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An electronic device to measure drive and recovery phases during wheelchair propulsion: A technical note

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Abstract—Using cinematography to identify the drive and recovery phases in wheelchair racing, it has been reported that the drive phase was approximately 33% of each propulsive cycle time, with remaining time devoted to the recovery phase. In this study, an electronic timing device has been developed to accurately measure the drive phase time and recovery phase time in each cycle of wheelchair racing. Seventeen wheelchair athletes with national and/or international racing experience were tested on four selected speeds. It was found that the drive phase was approximately 23% of each cycle time during wheelchair racing. The drive phase time decreased in each propulsive cycle as speed increased from 30 to 90% of the peak speed.

Key words: *cinematography, cycle time, drive phase, electronic timing, recovery phase, wheelchair propulsion.*

INTRODUCTION

Wheelchair propulsion, a basic and critical technique in wheelchair locomotion, is commonly divided into two phases, the drive phase and recovery phase, in each complete propulsive cycle (1–3). The drive phase is defined as the force production phase when the hand is in contact with the pushrim and applying a propulsive force. The recovery phase is the nonpropulsive phase when the hand is not in contact with the pushrim and is being positioned to restart the drive phase (1,2). Wheelchair propulsion is accomplished by the simultaneous repetitive action of the two upper extremities through both phases.

The force and torque applied to the pushrim during wheelchair propulsion have been studied intensively (4–8). Asato, Cooper, Robertson, and Ster (4) developed a system, SMART^{Wheels}, to detect the pushrim force and torque in the drive phase and indicated that there was a close agreement between the kinetic results and kinematic results during wheelchair propulsion. Brubaker, McLaurin, Gibson, and Soos (5), and Van Der Woude, Veeger, and Rozendal (8) investigated the relationship between torque and velocity and the effects of seat position during wheelchair propulsion. Strauss, Maloney, Ngo, and Phillips (6), and Strauss, Moeinzadeh, Schneller, and Trimble (7) developed a dynamic system to measure the linearity of torque during wheelchair propulsion. However, the drive phase time and the recovery phase time have been mainly studied with cinematography. Using traditional cinematography, it has been reported that the drive phase is approximately one third of the cycle time in a cycle of wheelchair propulsion while the remaining time is devoted to the recovery phase (2,3,9). In these studies, the two phases were determined by observing the film/video and noting when the hand made or broke the contact with the pushrim. The accuracy of the cinematographic method being used to identify the drive and

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recovery phases may have been questionable since there were usually several frames which were rather difficult to assign to either drive or recovery phase. Accurate measurement of these phases would help us understand how the wheelchair propulsion movement is being performed in wheelchair racing.

The purpose of this study is two-fold: to develop an electronic timing device to accurately measure the drive and recovery phases of wheelchair propulsion, and to determine how the ratio of the drive and recovery phases changes as speed increases in wheelchair racing.

METHODS

In order to differentiate the drive and recovery phases in a cycle during wheelchair propulsion, an electronic timing device was built to determine when the hand was in contact with the pushrim. Three-wheel racing chairs were used in the test. The diameters of the pushrims ranged from 34.0 to 38.3 cm and the diameters of the wheels ranged from 60.8 to 66.2 cm. A roller system fitting all the racing wheelchairs was used in this investigation. This roller system provided adjustable friction (resistance) to simulate the road conditions encountered in wheelchair racing, based upon a mean resistance estimated by the subjects.

Subjects

Seventeen wheelchair athletes (10 male, 7 female) with national and/or international wheelchair racing experience served as subjects; each signed a consent form indicating his/her voluntary participation. The ages of subjects ranged from 19 to 38 years, their injury levels from T-5 (the fifth thoracic vertebra) to L-2 (the second lumbar vertebra).

