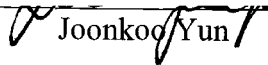AN ABSTRACT OF THE THESIS OF

Sanae Asahara for the degree of Master of Science in Movement Studies in Disability presented on September 23, 2004
Title: Kinematic Characteristics and Energy Expenditure during Manual Wheelchair Propulsion: A Comparison of Two Stroking Techniques in Non-experienced Users

Abstract approved: ___-Redacted for privacy___
Joonkoo Yun

Manual wheelchair propulsion is a physiologically stressful and biomechanically inefficient form of locomotion. The repetitious nature of propulsion puts wheelchair uses at high risk for developing upper extremity overuse injuries. Previous kinematic analysis has revealed that wheelchair users employ several distinct stroking techniques. One of the techniques, circular pattern (CP), may be recommended to prevent injuries in the upper extremity because of lower cadence, greater ratio of push time to recovery time, and lower joint accelerations. However, another technique, single-loop over pattern (SLP) is most commonly used among actual wheelchair users. A possible reason for this was that SLP may be related to lower energy expenditure required for propulsion. Organisms have a natural tendency, which is self-optimization process of motor performance. A movement pattern is adapted to minimize metabolic energy expenditure. SLP may result from this process. The purpose of this study was to examine the kinematics and energy expenditure of two stroking techniques (CP and SLP) after training non-experienced wheelchair users.

Sixteen participants completed a three-week training session for each stroking technique, CP and SLP, and were tested on their kinematics and energy expenditure

after each training session. They performed six-minutes of propulsion at a velocity of 0.9m/s. Three-dimensional motion capture data were collected at three and a half minutes to compute the kinematic variables: cadence (cycles/s), ratio of push time to recovery time, joint motion in the shoulder, elbow and trunk. Metabolic data were collected during the second three minutes of each trial, using a metabolic cart system.

Repeated measures MANOVA revealed a significantly lower cadence ($F(2,14)$ = 4.74, p < .05) and greater ratio of push time ($F(2,14) = 18.47$, p < .01) in CP than in SLP. No significant differences were found in the joint motion except a greater peak acceleration of elbow flexion in SLP ($F(2,14) = 6.82$, p <.02). Energy expenditure showed no differences between CP and SLP. No significant correlations were found between the joint motion and energy expenditure.

This study confirmed that CP may be beneficial propulsion technique for manual wheelchair users in terms of stroke cadence. CP had the same amount level of energy expenditure as SLP, but CP had a lower task frequency that is related to a reduction in the risk of overuse injuries. Further studies should examine mechanical efficiency in order to identify a more efficient technique. Also, more investigations are needed to reveal associations between physical function and stroking techniques. Reasons why more wheelchair users employ SLP were not answered in this study.

Kinematic Characteristics and Energy Expenditure
during Manual Wheelchair Propulsion:
A Comparison of Two Stroking Techniques in Non-experienced Users

by
Sanae Asahara

A THESIS

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APPROVED:

.Redacted for privacy

Major Professor, representing Movement Studies in Disability

Redacted for privacy

Chair of the Department of Exercise and Sport Science

Redacted for privacy

Dean of the Graduate School

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Sanae Asahara, Author

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Mikako, my best friend, thanks for sending me many letters, e-mails, calls and gifts far from Japan for this past two years. Your kindness gave me so much encouragement and fun. Thanks to my aunt and cousin, Mitsu and Masami, for sending me lots of things that really encouraged me.

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CONTRIBUTION OF AUTHORS

Dr. JoonKoo Yun and Dr. Michael Pavol were involved in designing the experiment, the data collection, data analysis, and writing of this manuscript.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

LIST OF APPENDIX FIGURE AND TABLE

KINEMATIC CHARACTERISTICS AND ENERGY EXPENDITURE DURING MANUAL WHEELCHAIR PROPULSION: A COMPARISON OF TWO STROKING TECHNIQUES IN NON-EXPERIENCED USERS

CHAPTER I

INTRODUCTION

BACKGROUND

Manual wheelchairs have been used as an essential locomotive device and as a piece of sport equipment for the past five decades. There are over 1.4 million wheelchair users in the United States, and about 75% of them use manual wheelchairs (Stakeholders Forum, 2003). Regular use of manual wheelchairs has been recommended because of two major advantages: the improvement of health and financial benefits. It has been found that manual wheelchair propulsion brings about improvement of physical work ability, such as cardiovascular capacity (Tordi, Gimenez, Predine, & Rouillon, 1998; van der Woude, Croonenborg, Wolff, Dallmeijer & Hollander, 1999). Hooker and Wells (1989) reported that wheelchair ergometer exercise decreased the blood lipid level of those with spinal cord injury. Tahamont et al. (1986) observed that long-term use of wheelchairs contributes to maintaining the level of activity in the daily living of persons with ambulatory disabilities. As a financial benefit, it is less expensive to possess and to manage manual wheelchairs than powered wheelchairs. In addition, manual wheelchairs are more compact to maneuver and to transport (Snowbeck, 1998; Stakeholders Forum, 2003).

Despite the benefits of manual wheelchair use, there are disadvantages to users (Koontz & Boninger, 2003; Veeger, Rozendaal & van der Helm, 2002; van der

Woude, Veeger, Dallmeijer, Janssen & Rozendaal, 2001). From a physiological viewpoint, numerous studies have indicated that manual wheelchair propulsion is a mechanically inefficient form of human locomotion, compared to other forms such as walking and cycling (Glaser, Sawka, Wilde, Woodrow & Suryaprasad, 1981; Veeger, van der Woude & Rozendaal, 1992). Due to its higher energy cost, manual wheelchair propulsion requires a higher level of energy cost (Muhkerjee, Bhowik & Samanta, 2002; Sawka, Glaser, Wilde & von Luhrte, 1980; van der Woude, van Kranen, Ariens, Rozendal & Veeger, 1995). Wheelchair users experience higher physical strain in their daily physical activity (Janssen, van Oers, van der Woude & Hollander, 1994). Physical strain is associated with fatigue and discomfort, and it leads to a decrease in the locomotive ability of wheelchair users (van der Woude, Veeger, Boer & Rozendal, 1993).

From a biomechanical view of point, the repetitious nature of propelling a wheelchair is associated with a high incidence rate of upper extremity overuse injuries (Bayley et al., 1987; Curtis et al., 1999; Newsam et al., 1999; Nichols, Norman & Ennis, 1979; Sie, Waters, Adkins & Gellman, 1992). Approximately 30-75% of wheelchair users have shoulder problems and/or carpal tunnel syndrome (Stakeholders Forum, 2003). The prevalence of rotator cuff tendonitis and carpal tunnel syndrome in the general population is approximately 3%, while that in wheelchair users is greater than 50% (Snowbeck, 1998). Since wheelchair propulsion imposes weight-bearing activities on the upper extremity, the shoulder and wrist of wheelchair users are overloaded and have pain (Curtis et al., 1999). Injuries of the upper extremity may lead to a decrease in mobility and activity level of wheelchair users (Janssen et al.,

1994). This vicious cycle in wheelchair propulsion can affect the health status and the quality of life of wheelchair users (Janssen et al., 1994).

In order to find proper propulsion techniques to prevent the vicious cycle, biomechanics researchers have investigated stroke patterns of manual wheelchair users. A few recent kinematic studies have identified that wheelchair users employ several types of stroke patterns, including the (a) circular pattern (CP), (b) single-loop over pattern (SLP), (c) double-loop over pattern (DLOP), and (d) pumping pattern (PP) (Boninger et al., 2002; Shimada et al., 1998). Figure 1 illustrates the uniqueness of the four distinct wheelchair stroke patterns described in the literature.

Figure 1: The Four Wheelchair Propulsion Patterns described in the literature

| CP | SLP | DLOP | PP |
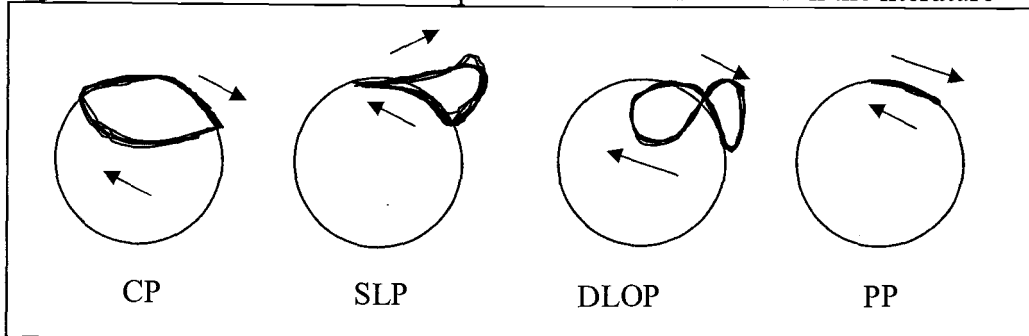
(Boninger et al., 2002; Shimada et al., 1998)

Shimada et al. (1998) first classified these stroke patterns and reported that CP was more beneficial because of the lower cadence (stroke frequency), the greater ratio of push time relative to the recovery time (% push time), and the lower joint accelerations at the shoulder and elbow. Boninger et al. (2002) examined similar kinematic variables in a larger number of subjects with paraplegia. They also found that CP showed a lower cadence and a greater ratio of push time. Shimada et al. (1998) and Boninger et al. (2002) concluded that CP may be recommended for preventing upper extremity injuries.

