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Torque and Power Outputs on Skilled and Unskilled Users during Manual Wheelchair Propulsion

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Abstract— **Manual wheelchair users are at a high risk of pain and injuries to the upper extremities due to mechanical inefficiency of wheelchair propulsion motion. The kinetic analysis of the upper extremities during manual wheelchair propulsion in various conditions needed to be investigated. We developed and calibrated a wheelchair dynamometer for measuring kinetic parameters during propulsion. We utilized the dynamometer to investigate and compare the propulsion torque and power values of skilled and unskilled users under four different conditions. Skilled manual wheelchair users generated lower torques with more power than unskilled users and reacted alertly and sensitively to changing conditions. We expect that these basic methods and results may help to quantitatively evaluate the mechanical efficiency of manual wheelchair propulsion.**

I. Introduction

Manual wheelchair users are at high risk of pain and injury to the upper extremities. Recent research has documented that repetitive motion and high loads during manual wheelchair propulsion were, at least in part, responsible for strain injury and pain [1,2]. Reducing mechanical inefficiency during wheelchair propulsion is crucial to decreasing physical strain and pain in daily life [3]. If the the mechanical efficiency of manual wheelchair propulsion is to be improved, insight into the underlying biomechanical mechanisms and kinetic as well as kinematic assessment are required [4]. For better understanding, the kinetic demands during propulsion, for various activities including these beyond the standard level require investigation [5].

Investigators have used their own devices, such as wheelchair treadmills, ergometers, and wheelchair dynamometers, which gave kinetic parameters about propulsion. These devices have the considerable advantage that subjects can be tested in their own personal wheelchairs, allowing for proper analysis of physiology, kinematics, and kinetics [6]. Dynamic calibration of the developed device has been emphasized in order to compare the results of one study to those of another. Determining the inertial and resistance components of the developed wheelchair dynamometer is indispensable [7].

The purpose of the present study is two-fold. First, we developed a torque-transducer-mounted inertial-type wheelchair dynamometer; then, we implemented a dynamic calibration test to characterize its properties. Secondly, we recruited experienced (skilled) and inexperienced (unskilled) manual wheelchair users as subjects for the propulsion motion analysis in order to compare their propulsion torques and powers.

II. Methods

A. Development and Dynamic Calibration of the Wheelchair Dynamometer

A simple inertia dynamometer was designed for this study (Fig. 1). The positions of its rollers were adjustable in compliance with the rear wheel size and the camber angle. The torque transducers (YDRM-50k, SETech, Korea) were mounted on each axis of the roller to record the torque. The moment of inertia of the fixed part was determined by using an acceleration test. Based on a linear regression of the weight as a function of the acceleration, the inertia was determined [7~9]. The total resistive torque for each subject was determined by using the coast-down test. Given the inertia values of the fixed part (rollers), the mobile part (flywheels), and the wheelchair wheel and an equation describing the speed as a function of time, we determined the resistance [6,7,10].

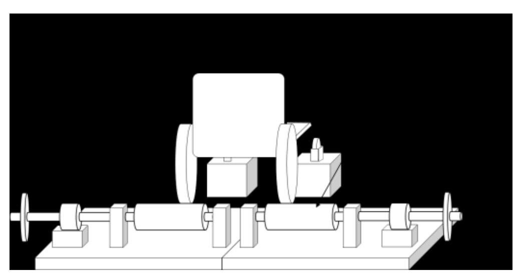

Figure 1. A wheelchair dynamometer developed for this study

B. Subjects and Experimental Protocol

Seven healthy volunteers with a mean height of 175.8±4.11 cm, mean mass of 72.62±5.88 kg, and mean age of 26.0±3.46 years were selected as unskilled wheelchair users. Four disabled volunteers with a mean height of 173.75±7.68 cm, mean mass of 67.75±11.76 kg, and mean age of 42.5±8.58 years were selected as skilled wheelchair users. No participants complained of injury or pain in their upper limbs. They were fully informed about the protocol and gave

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their informed written consent to participate in the experiment.

Each subject was asked to propel the wheelchair at a comfortable speed (slow) and maximum speed (fast) at each of two resistance loads. The load matching the original user-wheelchair system mass was the light load and that matching the 5 kg added to the user-wheelchair mass was the heavy load. In each trial, the subject propelled the wheelchair for 30 seconds (over 20 propulsion cycles). The data of ten propulsion cycles from the middle of each trial were collected for investigation. Subject motion and rear wheel kinematics were acquired at 250 Hz by using the VICON 612 system (Vicon system, Oxford Metrics Inc.). Analog outputs from the torque transducers on a dynamometer were synchronously collected at 1000 Hz with the motion data. Twenty-two retro-reflective markers were placed on the upper limbs, trunk, and head of each subject according to the Plug-In-Gait (PIG) model (Oxford Metrics) to determine the upper-limb-joint kinematics. Four additional markers were placed on the axle and the radial frame of the rear wheel of the wheelchair to determine the angular kinematics of the wheelchair.

C. *Statistical Analysis*

The general linear model for repeated measures (RMANOVA) in SPSS (SPSS Inc., IBM Company) was used to evaluate the main effect and the interaction of the factors in a complex mixed design, that had one between-subject factor and two within-subject factors at a significance level of 0.05. The Bonferroni corrected t-tests were used to evaluate the differences between mean values ($p \leq 0.05/n$, n=number of tests).

III. Results

A. *Temporal parameters*

Contact times, release times and linear velocities, averaged for each group and condition, are shown in Table I. They were significantly different from each other ($p<0.05$). The largest contact time was observed at the light-slow condition in both groups (unskilled: 0.35 s, skilled: 0.49 s). The largest linear velocity of the skilled group was observed at the heavy-fast condition (2.52 m/s); while that of the unskilled group was observed at the light-fast condition (1.87 m/s).