Electronic Timing Device

The schema of the electronic timing device is presented in **Figure 1.** This device consists of an IBM computer equipped with an analog-digital board, a light emitting diode (LED) box with four LEDs, two AA batteries, a leather glove, a racing wheelchair, copper tape, copper wire, and a spring wire. Fine copper wires (stripped 22 AWG alarm wire) were wrapped around the circumference of the pushrim and connected to the spokes fixed to the axis of the wheel. The spring wire made contact with the wheel axle underneath the seat. Thin copper tape (0.1 mm thick and 3.81 cm wide) was applied separately to the thumb and first fingers of the

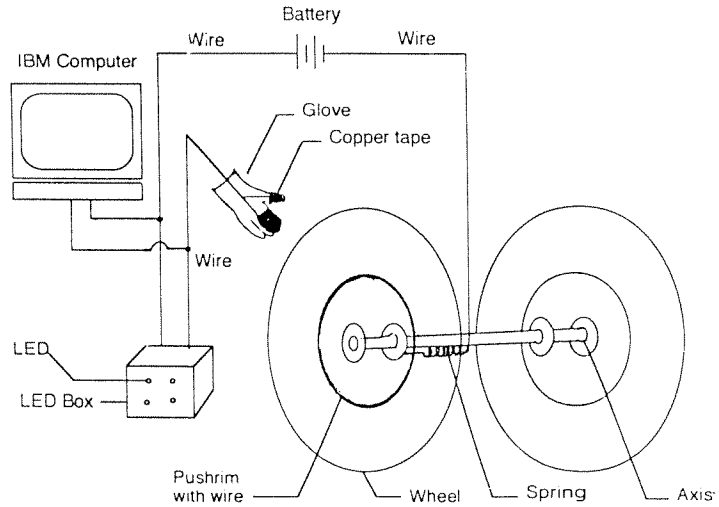

Figure 1.
A schema of an electronic timing device to measure the contact and noncontact time during wheelchair propulsion.

right-hand glove. The thumb contact was wired to the two top LEDs; the contacts of the index and middle fingers were wired to the two bottom LEDs of the LED box, which was wired to the battery pack and the remainder of the circuit. The computer takes its input through a parallel connection across the LED box.

This timing device is an open circuit before the hand touches the pushrim. Once any finger(s) touches the rim, the circuit is closed and the LEDs turned on during the drive phase. This contact timing signal is simultaneously sent to the computer and sampled at a frequency of 200 Hz. Therefore, the contact time between the fingers and the pushrim is known, and which finger is touching the pushrim is also known.

Validity and Reliability of the Electronic Timing Device

Two digital clock/counters (model 54035, Lafayette Institute Co., Inc., Lafayette, IN) were used to test the validity and reliability of this circuitry. The accuracy of the digital clock/counters is ± 1 ms. One digital clock/counter was connected to the electronic device (**Figure 1**) in place of the computer. That digital clock/counter was designated the "long circuit clock" (LCC). Another digital clock/counter was directly connected to the glove and the pushrim and designated the "short circuit clock" (SCC). Once the glove contacts the pushrim, both the LCC and the SCC record the time: the output of the two may be compared for agreement to serve as a check of the entire circuit's reliability.

In the test, the contact made between the glove and pushrim during wheelchair propulsion may be very short or maintained for several revolutions. The test was conducted in 2 consecutive days and 15 trials were performed each day. The results of test from Day One and Day Two are presented in **Table 1.** The time differences in ms between the LCC and SCC in Day One and Day Two ranged from 0.000 to 0.002 seconds. These differences included ±0.001 seconds (1 ms) accuracy error of the digital clock/counters. The mean time error over 15 trials on Day One was 0.53 ms (0.00053 seconds) and on Day Two it was 0.47 ms (0.00047 seconds). The correlation coefficient between LCC and SCC on Day One was R(X1·Y1)=1.000 and on Day Two R(X2·Y2)=1.000. These correlation coefficients indicated that our basic timing circuitry is very consistent and reliable; using it to test the drive and recovery phases during wheelchair propulsion is valid.

