Cs (0, 2, 8 and 12%) and 2 velocities: one imposed (Vi = 0.97 m s^{-1}), the other so-called "comfortable" (Vc), chosen by the subjects themselves. Under each of the 8 conditions, the subjects undertook 6 laps (300 m) around the track; this distance insured physiological parameter stability (Wilmore and Costill, 2004). The order of testing of the 8 conditions was random. The propulsion method was free. The travelling direction conditions the dominant body side in the most demanding side i.e. in the steeper Cs. The subjects used their own MWC. Wheel diameter was 24 inches and tyres were inflated to a pressure of 8 bar.

The imposed velocity Vi (0.97 m s^{-1}), constant for the 4 Cs, was monitored by electroluminescent diodes fixed every 2 m along the walls bordering the test track. The subjects adjusted the travelling velocity based on delayed lighting of the diodes. The Vi and the Vc, chosen by the subject, were measured by timing at each lap. Temperature and relative humidity were measured for each half-day using a portable hygro-thermometer (RH70, Omega®).

2.3. Measured variables

The measured physiological parameters were heart rate (HR in bpm), oxygen uptake (VO_2 in ml kg^{-1} min^{-1}) and carbon dioxide production (VCO_2 in ml kg^{-1} min^{-1}). Subjective strain was assessed based on the Rating of Perceived Exertion (RPE) scale (Borg, 1998).

HR was measured continuously for the whole day using a cardio frequency meter (Polar®, S 810 i) with a count integration time of 15 s. Cardiac strain parameters were: a) the HR, b) the absolute cardiac cost (ACC in bpm), which is the difference between the mean HR during the test and the HR when seated and at rest, c) the relative cardiac cost (RCC in %), which expresses the percentage strain of the HR reserve (HRR), which is the difference between the subject's HRmax and his HR at rest (Wilmore and Costill, 2004). The RCC is determined by the ACC/HRR ratio.

Respiratory parameters were recorded using a cycle-to-cycle gas analyser telemetric system (Cosmed K4b^{2}®). The respiratory parameters processed were: a) the VO_2, b) the energetic cost per metre travelled and per kg weight (ECmkg in J m^{-1} kg^{-1}) and, c) the relative energetic cost (REC in %). The ECmkg is the product of the oxygen cost (cVO_2) by the energy equivalent of 1 L of oxygen (k in kJ l^{-1}) divided by the velocity and the weight (P = subject + MWC weight in kg); ECmkg = cVO_2 k/V.P. The oxygen cost (cVO_2 in ml kg^{-1} min^{-1}) is the difference between the mean VO_2 during the test and the VO_2 at rest. The energy equivalent of 1 L of oxygen is calculated using the equation $k = 16.6 + 4.6$ RQ, in which the respiratory quotient (RQ) is the ratio VCO_2/VO_2. The REC represents the fraction of the oxygen reserve involved in the exercise. REC is the ratio between the cVO_2 and the oxygen reserve (VO_2R), equal to $VO_2max - VO_2rest$ (Wilmore and Costill, 2004).

Subjective strain was obtained using the RPE scale (Borg, 1998). A global and 5 local assessments (back, shoulders, upper limbs) were asked for at the end of each track test.

2.4. Statistical analysis

Results are expressed by their mean and standard deviation (SD) shown in brackets for the 25 subjects. Student t tests on the paired samples allow us to analyse the effects of Cs on: travelling velocity (Vc and Vi), HR, VO_2 and subjective strains. Distribution normality was checked and achieved by variable transform if needed. Three-factor variance analyses (ANOVA) with correction for co-variable effects qualify the effects of Cs, velocity and injury level on the cardiac, energetic and subjective strains. Simple and multiple regression models based on the least square method were used to establish the relationships between the different variables. A 5% significance threshold was retained ($p < 0.05$). Statistical analyses were conducted using Statgraphics® Centurion XVI software.