TABLE I. Mean values of the time and the speed parameters during a propulsion cycle

Load	Speed	Group	Contact time	Release time	Linear velocity
Light	Slow	Unskilled	0.35 (0.07)	0.48 (0.14)	0.99 (0.11)
		Skilled	0.49 (0.04)	0.74 (0.06)	0.89 (0.01)
	Fast	Unskilled	0.24 (0.04)	0.25 (0.08)	1.87 (0.14)
		Skilled	0.24 (0.01)	0.32 (0.04)	2.25 (0.04)
Heavy	Slow	Unskilled	0.32 (0.03)	0.53 (0.11)	1.05 (0.01)
		Skilled	0.37 (0.02)	0.62 (.04)	1.33 (0.01)
	Fast	Unskilled	0.26 (0.04)	0.28 (0.08)	1.81 (0.12)
		Skilled	0.24 (0.04)	0.23 (0.02)	2.52 (0.04)

a. Mean (sd)

B. *Propulsion Torque (Rear-wheel Torque of the Wheelchair)*

The magnitude of the maximum propulsion torque was the highest for the heavy-fast condition in both groups (unskilled: 19.21±1.99 Nm, skilled: 15.98±2.25 Nm) and was the smallest at the light-slow condition (unskilled: 12.47±1.08 Nm, skilled: 9.23±1.13 Nm). The maximum torque of the heavy-slow condition was larger than that of the light-fast condition (Table II). All the maximum torques of the unskilled group at each condition were larger than those of the skilled group (Figure 2 and 4(a)). The difference between the largest torque and the smallest torque of the unskilled group was similar to that of the skilled group.

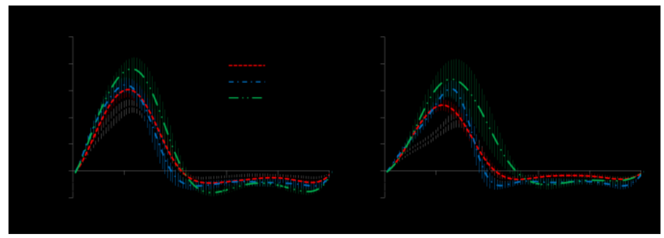

Figure 2. Mean propulsion torques for (a) unskilled and (b) skilled groups during manual wheelchair propulsion under four different conditions

C. *Propulsion Power (Rear-wheel Power of the Wheelchair)*

The magnitude of the maximum propulsion power showed patterns similar to the propulsion torque patterns (Table II), but the value for the unskilled group in the light-slow condition was larger than that of skilled users. The order of the maximum propulsion power was light-slow (unskilled: 0.28±0.06 J/s, skilled: 0.18±0.04 J/s), light-fast (0.34±0.05 J/s, 0.39±0.05 J/s), heavy-slow (0.55±0.05 J/s, 0.57±0.05 J/s), and heavy-fast (0.64±0.06 J/s, 0.80±0.07 J/s). There were also significant differences between groups and within groups (Figure 3 and 4(b)). The difference between the largest power and the smallest power of the skilled users was larger to that of the unskilled users.

TABLE II. Mean values of the maximum propulsion torque and power of the two groups at each condition

	Peak torque		Peak power	
	Unskilled	Skilled	Unskilled	Skilled
Light-Slow	12.47 (1.08)	9.23 (1.13)	0.28 (0.06)	0.18 (0.04)
Light-Fast	15.41 (1.48)	12.52 (1.25)	0.34 (0.05)	0.40 (0.05)
Heavy-Slow	16.47 (1.38)	15.13 (1.73)	0.55 (0.05)	0.57 (0.05)
Heavy-Fast	19.22 (1.99)	15.98 (2.25)	0.64 (0.06)	0.80 (0.07)

a. Mean (sd)

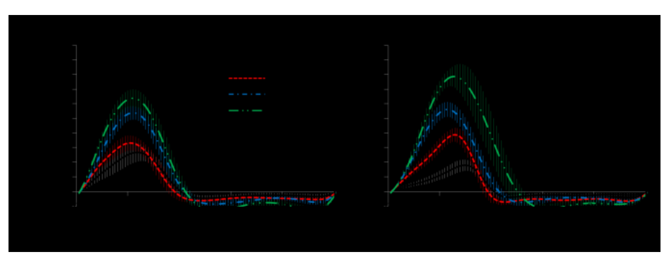

Figure 3. Mean propulsion powers for (a) unskilled and (b) skilled groups during manual wheelchair propulsion under four different conditions

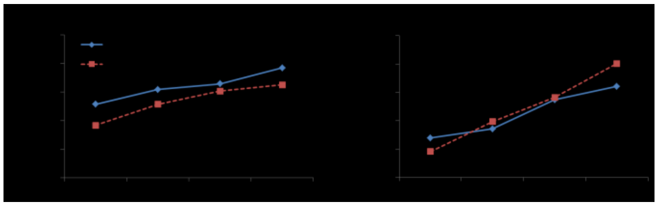

Figure 4. Maximum propulsion (a) torques and (b) powers during manual wheelchair propulsion under four different conditions

IV. Discussion and Conclusion

Variations in contact time, release time, and linear velocity of the skilled group were all larger than those of the unskilled group. Skilled wheelchair users seemed to react more alertly and sensitively to changes in conditions. They generated lower torques and more power than the unskilled group. Quick and significant manipulation ability to react to environmental changes is considered to be one of the important factors for efficient propulsion. Skilled subjects were all professional wheelchair tennis players with five or more years of experience. Therefore, we believe that they had optimal mechanical efficiency in using manual wheelchairs. We expect the basic methods and results of this study to help in evaluating quantitatively the mechanical efficiency of manual wheelchair propulsion.

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