Experimental Procedure

Following a 15-minute warm-up of pushing the wheelchair on the roller, each subject's peak speed was measured by an electronic chair speed meter and four relative speeds—90, 70, 50, and 30 percent of the peak speed—were calculated for each subject. Based on the racing experience of the wheelchair athletes and coaches, 85 to 90 percent of the individual peak speed is close to the sprinting speed that wheelchair racers can achieve under racing conditions. The order of these four speeds was randomly assigned to each subject. When a subject pushed his/her wheelchair on the roller, the wheel speed was indicated by the speed meter. Once he/she reached the target speed (±2 percent) and maintained this speed stably, the computerized electronic timing device collected data for 5 seconds. If the wheel speed, monitored by the experimenter, was off the target speed during the data collection, the trial was restarted. One trial at each of the four speed conditions was recorded with a 3-minute interval between the trials.

Table 1.
Time data (in seconds) and correlation coefficients between the long circuit clock (LCC) and short circuit clock (SCC) on two consecutive days.

Trial	Day 1 LCC X1	SCC Y1	Diff X1-Y1	Day 2 LCC X2	SCC Y2	Diff X2-Y2
1	1.506	1.506	0.000	1.430	1.431	0.001
2	1.125	1.125	0.000	0.504	0.505	0.001
3	1.309	1.309	0.000	0.360	0.363	0.000
4	3.111	3.112	0.001	0.626	0.626	0.000
5	5.814	5.815	0.001	0.180	0.180	0.000
6	2.260	2.260	0.000	0.239	0.239	0.000
7	3.308	3.309	0.001	0.318	0.318	0.000
8	0.535	0.535	0.001	3.163	3.163	0.000
9	5.765	5.766	0.001	0.599	0.601	0.002
10	2.041	2.041	0.000	0.575	0.575	0.000
11	0.189	0.190	0.001	1.130	1.131	0.001
12	3.170	3.170	0.000	0.647	0.648	0.001
13	0.015	0.015	0.000	2.362	2.362	0.000
14	0.020	0.020	0.000	0.065	0.066	0.001
15	0.910	0.912	0.002	0.524	0.524	0.000
Mean error:			0.00053			0.00047
Correlation coefficient:		R(X1·Y1) = 1.000 ($p<0.01$)			R(X2·Y2) = 1.000 ($p<0.01$)	

Diff=Difference.

Data Treatment

Starting from the first drive phase, three complete cycles of wheelchair propulsion under each speed condition were selected from the computerized cycle timing data, since only three or four complete cycles could be obtained at the lowest (30 percent) speed condition. Then the time and respective percentages of the drive and recovery phases of each cycle were calculated.

RESULTS

The descriptive cycle data in the drive and recovery phases on the four speed conditions are presented in **Table 2.** The actual speed was 2.61 m/s at the 30 percent and 7.82 m/s at the 90 percent speed condition. The cycle time ranged from 1.097 to 0.579 seconds, and the cycle rate ranged from 0.912 to 1.727 cyc/s as the speed conditions increased from 30 to 90 percent. At the 30 percent speed condition the drive phase time was 0.386 seconds which was 35.6 percent of the cycle time. At the 90 percent speed condition this time value decreased to 0.134 seconds which was 23 percent of the cycle time. A similar trend was found in the recovery phase time as the speed condition increased from 30 to 90 percent. The decreased cycle time was a result of decrease in both the drive phase time and the recovery phase time. With the increase in cycle rate, the drive phase became a smaller percentage in each cycle time while the recovery phase became a higher percentage.

DISCUSSION

As mentioned above, 90 percent of individual peak speed is close to a racing speed. With the measurement from this electronic timing device, the main difference between the present study and the previous studies was the time ratio of the drive and recovery phases in each propulsive cycle. In the previous studies, it was reported that the drive phase was about 33.3 percent of each cycle during wheelchair racing (2,3,9,10). The drive time in the present study was about 10 percent less than those found in the previous studies.

The drive times reported in the earlier studies were determined by counting the number of film/video frames based on the observation at a lower sampling frequency (30–150 Hz). It was evident that several film/video frames were rather difficult to identify as to whether they belonged to the drive phase or the recovery phase. The technique used in this study measures contact time (drive phase) directly with an

Table 2.
The descriptive cycle data in the drive and recovery phases on the four speed conditions.