However, CP is not commonly used among wheelchair users. The most common stroking technique is SLP (Boninger et al., 2002; Koontz & Boninger, 2003). In Boninger et al.'s (2002) study with 38 users, 45% of users were employed SLP. There could be several reasons why SLP is commonly used. One possible explanation may be associated with energy expenditure.

Sparrow & Newell (1998) argued that energy expenditure is considered as a primary factor for regulating the coordination and control of movement. Movement patterns are adapted to minimize metabolic energy cost. This tendency is widely recognized as a natural selection mechanism to optimize movement economy (Anderson, 1996; Schot & Decker, 1998). Sparrow and Irizarry-Lopez (1987) stated that movement patterns represented by kinematics would be adapted in response to metabolic energy expenditure. From this point of view, wheelchair users may have a tendency to reduce their energy expenditure during propulsion, and their limb motions of propulsion may be changed to minimize energy expenditure. SLP may be an outcome of this natural process of developing motor performance. If SLP required a lower level of energy expenditure for propulsion, more individuals may prefer to use SLP. It is necessary to characterize wheelchair stroking techniques not only by kinematics but also by energy expenditure.

RATIONALE

Individuals who use a manual wheelchair seek a more efficient propulsion technique for their mobility (Stakeholders Forum, 2003). Professionals have indicated the necessity and importance of developing training guidance on how best to propel a

wheelchair to reduce energy expenditure and the risk of upper extremity injuries for wheelchair users (Boninger et al., 2002; Dallmeijer, van der Woude, Veeger & Hollander, 1998; Koontz & Boninger, 2003; Shimada et al., 1998; van der Woude, Botden, Vriend & Veeger, 1997). Therefore, there is a strong need for investigating efficient propulsion techniques. However, there are very few studies that have investigated kinematics and metabolic energy together. No studies have done training on specific stroking techniques as presented above.

The purpose of this study was to examine the kinematic characteristics and energy expenditure after training non-experienced users in two manual wheelchair stroking techniques: the circular pattern (CP) and the single loop over pattern (SLP). Outcomes from this study may provide information to wheelchair users and instructors for considering a more efficient propulsion technique, which would lead to an increase in mobility and quality of life.

RESEARCH QUESTIONS

The following questions were answered in this study:

1) After training, were there any significant differences between CP and SLP in the kinematics of the upper extremity?

2) Was there a significant difference in energy expenditure between CP and SLP?

3) Were there any significant correlations between the joint motions of the upper extremity and energy expenditure during CP and SLP?

HYPOTHESES

1) H_0: There was no difference between CP and SLP in the kinematics

   H_1: There was a significant difference between CP and SLP in the kinematics

   H_0: μ CP kinematics = μ SLP kinematics

   H_1: μ CP kinematics $\neq$ μ SLP kinematics

2) H_0: There was no difference between CP and SLP in energy expenditure

   H_1: There was a significant difference between CP and SLP in energy expenditure

   H_0: μ CP energy expenditure = μ SLP energy expenditure

   H_1: μ CP energy expenditure $\neq$ μ SLP energy expenditure

3) H_0: There was no correlation between joint motion and energy expenditure

   H_1: There was a significant correlation between joint motion and energy expenditure

ASSUMPTIONS

1. All participants mastered an assigned wheelchair propulsion pattern.

2. All participants performed their best during training.

3. All participants had no considerable physical problems during this study.

4. The speedometer displayed the accurate velocity of wheelchair propulsion, and participants were able to propel a wheelchair at the constant speed.

DELIMINATIONS

The study was delimited as follows:

1. Participants in this study were volunteers with ages ranging from 19 to 27 years from Oregon State University (OSU).

2. Propulsion was performed on a wheelchair roller in the Biomechanics Laboratory at OSU.

3. This study used non-customized wheelchairs.

4. Participants propelled a wheelchair at a specified speed (0.9 m/s).

LIMITATION

The following factors were limitations for this study:

1. The pushing mechanism of non-experienced wheelchair users may be different from those of actual wheelchair users.

CHAPTER II

KINEMATIC CHARACTERISTICS AND ENERGY EXPENDITURE DURING MANUAL WHEELCHAIR PROPULSION: A COMPARISON OF TWO STROKING TECHNIQUES IN NON-EXPERIENCED USERS

Sanae Asahara

Department of Exercise and Sport Science
Oregon State University, Corvallis, Oregon

ABSTRACT

Purpose. This study was designed to examine the kinematic characteristics and energy expenditure in two types of manual wheelchair stroking techniques.

Methods. Sixteen participants (non-experienced wheelchair users) completed a three-week training session for each stroking technique, circular pattern (CP) and single-loop over pattern (SLP). After each training session, the participants were tested on their kinematics and energy expenditure, by using a three-dimensional motion capture system and a metabolic cart system. The obtained kinematic data was stroke cadence (cycles/s) and ratio of push time to recovery time, and joint motion (range of motion, peak range of motion and peak joint acceleration) at the shoulder, elbow and trunk.

Results. CP showed a significantly lower cadence and a greater ratio of push to recovery time than SLP, $F(2, 14) = 4.74$, $p < .05$ and $F(2, 14) = 18.47$, $p < .01$, respectively. Repeated measures MANOVA revealed a significant difference between CP and SLP in the shoulder and elbow joint motion, $F(5, 11) = 7.36$, $p < .01$ and $F(4, 12) = 7.11$, $p < .01$, respectively. The follow-up univariate tests indicated a significant difference between CP and SLP in only one variable, peak joint acceleration in elbow flexion ($F = (2, 14) = 6.82$, $p < .05$). No significant difference was found in energy expenditure between CP and SLP. Pearson correlation coefficient analysis showed no correlations between the joint motion and energy expenditure both in CP and SLP.

Conclusion. CP may be more beneficial to reduce the risk of upper extremity injuries, but did not appear to be a more efficient technique than SLP in terms of energy expenditure.

INTRODUCTION

Wheelchairs are essential locomotive devices for many individuals with ambulatory disabilities. Manual wheelchair use has more benefits than powered wheelchair use in health maintenance. Manual wheelchair propulsion exercise and/or regular use contributes to maintaining higher levels of physical activity in daily life and improveing physical capacity (Tahamont, Knowlton, Sawka & Miles, 1986; Tordi, Gimenez, Predine & Rouillon, 1998; van der Woude, Croonenborg, Wolff, Dallmeijer & Hollander, 1999). On the other hand, manual propulsion has disadvantages for wheelchair users in the aspects of physiology and biomechanics. Previous studies reported that manual wheelchair propulsion is physically strenuous due to mechanical inefficiency (Glaser, Sawka, Wilde, Woodrow, & Suryaprasad, 1981; van der Woude, van Kranen, Ariens, Rozendal & Veeger, 1995). In addition, the repetitive nature of manual propulsion is associated with a high incidence of upper extremity overuse injuries (Boninger, Cooper, Baldwin, Shimada & Koontz, 1999; Curtis et al., 1999). Surveys have found that 30-73 % of wheelchair users have shoulder injuries or pain (Bayley et al., 1987; Barber, Janus & Wade, 1996; Nicholas, Norman & Ennis, 1979). In addition, over 50% of users have experienced complaints of carpal tunnel syndrome (Boninger et al., 1999; Sie, Waters, Adkins & Gellman, 1992). Information on proper propulsion techniques is a critical need for wheelchair users (Curtis, 1997; Koontz & Boninger, 2003; Veeger, Rozendaal & van der Helm, 2002).

A few recent kinematic studies have analyzed the hand trajectories during propulsion and identified that wheelchair users employed at least four distinct stroke patterns: (a) circular pattern (CP), (b) single-loop over pattern (SLP), (c) double-loop over patter (DLOP), and (d) pumping pattern (PP) (Boninger et al., 2002; Koontz & Boninger, 2003; Shimada, Robertson, Boninger & Cooper, 1998). CP is characterized by a circular hand trajectory passing below the handrim. Kinematics measured in their studies revealed that CP showed a lower cadence, a greater ratio of push time to recovery time, and lower joint accelerations (Koontz & Boninger, 2003). Based on the biomechanics, the researchers suggested that CP may be recommended as a propulsion technique to reduce the risk of injuries (Boninger et al., 2002; Koontz & Boninger, 2003; Shimada et al., 1998). However, CP did not appear to be a technique commonly used among wheelchair users. In Boninger et al.'s study (2002), the most common pattern observed was SLP, which has a hand trajectory of loop above the handrim.

A possible reason for SLP being widely used may be related to energy expenditure. Human organisms tend to minimize their metabolic energy cost when they learn motor tasks or skills (Anderson, 1996; Schot & Decker, 1998; Sparrow & Irizarry-Lopez, 1987; Sparrow & Newell, 1998). SLP may be an outcome of a natural selection mechanism to reduce energy expenditure. No studies have done training on particular stroke techniques to measure kinematics and energy expenditure together.

The purposes of this study were (a) to compare the kinematic characteristics between the CP and SLP techniques after training non-experienced wheelchair users; (b) to compare energy expenditure between CP and SLP after training; and as the

secondary purpose, (c) to investigate correlations between the kinematics and energy

expenditure in CP and SLP.

METHODS

Participants

Nineteen participants were recruited as volunteers via posted advertisements

from the Oregon State University (OSU) campus, Corvallis, Oregon (Appendix B).