% of Peak	Speed (m/s)	Cycle (s)	Time/Rate (cyc/s)	Drive (s)	Phase (%)	Recovery (s)	Phase (%)
30%							
M	2.61	1.097	0.912	0.386	35.6	0.711	64.4
SD	0.31	0.167	0.139	0.075	6.6	0.157	6.6
50%							
M	4.36	0.777	1.287	0.236	30.7	0.541	69.3
SD	0.51	0.083	0.137	0.037	5.5	0.089	5.5
70%							
M	6.09	0.666	1.502	0.176	27.0	0.490	73.0
SD	0.72	0.073	0.165	0.028	6.5	0.087	6.5
90%							
M	7.82	0.579	1.727	0.134	23.5	0.445	76.5
SD	0.23	0.054	0.161	0.027	5.4	0.064	5.4

n=51; s=second; m/s=meters per second; cyc/s=cycles per second; M=Mean; SD=Standard deviation.

electronic circuit at a higher sampling frequency of 200 Hz. Therefore, the difference of the time ratio of the drive and recovery phases between the present study and the previous studies may be due to the measurement techniques. However, this difference also may be due to some other factors, such as chair style, seating position, power output demands, training experiences, and the modification of the wheelchair propulsion techniques.

Although both the drive and recovery times decreased as the speed increased from 30 to 90 percent of peak (**Table 2**), the drive time decreased more rapidly (65.3 percent = [0.386−0.134]/0.386) from the 30 to 90 percent speed conditions than did the recovery time (37.4 percent = [0.711−0.445]/0.711). Thus the drive time decreased 27.9 percent faster than the recovery time as speed increased. The differences of time and percentage time between the drive and recovery phases on the four speed conditions are presented in **Figure 2.**

Walsh (11), Siler, Martin and Mungiole (10) stated that to increase velocity during wheelchair racing, the hand should stay on the rim path as closely as possible in the recovery phase, and the recovery phase should be executed as quickly as possible. The results from this study demonstrated that as speed increased, executing the drive phase quicker than the recovery phase is more important: executing the drive phase as quickly as possible would generate a higher speed in wheelchair racing. The relationships of the actual speed (m/s) to the drive phase time and to the recovery phase time are shown in **Figure 3.**

Both the drive phase and recovery phase times as a function of the actual speed (generated from the four speed conditions) showed the similar curvilinear relationships. The correlation coefficient between the speed and drive phase times was 0.957, and between the speed and recovery phase times was 0.918. As speed increased from 50 to 90 percent of the peak speed, more linear relationships of the speed to the drive phase time and to the recovery phase time can be observed in **Figure 3.**

With this electronic timing device, the finger(s) contacting the pushrim could be identified during the drive phase. The pattern of fingers contacting the pushrim during wheelchair propulsion is shown in **Figure 4.** It was interesting to find that the thumb always contacted the pushrim earlier than the index and middle fingers during wheelchair propulsion as speed varied. At the 90 and 70 percent speed conditions, the thumb contacted the pushrim about 25 ms earlier than the index and middle fingers did at the initial contact of the drive phase. At the 50 and 30 percent speed conditions, the thumb was about 35 ms earlier in contacting the pushrim than the index and middle fingers were. At the end of the drive phase, the thumb, index, and middle fingers released from the pushrim almost at the same time (within 5 ms).