Two of them withdrew their participation from the experiment due to a scheduling

conflict. Another could not be correctly tested because of a failure of the experimental

system. Sixteen participants (9 men, 7 women) completed the whole training and

testing protocols. Table 1 summarizes the participants' demographic information.

Table 1: Participant Characteristics (N = 16)

	Mean	SD	Min.	Max.
Age (years)	22.5	2.73	19	27
Height (cm)	174.83	9.23	162.3	198.0
Body mass (kg)	72.49	14.61	55.5	98.6

Before implementing the experiments, all participants were screened with a

health history questionnaire (Appendix C). Criteria for inclusion were absence of any

clinical musculoskeletal and cardiopulmonary conditions that could potentially affect

their performance for wheelchair propulsion. Non-experienced wheelchair users were

purposely selected for study subjects. This was to exclude influences due to motor

skills already acquired for wheelchair propulsion. Institutional Review Board (IRB)

approval was obtained from the investigators' institution prior to implementing the

study (Appendix D). Each subject signed an informed consent form meeting the IRB guidelines before participating in this study (Appendix E).

Instrument/Apparatus

Wheelchairs and wheelchair roller

Three sizes of Quickie II standard wheelchair (Sunrise Medical, Fresno, CA) - small, medium and large - were used in training and testing sessions in this experiment. The participants chose one size which was the most comfortable for them to propel. All the wheelchairs had the same size of tires ($23 \times 1^{3/8}$ inches). A bicycle speedometer with a digital display (CC-CD 300N, Cateye, Osaka, Japan) was attached to the right wheel of the chair in order to provide visual feedback of propulsion velocity to participants during training sessions. A wheelchair roller ((MCLAINROLLER WC-1 (width 95.5cm, depth 155.0cm, height 16.0cm), Mclain rollers Inc., Lansing, MI) was used as a stationary wheelchair roller to allow participants to propel a wheelchair both for the training and testing trials.

Biomechanical measurement

Six cameras of a three-dimensional (3D) optical motion capture system (Vicon 612, Oxford Metrics Ltd, Oxford) was used to collect the kinematic data. All of the collected data was computed with a computer software to obtain joint kinematics (Body Builder, Oxford Metrics Ltd, Oxford). Few studies have investigated the reliability and validity of biomechanical analysis using a wheelchair ergometer and a 3D camera system (Finley, Rodgers, Rasch, McQuade & Keyser, 2002; Davis,

Growney, Johnson, Iuliano & An, 1998). Finley et al. (2002) examined the reliability of biomechanical measurements during repeated wheelchair ergometer exercise tests. Their findings showed that the major biomechanical variables, such as joint kinematics, were reliable.

Physiological measurement

To obtain values of energy expenditure, the TrueMax 2400 (Parvo Medics, Sandy, UT) was used for measuring oxygen consumption (VO_2) and metabolic rates (METs). The reliability and validity of metabolic cart system have been investigated experimentally (Bassett et al., 2001; Novitsky, Segal, Chatr-Aryamontri, Guvakov & Katch, 1995). Bassett et al. (2001) compared the accuracy of the TrueMax 2400 with the Douglas bag system that used the most reliable measurement system for oxygen consumption. Their results showed that the TrueMax 2400 provided sufficiently accurate measurements.

Procedure

Experimental design

Figure 2.1 describes the timeline of the experiments. All participants were randomly assigned into one of two training groups. Group A was assigned training CP for the first three weeks and then SLP for the second three weeks. Group B was assigned in the opposite order, training SLP, then CP. Participants trained twice per week during each three-week session. After each training session, participants were

tested on their assigned stroke pattern. At least one-week break was taken between the first testing session and the second training session.

Figure 2.1: Timeline of Experiment
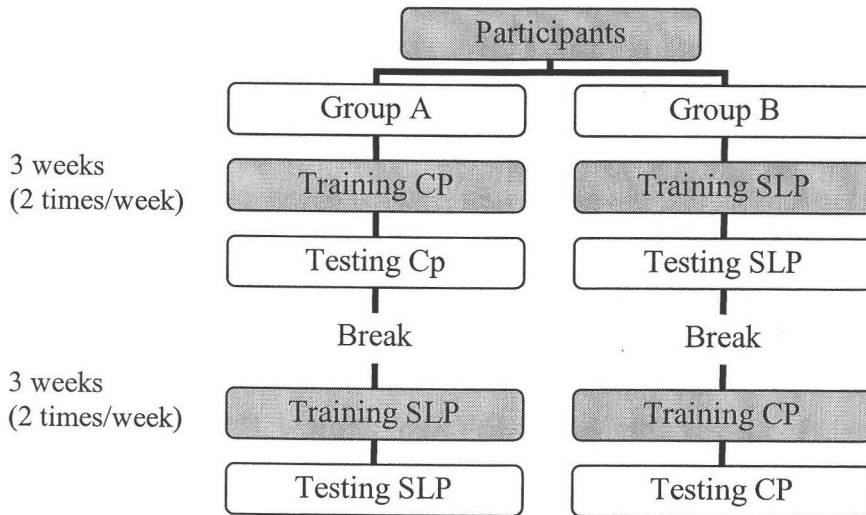
* <u>At least one week break</u> after the first testing session

Training procedures

Each training session lasted approximately 45 minutes, including resting time, and comprised five six-minute practice blocks. Participants were allowed to take a resting period between each practice block until they felt ready for the next block. All practices were performed on the wheelchair roller. The investigator instructed the participants on how to appropriately perform their assigned stroke patterns. Participants were required to propel a wheelchair a specified velocity of 0.9m/s. The investigator or assistant staff supervised all training protocols and monitored the propulsion techniques and the velocity that participants performed. All training

sessions were conducted in the Sports Medicine and Disability Laboratory in the Women's Building at OSU.

Groot et al. (2002) investigated the training effects of a three-week practice (3 times/week, 9 practices in total) on wheelchair propulsion in non-experienced users. Each practice had two four-minute trials at two different speeds. The three-week practice period had a favorable effect on mechanical efficiency and some kinematic variables such as stroke frequency, push time and cycle time in non-experienced users (Groot, Veeger, Hollander & van der Woude, 2002).

Testing procedures

All test trials were conducted in the Biomechanics Laboratory in the Women's Building at OSU. All the participants had their height and weight measured. The same wheelchair as one used for training was set on the wheelchair roller. The six cameras were placed at the left side of the wheelchair roller. The metabolic cart and the heart rate monitor were set at the right side of the wheelchair roller. Calibrations of the motion capture system were performed prior to each experiment. Flowmeter calibration for the metabolic cart system was conducted with room air before data collection, and gas calibration was conducted for each testing trial. Figure 2.2 illustrates the data collection setup.

Figure 2.2: Diagram of the Data Collection Setup
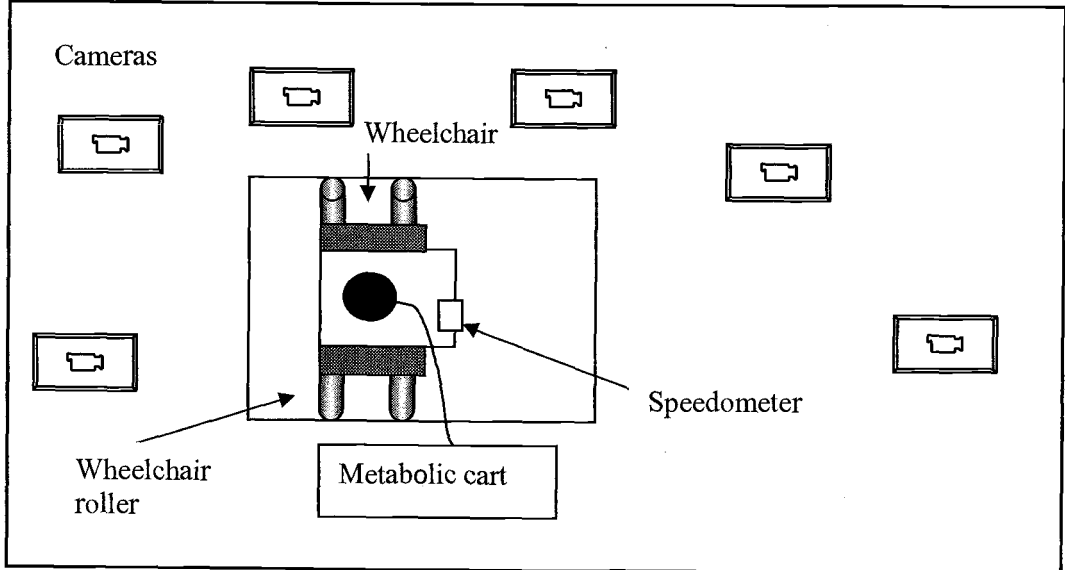
For kinematic data collection, ten reflective markers (diameter: 9mm) were placed on a) the left acromion; b) the left arm (back of arm on the midline below the deltoid); c) the left humeral epicondyle; d) the left forearm; e) the left ulnar styloid process; f) the left base of thumb; g) cervical vartebra 7; h) thorax (thoracic spine above the seatback of a wheelchair); i) the axis of the left wheel and j) one spoke of the left wheel. The markers used for the analysis are pictured in Figure 2.3.