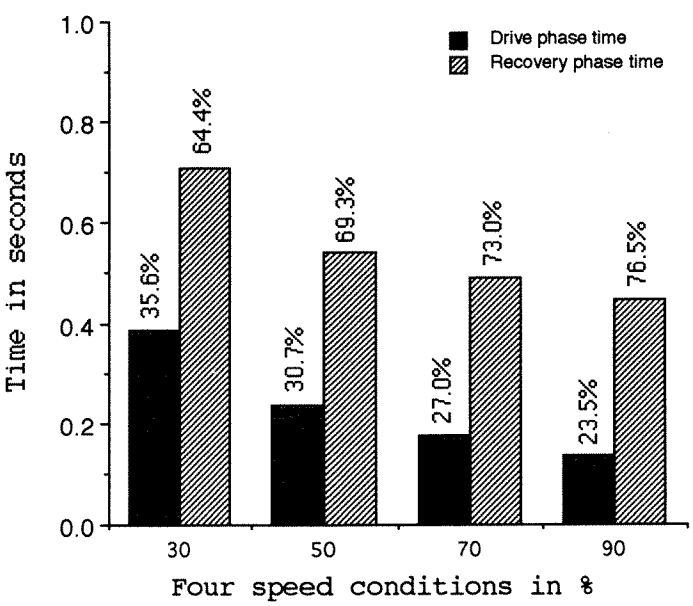

Figure 2.
Time and percentage time in the drive and recovery phases across four speed conditions.

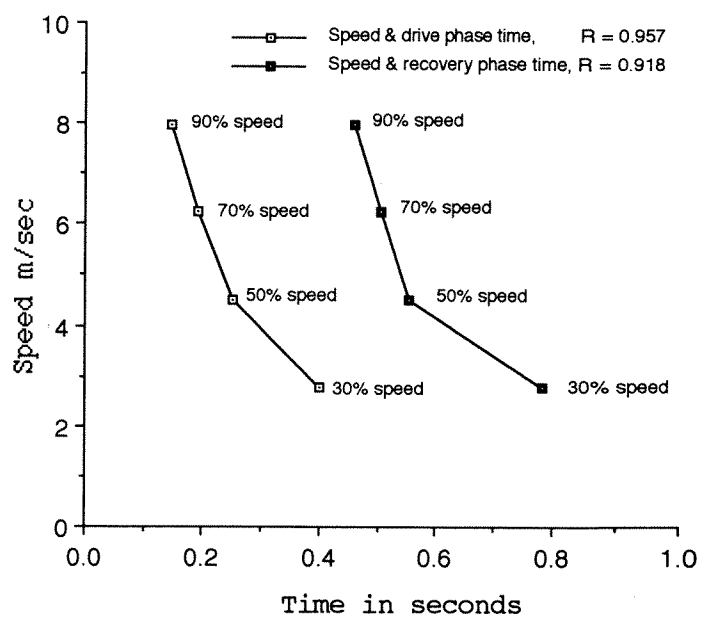

Figure 3.
Relationships of speed (generated from the four speed conditions) to the drive phase time and to the recovery phase time.

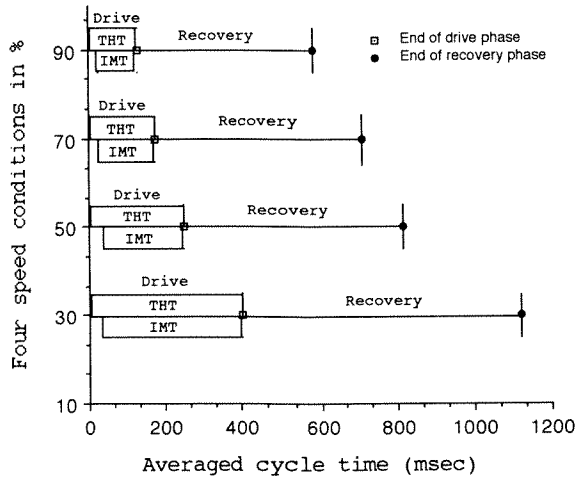

Figure 4.
Finger contact and noncontact time in the drive and recovery phases in each propulsive cycle under the four speed conditions. THT = thumb contact time; IMT = index and middle finger contact time.

In summary, this electronic timing device is an accurate means of measuring the drive and recovery phases during wheelchair propulsion. The drive phase was approximately 23 percent of each cycle time during wheelchair racing. The drive phase time decreased in each propulsive cycle as speed increased from 30 to 90 percent of the peak speed. However, the drive phase time as a percentage of the complete push cycle time decreased as speed increased. The thumb contacting the pushrim earlier than index and middle fingers may be a strategy of pushing a chair during wheelchair racing.

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