Figure 2.3: Marker location
(a) ~ (c) are corresponded to the marker as described above.
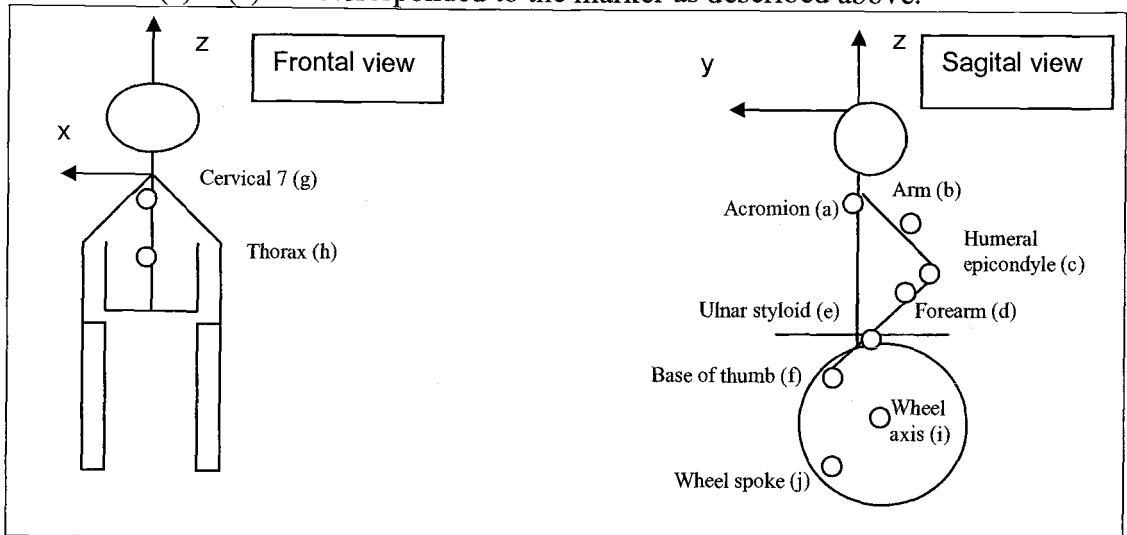
Participants were allowed to propel the wheelchair for approximately one minute prior to the test trials for a warm-up exercise. Participants pushed the wheelchair for six minutes at the required velocity of 0.9 m/s. An assistant staff provided them verbal feedback of their propulsion velocity. Kinematic data were collected at 3 minute 30 seconds point by manual counts of ten pushing cycles. At least seven pushing cycles were used to compute the kinematic variables from the recorded data, and their averages were calculated for each kinematic variable. The sample frequency was 60Hz.

Average propulsion velocity over the recorded period was calculated to confirm if participants performed the required velocity (Appendix F). A paired sample t-test showed no significant difference (t = .14, p < .89) between CP and SLP in the propulsion velocity during the trials that were performed by participants. Velocities were 0.94 m/s (SD = .06) and 0.94 m/s (SD = .03) for CP and SLP, respectively.

Metabolic data (VO_2) was taken from the second three minutes during each trial as a stable stage of metabolic rate. After each testing trial, participants were asked about a perceived exhaustion scale (PES), 1~20, which indicates exercise intensity how they felt during trials.

The specified velocity of 0.9 m/s has been used as a target velocity in many previous wheelchair studies using either wheelchair users or non-experienced users (Boninger et al., 2002; Finley et al., 2002; Rodgers et al., 1994; Rodgers, Keyser, Gardner, Russell & Gorman, 2000). Also, previous studies reported that the velocity, 0.9 m/s was close to the speed when subjects propelled a wheelchair at their freely

chosen speed (FCS) (Mattison, Hunter & Spence, 1989; Mukherjee, Bhowik & Samanta, 2002; Mukherjee & Samanta, 2001).

Data analysis:

Filtering

The raw marker position data were filtered with a recursive 4th order Butterworth digital filter. The cut-off frequency ranged from 6 Hz to 10 Hz across markers. Before performing the filtering, a residual analysis was used in order to select the cut-off frequency levels for each marker used in the kinematic model (Appendix F).

Kinematic variables

Kinematic variables included (a) cadence (cycles/s), (b) ratio of push time to recovery time (push-to-recovery ratio), (c) range of motion (ROM), (d) peak position of ROM (Peak ROM), and (e) peak angular acceleration. Cadence and push to recovery ratio were calculated from the curves of instantaneous wheel velocity versus time (Appendix F). ROM, peak ROM and peak joint accelerations were calculated from the joint angle data acquired from a custom 3D kinematic model of the Body Builder program. The kinematic model was constructed with the convention of Grood and Suntay (1983) for Cardan angles. A static trial and body measurements were used to determine a reference of joint center locations and segment axis orientation (Appendix F). ROM variables included the shoulder flexion-extension, elbow flexion-extension, and trunk flexion-extension. Peak ROM was determined for shoulder

extension, shoulder abduction, elbow flexion and trunk flexion. Peak angular accelerations of the shoulder and elbow joint in flexion and extension were calculated.

Physiological variables:

Three sets of physiological variables included (a) average oxygen consumption (VO_2 (ml/kg/min.)), (b) METs (metabolic equivalent, which is equal to the oxygen consumption divided by 3.5ml/kg/min), and (c) Perceived Exhaustion Scale (PES). Oxygen consumption has been commonly used to measure the energy cost of wheelchair propulsion as empirically valid measures (Beekman, Miller-Porter & Schoneberger, 1999; Janssen, Dallmeijer, Veeger & van der Woude, 2002; Sawka, Glaser, Wilde, von Luhrte, 1980). PES was used for a reference that indicates exercise intensity how participants felt during their testing performance.

Statistics

Data analysis was conducted by SPSS version 11.5. A probability of .05 was set as the level of statistical significance. Five separate repeated measures multiple analysis of variances (MANOVAs) were used to compare the differences between two stroking techniques for a) cadence and push-to-recovery ratio, b) the shoulder motion, c) the elbow motion, d) the trunk motion, and e) energy expenditure. Pearson product correlation coefficients were used to analyze correlations between joint motion and energy expenditure.

RESULTS

Kinematics

Stroke patterns

The hand trajectories showed the expected difference between the two stroke patterns. Sample trajectories in the sagital plane are shown for one randomly selected participant in the Figure 2.4.

Figure 2.4: Stroke patterns for a single participant

Notes: Forward direction ⟶
The trajectories of the marker of the base of thumb
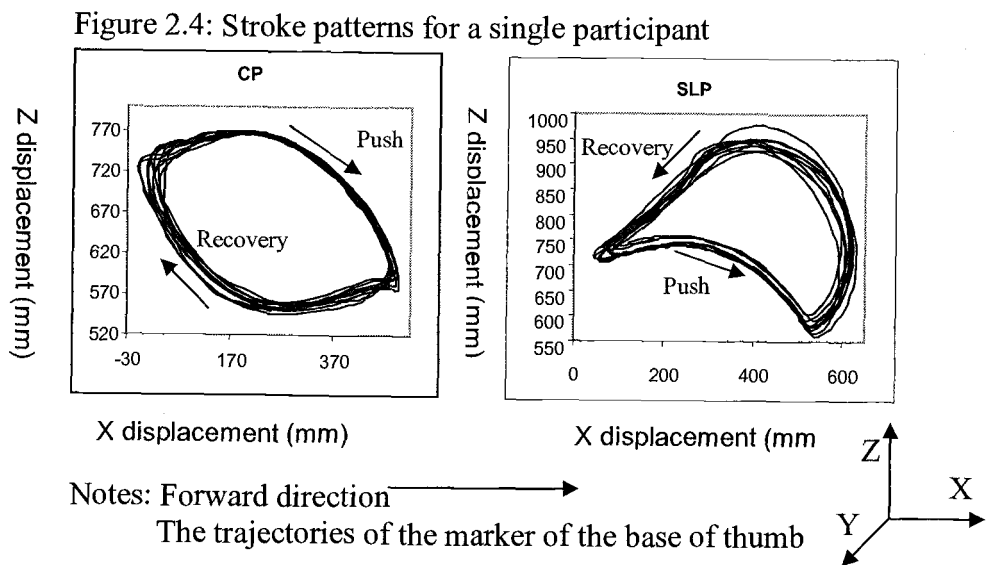
Cadence and Push-to-Recovery Ratio

Table 2 summarizes the results of descriptive statistics for cadence (cycles/s) and push-to-recovery ratio. Repeated measures MANOVA showed a significant difference between CP and SLP (Wilks' Lambda = .43, $F_{(2, 14)} = 9.31$, $p < .01$). A follow-up univariate test in repeated measures ANOVA indicated that CP had a significantly lower cadence ($F_{(2,14)} = 4.74$, $p < 0.05$) and a greater push to recovery ratio ($F_{(2, 14)} = 18.47$, $p < 0.01$) than SLP did.

Table 2: Cadence and Push-to-recovery ratio

	CP		SLP	
	Mean	*SD*	Mean	*SD*
Cadence (s-1)*	.95	.10	1.02	.12
Push to recovery ratio** (push/recovery)	1.00	.13	0.87	.12

Note: * $p < .05$, ** $p < .01$, SD = standard deviation

Joint motion

Shoulder

The multivariate test indicated a significant difference in shoulder kinematics between CP and SLP (Wilks' Lambda = .23, $F(5,11) = 7.36$, $p < .01$). However, no differences between CP and SLP were found in any of the univariate tests in repeated measures ANOVA of joint shoulder motion. Table 3 summarizes the descriptive information on the shoulder motion.

Table 3: Shoulder Motion

Stroke pattern		CP		SLP	
Variables		Mean	*SD*	Mean	*SD*
ROM (degree)	Flexion-Extension	79.82	7.70	82.75	11.62
Peak ROM (degree)	Extension	50.54	7.28	44.56	14.85
	Abduction	33.65	10.52	34.73	7.77
Peak Acceleration ($°/s^2$)	Flexion	2940.31	606.73	3065.55	622.07
	Extension	4074.75	1008.76	4497.88	1133.82

Note: None of the univariate tests was statistically significant ($p > .05$)

Elbow

There was a significant difference in the multivariate repeated measures ANOVA test (Wilks' Lambda = .30, $F(4,12) = 7.11$, $p < .01$). The follow-up

univariate repeated measure ANOVA test indicated that the peak joint acceleration in elbow flexion was significantly greater in SLP than in CP ($F(2,14) = 6.82$, $p < .05$). Peak accelerations in flexion occurred mostly during a phase just before the elbow was most extended. For the other variables, no significant differences were founded between the two stroke patterns (Table 4).

Table 4: Elbow Motion

Stroke pattern		CP		SLP	
Variables		Mean	SD	Mean	SD
ROM (degree)	Flexion – Extension	78.14	11.37	81.59	17.04
Peak ROM (degree)	Flexion	97.74	12.17	102.78	14.68
Peak Acceleration ($°/s^2$)	Flexion	8061.55*	2703.47	11254.32*	4297.81
	Extension	4869.43	1726.77	5255.73	4331.21

Note: *$p < .05$

Trunk

There was no difference between CP and SLP in the motion of the trunk between in the multivariate repeated measures ANOVA test (Wilks' Lambda = .76, $F(2, 14) = 2.21$, $p > .05$). Table 5 presents the results of a follow-up univariate tests in the trunk motion.

Table 5: Trunk Motion

Stroke pattern		CP		SLP	
Variables		Mean	SD	Mean	SD
ROM (degree)	Flexion – Extension	3.96	1.01	5.55	2.54
Peak ROM (degree)	Flexion	15.31	5.82	13.81	4.58

Energy expenditure

Repeated measures MANOVA revealed that there were no significant differences in VO_2 (ml/kg/min), METs between CP and SLP (Table 6). There was no significant difference between CP and SLP in PES.

Table 6: Comparison of Energy Expenditure and PES

Stroke Pattern	CP		SLP	
Variables	Mean	*SD*	Mean	*SD*
VO_2 (ml/kg/min)	13.80	1.08	14.03	1.24
METs	4.32	0.36	4.39	0.47
PES	10.94	1.61	11.31	1.74

Correlations between kinematics and energy expenditure

The Pearson correlation coefficient showed no statistically significant correlations between any joint motion variables and energy expenditure. Table 7 shows each correlation coefficient between the joint motion and VO_2.

Table 7: Correlations between Joint Motion and VO_2

	Variables	**CP**	**SLP**
ROM	Shoulder Flexion-Extension	0.39	0.12
	Elbow Flexion-Extension	0.18	-0.13
	Trunk Flexion-Extension	0.03	0.24
Peak ROM	Shoulder Extension	0.16	-0.01
	Shoulder Abduction	0.06	-0.04
	Elbow Flexion	0.20	-0.20
	Trunk Flexion	0.17	0.29
Peak Acceleration	Shoulder Flexion	0.24	0.16
	Shoulder Extension	-0.42	-0.27
	Elbow Flexion	-0.40	-0.23
	Elbow Extension	0.08	-0.11

Note: None of Pearson correlation coefficient was statistically significant ($p > .05$)

DISCUSSION

Kinematics

After training non-experienced users, CP showed the lower cadence and the greater ratio of push time to recovery time, similar to the findings of previous studies of actual wheelchair users (Boninger et al., 2002; Shimada et al., 1998). The training instruction provided for participants in this study brought out the expected results for these two variables. Research has reported that overuse injuries in repetitive motion are associated with increasing a task frequency (Boninger et al., 1999; Novak & Mackinnon, 1998; Silverstein, Fine & Armstrong, 1987). CP has a lower cadence than SLP for propulsion at the same speed in this study. In terms of cadence, this outcome would support the suggestion that CP may be the recommended technique for users to prevent upper extremity injuries.

Shoulder motion

Figure 2.5 showed the relationship between the shoulder angles and the phase of pushing cycles for one randomly selected subject. The shoulder joint was most extended at the beginning of the push phase and was most flexed at the end of the push phase both in CP and SLP. This result was consistent with the findings of Koontz et al. (2002) and Boninger et al. (1998) studies. During the push phase, joint motion of the upper extremity may not be different based on stroke patterns (Boninger et al., 2002). The total ROM of shoulder flexion-extension would be determined by motion during the push phase, so no significant difference was found between the two stroke patterns.

Figure 2.5: Shoulder angle in a single participant
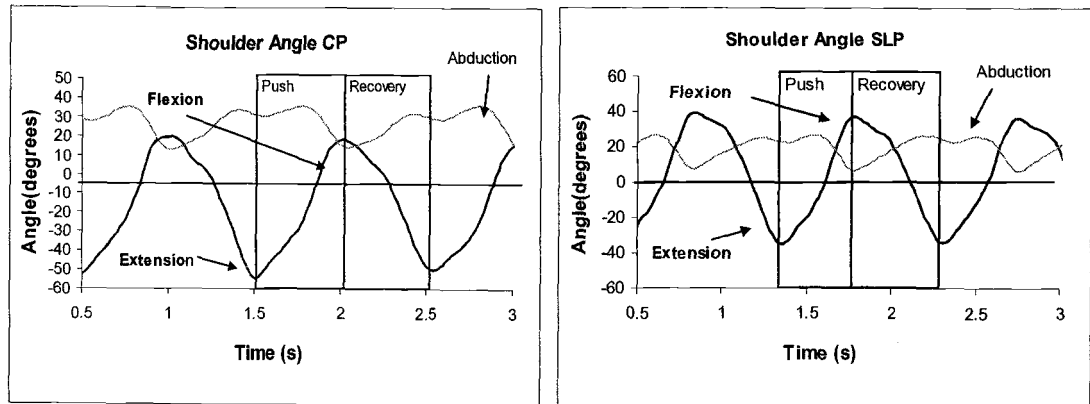
Also, Figure 2.5 shows that the peak ROM of shoulder abduction occurred

mostly during the push phase or just before the beginning of the push phase. It means

that when the shoulder was most abducted, the hands were on the handrims. The

positions of the handrims are fixed. Therefore, peak shoulder abduction would depend

on the width of the wheelchair rather than the stroke patterns examined in this study.

Even though, the univariate test indicated that the two stroke patterns showed

the same degree of total shoulder motion in ROM and peak ROM, the multivariate test

indicates a significant difference. One possible explanation may be a complex of the

shoulder structure. Shoulder has a freedom of motion and some combination of

motion, for example, flexion and abduction. In Figure 2.5, the curves of shoulder

flexion-extension and peak abduction were similar, but a combination of those two

motions might be different at the same point. However, it is unable to specify what

combinations are different between CP and SLP in this study. Also, this study did not

measure internal-external rotation angle and horizontal abduction-adduction angle of

the shoulder. More detailed variables may reveal a difference in shoulder motion

between CP and SLP.

Elbow motion

This study showed that CP had a significantly lower peak joint acceleration of elbow flexion than SLP. Shimada (1998) also reported that CP showed a significantly lower peak acceleration of the elbow joint than SLP. Their propulsion velocity was 1.2m/s and 2.2m/s, while this study used 0.9m/s. The result of this study indicates that SLP may require higher joint accelerations than CP even at lower velocity. It has been indicated that high joint accelerations are associated with excessive stress on joints and will be a causal factor of joint injuries (Fleisig, Andrews, Dillman & Escamilla, 1995; Glousman, Barron, Jobe, Perry & Pink, 1992; Xue & Masuda, 1997). As far as the elbow joint, CP may be beneficial to avoid the risk of injuries.

Energy expenditure

The hypothesis that SLP requires less energy expenditure was rejected. A possible explanation may be that the two stroke techniques had the same amount of joint motion in the shoulder, elbow and trunk. Sparrow and Irizarry-Lopez (1987) presented that the mechanical efficiency measures correlated significantly with changes in limb kinematics. The major difference in propulsion techniques, such as CP and SLP, is the trajectories of the hands in the recovery phase that does not require force generation. However, the propulsion forces are generated during the push phase. It is expected period that the most energy is required during this phase. Shimada et al. (1998) and Boninger et al. (2002) reported no difference in force application on the handrims, based on stroke patterns. Muscle forces generated would not vary with

stroke patterns. However, actual forces generated for CP and SLP are unknown since force application was not measured in this study.

A proportional relationship between cadence and push-to-recovery ratio may explain why no difference in energy expenditure was found, despite the difference in the kinematic characteristics of those two variables. There was a significantly negative correlation between cadence and push-to-recovery ratio across CP and SLP. (Table 8 and Figure 2.6).

Table 8: Correlation between Cadence and Push-to-recovery ratio

	Cadence	Push-to-recovery ratio
Cadence	1	
Push-to-recovery ratio	-0.61*	1

Note: Pearson correlation (2-tailed)
* Correlation was significant at the 0.01 level

Figure 2.6: Scatter graph between Cadence and Push-to-recovery ratio
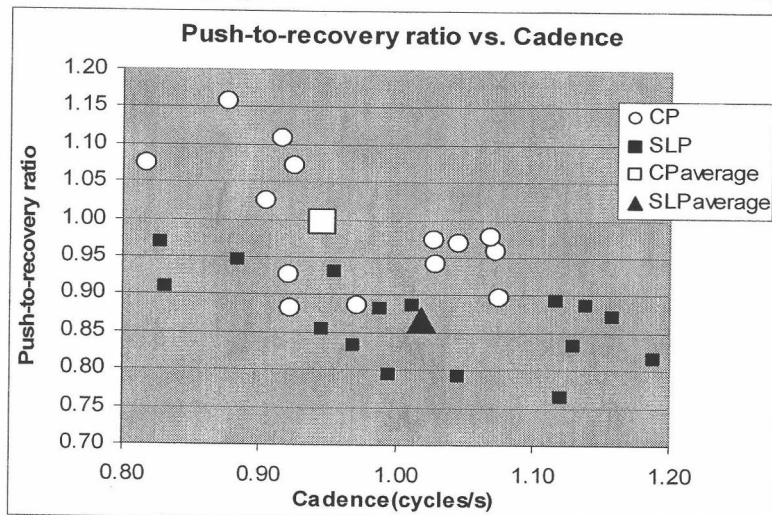
Assuming the same amount of torque created per pushing cycle both in CP and SLP, CP would produce a greater impulse per cycle than SLP because of the greater push-to-recovery ratio, which means a greater change in time per cycle in CP. Therefore, the greater impulse per cycle required a lower cadence for performing CP.

An increase in impulse can increase the work done on the wheels. Increasing the work rate could be related to an increase in energy expenditure. Comparing the average cadence between CP and SLP, CP may produce greater impulse per pushing cycle but at a lower cadence. SLP was vice versa. Therefore, the total energy expenditure required may not be different between the two. However, this study did not measure torque, so it cannot be stated that CP generated greater impulse per cycle than SLP.

Correlation between joint motion and energy expenditure

In this study, participants were trained to learn the specific propulsion techniques. As a consequence, their joint motion would fall into a small range that is characterized by CP and SLP. In addition, energy expenditure did not show a difference between techniques. In this study, the small variability in both the joint motion and the metabolic data resulted in no correlations between the two.

One study reported that there were a few significant correlations between the kinematics and physiological data. O'Connor et al. (1998) showed a high correlation between the wrist velocity and VO_2, and the elbow velocity and VO_2 in six wheelchair racers. The stroke pattern of all subjects was categorized into CP. Although examining the same technique, some correlation was found. Their testing velocity and exercise intensity were much higher than the present study. In Boninger et al. (2002) study, several subjects changed their stroke patterns from CP to SLP, when the tested velocity was changed from 0.9m/s to 1.8m/s. A different propulsion velocity would show some changes in kinematics, which could be related to changes in the rate of energy expenditure.

Selection of movement patterns

This study did not answer the question of why SLP is most commonly used among wheelchair users. Participants in this study were non-experienced users and were provided the instructions on how to propel a wheelchair before learning on their own. Boninger et al.(2002) had a larger number (n = 38) of actual wheelchair users. There was no information on how they developed their techniques. Some might get instruction or information, some might not. The author suggested that SLP is the most intuitively natural way to propel a wheelchair.

Hodges and Franks (2002) stated that the acquisition of motor skills is influenced by pre-practice information. Without instruction and/or information, individuals may learn motor skills in an intuitively natural way and optimize their performance. In order to answer this question of whether SLP is the most intuitively natural way, an experiment with a control group will be needed. The control group will be organized from non-experienced users, who will train and learn wheelchair propulsion without any instructions and information. Then, their techniques will be categorized by their hand trajectory and compared to stroke patterns already classified by the previous studies.

Boninger et al. (2002) showed that SLP is widely used in subjects with paraplegia below T2. Their physical function might vary in subjects because of their injury level. Like in a spinal cord injury, it is possible that differences in physical function are responsible for limitations to learning particular motor skills. There are some obvious differences in movement patterns between CP and SLP. For example, Figure 2.7 presents the angular- angular diagrams that reveal the differences of the

shoulder and elbow joint coordination between CP and SLP for four randomly selected participants. This graphical technique is used to visualize joint coordination and has proved useful in comparing movement patterns, especially cyclic activities such as walking (Enoka, 1994; Low & Reed, 1996).

Figure 2.7: Angular-angular diagrams for four randomly selected participants

(a)   (b)
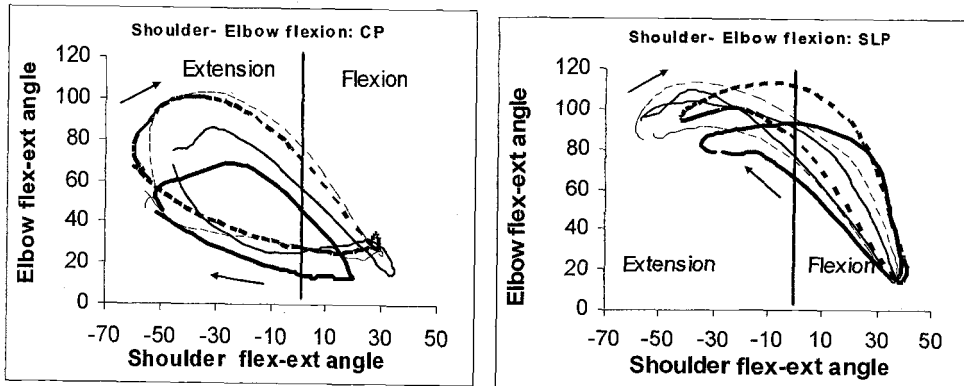
Note: Arrows indicates the direction of motion
The same style of line indicates the same participant between CP and SLP

As illustrated in Figure 2.7(a) and 2.7(b), CP requires that the arm be extended longer than SLP and shows gradual changes in elbow flexion angle relative to shoulder flexion-extension angle. On the contrary, SLP requires the arm be flexed longer and shows a rapid motion at the elbow. There must be some different coordination of muscle activity, which would be associated with learning motor skills.

There were some limitations in this study. This study did not measure propulsion torque, so it was not able to examine impulse per cycle and mechanical efficiency. In order to find out a more efficient technique, kinetic analysis will be needed. Participants had no disabilities and were relatively young age. There was a limitation to generalize the results to the population of actual wheelchair users. Although there was no significant difference in trunk motion, differences between

actual wheelchair users and persons without disabilities in the trunk functionality may be a major considerate factor when training specific stroke patterns. The wheelchair roller used in this study had the two roller drums, and a wheelchair was placed on them. There were two contact points between the wheelchair roller and the wheelchair. It was implied that there was more friction and resistance in this experimental setup than in a normal floor and/or other type of experimental setup such as a treadmill. Stroking techniques may be altered with these conditions. On the other hand, a strength of this study was that the experiment design was a cross-over method. Influences of individual differences and effects on training order could be cancelled. Even though, the experimental setup was different from conditions of actual wheelchair propulsion, those factors could less affect the results to compare between the two techniques.

This study confirmed that training CP had a positive effect on stroke cadence and push to recovery ratio during wheelchair propulsion in this subject group. Since CP showed the lower cadence and the same energy expenditure spent than SLP, CP may be more beneficial to reduce the risk of injuries.

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Chapter III

SUMMARY

The following summary will discuss each research question presented in the introduction and suggest future research directions.

RESEARCH CONCLUSIONS

1) After training, were there any significant differences between the circular pattern (CP) and the single-loop over pattern (SLP) in the kinematics of the upper extremity?

The results demonstrated significant differences between CP and SLP in cadence and ratio push time to recovery time (Wilks' Lambda = .43, $F(2, 14) = 9.31$, $p < .01$). CP showed a significantly lower cadence ($F(2,14) = 4.74$, $p < 0.05$) and greater ratio of push time ($F(2, 14) = 18.47$), $p < 0.01$) than SLP. However, despite the distinct joint motions in the two stroke patterns, ROM, peak ROM and peak joint accelerations were not significantly different between CP and SLP except peak acceleration in elbow flexion. These findings support the previous studies that suggested that CP may be more beneficial to preventing upper extremity injuries in terms of cadence, ratio of push time and elbow peak acceleration.

2) Was there a significant difference in energy expenditure between CP and SLP?

Although SLP was hypothesized to require less energy expenditure as the result of a self-optimization process, energy expenditure was not significantly different between CP and SLP. One of the possible explanations was that propulsion forces generated would not vary with the stroke patterns. Therefore, energy expenditure also

would not be different between the two stroke patterns. As another explanation, the cadence - ratio push time combination brought about no difference in energy expenditure. CP had a lower cadence, but took a longer pushing trajectory. This study did not answer the question as to why SLP is commonly used among wheelchair users in terms of energy expenditure.

3) Were there any significant correlations between the joint kinematics of the upper extremity and energy expenditure during CP and SLP?

No joint kinematic variables were correlated to energy expenditure in both CP and SLP. A correlation would not appear in the small variability of the kinematics and energy expenditure in this experiment.

FUTURE RESEARCH DIRECTIONS

CP may be a technique to recommend to wheelchair users to reduce the risk of upper extremity injuries. However, there would be two next steps suggested before recommending CP as a beneficial stroke pattern. The first step is to measure force application to obtain a value of mechanical work done in performing motor tasks. To determine an efficiency of motor performance, mechanical efficiency is calculated from mechanical work done and energy used for work (Sparrow & Newell, 1987). Future studies will be suggested to examine mechanical efficiency on stroke patterns in order to identify a more efficient technique. The second step is to investigate associations between specific stroking techniques and physical function and other

disabilities such as lesion levels of spinal cord injury. That would provide information on who is to be recommended a specific stroking technique like CP.

In addition, more varieties of study design will reveal a correlation between kinematics and energy expenditure. For example, different velocities, experimental protocols, and experimental setup will be helpful to get insight into correlations between the two.

The kinematic characteristics and energy expenditure examined in this study could not explain the underlying reasons why SLP is most commonly used. Further investigations are needed to reveal other factors besides biomechanical and physiological variables. A future study will be suggested to examine a natural learning process of stroke patterns without directing a specific training instruction and/or information. It will aid in considering effects of instruction on wheelchair propulsion techniques.

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APPENDICES

APPENDIX A: REVIEW OF LITERATURE

The purpose of this review is to provide the readers with background information on the area of biomechanics and physiology in manual wheelchair propulsion. This material aided in establishing a rationale and experiment design for this study.

Manual wheelchair

A wheelchair is an essential assistive-device for individuals with mobility impairments. Manual wheelchairs are used as a locomotion device and as a piece of sport equipment (Rose & Ferguson-Pell, 2002). Jones and Sanford (1996) reported an estimated 1.1 million manual wheelchair users in the United States alone. This is approximately 75% of wheelchair users (Stakeholders Forum, 2003). Three major trends account for the rise of wheelchair users due to mobility impairments: (a) an increase of length time that people live with disabilities, (b) a decrease in mortality rates, (c) the aging society. Consequently, the prevalence of manual wheelchair users is increasing steadily (Jones & Sanford, 1996).

Using manual wheelchairs has been recommended to provide an active lifestyle, which appear to be important factors in the management of physical fitness. Daily use of manual wheelchairs has a positive impact on health status since it demands an adequate amount of physical activity (Dallmeijer, van der Woude, Hollander & Angenot, 1994b; Janssen et al., 1994). Previous studies documented the associations between manual wheelchair propulsion and physical capacity. The aerobic training

programs using manual wheelchairs demonstrated an improvement of physical capacity in able-bodied subjects (Tordi et al., 1998; van der Woude et al., 1999). Hooker and Wells (1989) reported that their manual wheelchair training had an effect on the decrease of blood lipids in persons with spinal cord injury. Tahamont et al.'s (1986) investigation showed that the women with long-term use of manual wheelchairs had a higher level of activity of daily living. Manual wheelchair use in sport participation is highly recommended for maintaining health status (Dallmeijer et al., 1994b; Dallmeijer et al., 1996; Janssen et al., 1994).

Biomechanical issues: strains in the upper extremity

As a form of human locomotion, biomechanical disadvantages for the shoulder during manual wheelchair propulsion have been well-documented in research reports (Boninger, Towers, Cooper, Dicianno & Munin, 2001; Curtis et al, 1999; Koontz & Boninger, 2003; van der Woude et al., 1995; van der Woude et al., 2001). Manual wheelchair locomotion relies more on the upper extremity to produce movement forces, while walking utilizes a larger potion of muscles of the body (Glaser et al., 1981). Consequently, manual wheelchair propulsion has a low mechanical efficiency, which yields a high load on the upper-extremities.

Survey studies have reported that manual wheelchair users have a high incidence of upper extremity injuries, especially shoulder injuries and carpal tunnel syndrome (Bayley et al, 1987; Nicholas et al., 1979; Sie et al., 1992). An estimated 30 to 75% of manual wheelchair users will develop shoulder pain during their lifetime (Stakeholders Forum, 2003). Also, other investigations reported the associations

between the incidence of carpal tunnel syndrome and the repetitive motion of wheelchair propulsion (Boninger et al., 1998: Boninger et al., 1999) The higher task frequency is a significant causal factor of carpal tunnel syndrome (Silverstein et al., 1987).

In previous studies, kinematic variables mainly used to examine stress on the upper extremity were range of motion, joint acceleration, stroke frequency, percentage of push time relative to recovery time, and stroke efficiency. It has been reported that a higher range of motion and joint acceleration contribute to overuse injuries (Fleisig et al., 1995; Glousman et al., 1992; Xue & Masuda, 1997). Percentage of push time (% push time) is the ratio of pushing time per recovery time during a cycle of propulsion. A more efficient propulsion pattern may have a greater % push time (Boninger et al., 2002; Shimada et al., 1998).

Stroke Patterns

Stroke patterns are represented by the trajectory of the hand motion to propel a wheelchair. Recent research has reported that wheelchair propulsion showed several different stroke patterns performed by wheelchair users (Boninger et al., 2002; Dallmijer et al., 1994a; Sanderson & Sommer, 1985; Shimada et al. 1998; Veeger, van der Woude & Rozendal, 1989). Sanderson and Sommer (1985) first investigated stroke patterns. Their subjects were three wheelchair athletes, whose stroke pattern showed two types: circular and pumping patterns. Their circular pattern consisted of keeping the motion of the hands generally circular and followed the path of the push-rim. Their pumping patterns had a short and not smooth pushing motion that followed

the push-rim only for a small arc. The circular pattern showed a higher percent propulsion time and a lower percent recovery time than the pumping pattern. Sanderson and Sommer (1985) summarized that there appeared to be considerable freedom in choosing a style of wheelchair propulsion. There does not seem to be an argument in favor of one particular pattern. The investigators discussed that the circular pattern may be superior to the pumping pattern. However, there was neither physiological nor biomechanical data that was able to point to any clear characteristics of the two styles observed in their study.

Veeger et al. (1989) studied the variation in stroke patterns at the different speeds in five wheelchair athletes. They measured the trajectory of the hand, external power and energy expenditure. There were considerable inter-individual differences in stroke pattern, which demonstrated circular and pumping pattern. The circular pattern showed a significantly higher mechanical efficiency. On the other hand, the pumping pattern showed a higher value of external power. The investigators concluded that a causal relationship between the stroke patterns and the mechanical efficiency would not be drawn due to the small subject pool.

Dallmeijer et al. (1994a) studied the influence of the level of the spinal cord injury (SCI) on anaerobic or short-term power production and propulsion technique. Twenty-three male with SCI showed that propulsion techniques appeared to be intra-individually consistent. This is reflected in the consistency of the force curves, power output curves, and in the movement patterns of the hand (Dallmeijer et al., 1994a). The researchers presented two types of stroke patterns expressed by the trajectory of

hand movement. The graphical illustration of these patterns seemed to be a single loop pattern (SLP) and pumping pattern (PP), but they did not name these patterns.

Shimada et al. (1998) first characterized the propulsion stroke patterns, using three-dimensional kinematic analysis that included joint accelerations, joint range of motion, stroke frequency, percentage of push time to recovery time (% push time), and stroke efficiency. Three distinct stroke patterns were observed from the trajectories of the second metacarpophalangeal joint marker and were named: semi-circular pattern (equivalent to CP), single-loop over pattern (SLP) and double-loop over patterns (DLOP). CP showed the same motion as the circular pattern that the previous studies mentioned above presented. The characteristic of this pattern is to drop the hands below the propulsion path during the recovery phase. Those using SLP lifted their hands over the propulsion path during the recovery phase. Those using DLOP also lifted their hands and moved in a figure eight, showing loops during the recovery phase, while those using SLP made a single loop. Shimada et al. (1998) concluded that CP had the most biomechanical benefits for the upper extremity because of associating with the less joint accelerations, the lower stroking frequency and the greater % push time, while the applied forces on the handrim showed no significant differences from the other patterns. Their study had only seven subjects that were wheelchair athletes, so there was a delimitation and limitation for generalization.

Boninger et al. (2002) did a similar study design to Shimada et al's (1998) study but with a larger number of subjects, 38 wheelchair users with paraplegia who use manual wheelchairs for mobility. The researchers classified stroke patterns and determined if different stroke patterns led to different stroke efficiencies. Their

classification consisted of four patterns, with three of the same patterns in Shimada's study, along with the pumping pattern (PP) indicated in the other previous studies. CP showed the lowest cadence and the greater % push time. CP follows an elliptical pattern, which avoids a large amount of changes in joint direction and minimizes the need for extra hand movement. CP may be the most biomechanically beneficial stroke pattern in terms of reducing the stress on the upper extremity. As a consequence, Boninger et al. (2002) summarized that CP could be recommended for preventing upper extremity injuries.

Despite the fact that CP showed the greater biomechanical benefits for the upper extremity, it did not appear to be common in the subjects in Boninger et al.'s study (2002). SLP was the most common and accounted for 45% of the stroke patterns in the subjects. CP was used only 16%, and DLOP and PP were used 25% and 14%, respectively. The subjects participating in previous studies may have developed their stroke patterns on their own without instruction. They might have established their own patterns as the best technique for their energy expenditure. Stroke patterns should be investigated by combined biomechanical and physiological approach (O'Connor et al., 1998; van der Woude et al., 1993; van der Woude et al., 2001).

Physiological issues

Physiological inefficiency of manual wheelchair propulsion has been frequently discussed. (Glaser et al., 1981; van der Woude et al., 1993; van der Woude et al., 1995; van der Woude et al., 1997). Glaser et al. (1981) investigated the energy cost and cardiopulmonary responses for wheelchair locomotion and walking on tile and

carpet between wheelchair users and able-bodied persons. The variables of energy cost were gross energy cost (VCO_2/VO_2), net locomotive energy cost ($VCO_2/VO_2gross -$ $VCO_2/VO_2rest)/(Weight * Distance)$, pulmonary ventilation (VE) and heart rate (HR). Their findings showed that on tile, gross and net energy costs appeared to be lower, whereas pulmonary ventilation and heart rate were higher in wheelchair locomotion than in walking. On carpet, all variables were found to be higher in wheelchair locomotion than in walking. Comparing the floor condition, wheelchair locomotion showed a significant increase of all the variables on carpet. On the contrary, walking had a similar response concerning energy cost on both floor conditions. Glaser et al. (1981) concluded that wheelchair locomotion in the activities of daily life is more physiologically stressful compared to walking.

Demanding physical workload resulted from manual wheelchair propulsion leads to a decrease of physical activity in wheelchair users. Janssen et al. (1994) argued that higher physical strain is related to an inactive lifestyle of the majority of wheelchair users. Less physical activity in daily life may lead to health risks in the cardiorespiratory system in wheelchair users (Dallmeijer et al., 1996). Therefore, wheelchair users need more efficient stroke patterns (Janssen et al., 1994; van der Woude et al., 1993; van der Woude et al., 1995).

Energy expenditure and Self-optimization of movement

Humans develop their own movement patterns though learning motor control and acquiring a self-optimizing behavior. This process is based on a natural selection mechanism. Numerous researchers have studied the factors that contribute to

establishing an optimal movement pattern in the motor learning process (Brisson & Alain, 1996).   Anderson (1996) reviewed the literature that studied biomechanics and running economy. The reports suggest that kinematics characteristics are likely to contribute to better economy in running and gait. However, research has not identified a direct relationship between biomechanical advantage and less metabolic cost in running. It was mentioned that persons at non-athlete level may tend to use less energy for running. Sparrow and Irizarry-Lopez (1987) provided an empirical support for this conception of natural selection of movement. The researchers examined the changes in mechanical efficiency and metabolic cost on a novel gross motor skill. Five male healthy adults were assigned to walk on their hands and crawling on a motor-driven treadmill. Mechanical efficiency was calculated by the formulae, which is the ratio of mechanical work rate to metabolic rate. Mechanical efficiency showed an overall improvement but not sufficiently significant. The results indicated that economy of movement remarkably correlated with changes in limb kinematics. Sparrow and Irizarry-Lopez (1987) concluded that skilled performance is characterized by changes in the movement pattern that are reflected in a reduction in the caloric cost of exercise. Minimization of energy expenditure as a principle of organization governing the coordination and control of normal gait, might be considered a natural consequence of evolutionary adaptation (Sparrow & Irizarry-Lopez, 1987).

Another paper supports this conception. Schot and Decker (1998) investigated the relationship between the stride frequency and metabolic cost in walking. When gait speed was freely selected, there was a strong natural tendency for a stride rate and length combination to be utilized resulting in minimized metabolic cost. A motor

learning mechanism has a characteristic that individuals adopt an optimal movement pattern to reduce energy cost.

Groot et al. (2002b) examined by physiological measures (oxygen uptake and power output) and biomechanical measures (force and torque on the hand rims), comparing the effect of visual feedback on handrim wheelchair force production. Ten experimental subjects practiced propulsion with the visual feedback, and ten control subjects practiced the same task without the feedback. All participants practiced three weeks (three times a week). The data demonstrated that the experimental group had a significantly more effective force production than the control group, but had a significantly a higher energy cost. Findings indicated that the most biomechanically effective force production was not necessarily the most economical way in terms of energy cost (Groot et al., 2002b).

In manual wheelchair propulsion, individuals also develop their own propulsion patterns for locomotion. Their motor skills for propulsion might be adapted to minimizes energy cost (Groot et al., 2003a; Mukherjee et al., 2001; Mukherjee et al., 2002; Rodgers et al., 2000; van der Woude et al., 1988).

<u>Non-wheelchair user subject experiments for wheelchair propulsion</u>

A large number of studies with non-wheelchair user participants have been done to investigate the biomechanical and the physiological properties in manual wheelchair propulsion. It has been known that subjects without disabilities show a different response to the same experiment compared to experienced subjects (Patterson & Draper, 1997). Despite of the fact that there are considerable limitations

and delimitations for inference to the wheelchair user population, researchers commonly use non-experienced wheelchair users for subjects only to search effects of several dependent variables such as training effects on physical capacity, biomechanics of the upper extremity and wheelchair design.

One reason for preferring non-experienced user subjects is their feature of novice. Experienced wheelchair users have already established their own motor behavior, which may affect potential outcomes of true experiment. Groot et al. (2003b) indicated that experienced wheelchair subjects tend to show a low intra-subject variability, which may influence the training effects on learning a motor skill. Also, well-experienced subjects usually have their own customized wheelchair. The difference in wheelchair design leads to more complex factors as results are interpreted. Therefore, when studies simply determine a difference of training effects on wheelchair propulsion, investigators favor an non-experienced user subject pool.

The second reason is that wheelchair users have a variety of physical conditions in terms of postural control, skeletal structures, muscle and/or sensory disorders, cardio-respiratory regulation, and coordination skills (Mattison, Hunter & Spence, 1989). Those factors interact with each other to perform wheelchair propulsion and result in complicated outcomes to draw a conclusion or summary. Researchers use able-bodied subject pool to eliminate multiple interactions of variables in those with disabilities.

APPENDIX B: RECRUITMENT FLYER

Research Participants Needed for Wheelchair Propulsion Study

The purpose of this study is to determine the most effective wheelchair propelling technique to reduce shoulder injury and energy cost.

The study involves:
2 × 3 weeks training sessions (2 times a week; 45 minutes for each)
2 testing sessions (30 minutes for each)
in Winter & Spring 04

Your time will be financially compensated

Your benefits:
Contribute to the OSU research in EXSS
Help 1.1 million Wheelchair users nationwide
See biomechanics laboratory

If you are: healthy and between the ages of 18 and 50 years old
& interested in this
Contact:

Sanae Asahara
Email: asaharas@onid.orst.edu

or
737-6919 (Room 8: Women's Building)
Movement Studies in Disabilities
Department of Exercise and Sport Science

Sanae Asahara asaharas@onid.orst.edu | Sanae Asahara asaharas@onid.orst.edu | Sanae Asahara asaharas@onid.orst.edu | Sanae Asahara asaharas@onid.orst.edu | Sanae Asahara asaharas@onid.orst.edu | Sanae Asahara asaharas@onid.orst.edu | Sanae Asahara asaharas@onid.orst.edu | Sanae Asahara asaharas@onid.orst.edu | Sanae Asahara asaharas@onid.orst.edu

APPENDIX C: HEALTH HISTORY QUESTIONNAIRE

HEALTH HISTORY QUESTIONNAIRE

The purpose of this questionnaire is to obtain your health information necessary for the researchers in assisting you with your participation in this study. Please answer all questions below to the best of your knowledge.

1. Do you have high blood pressure?   YES   NO
2. Have you ever had a heart attack?   YES   NO
3. Do you have any respiratory problems?   YES   NO
4. Do you have any orthopedic problems with the upper-extremities? YES   NO
   (e.g. carpal tunnel syndrome, rotator cuff injury
5. If so, list them. _____
6. Do you have any recent illness, hospitalization, or surgeries?   YES   NO

   _____

7. If so, list them and when?
8. Are you currently taking any medications?   YES   NO

   _____

9. If so, list them.
10. Do you have any considerable conditions that may affect your ability to exercise?

                                                                       YES   NO
11. If so, list them. _____

APPENDIX D: INFORMED CONSENT DOCUMENT

INFORMED CONSENT DOCUMENT

Project Title: Kinematic Characteristic and Energy Expenditure during Manual Wheelchair Propulsion: A Comparison of Two Stroking Techniques in Non-experienced users

Principal Investigator: Joonkoo Yun, PhD

**Student Researcher:**   Sanae Asahara, Graduate Student

PURPOSE

Manual wheelchair propulsion (MWP) is an essential locomotive device for individuals with disabilities. MWP, however, is stressful for wheelchair users because of the issues associated with higher energy cost and higher biomechanical load on the shoulder. About 50% of users have shoulder problems. Wheelchair users seek a propulsion technique easier to push a chair with lower energy cost and less stress on the shoulder. However, there is very limited information on how best to push a wheelchair in order to reduce energy cost and to lessen the risk of shoulder injury. In recent years, some biomechanical researchers have recommended using a stroke technique (the circular pattern, CP) because the circular pattern reduces biomechanical strain on the shoulder. However, the other pattern (the single-loop over pattern, SLOP) is most commonly used by wheelchair users. There is no information related to energy cost for both patterns. Without understanding both the biomechanical benefits and energy cost, it is difficult to recommend a particular stroke technique to manual wheelchair users. The purpose of this study is to examine the most effective wheelchair stroke technique that reduces energy cost and shoulder injury.

This consent form includes information to help your decision to participate in this study. Please read the form carefully. You may ask any questions about the research - what you will be asked to do, the possible risks and benefits, your rights as a volunteer, and anything else about the research or this form that is not clear. This process is called "informed consent." You will be given a copy of this form for your records.

PROCEDURES

This study involves wheelchair propulsion training and test sessions as shown in the diagram below:

Timeline of study
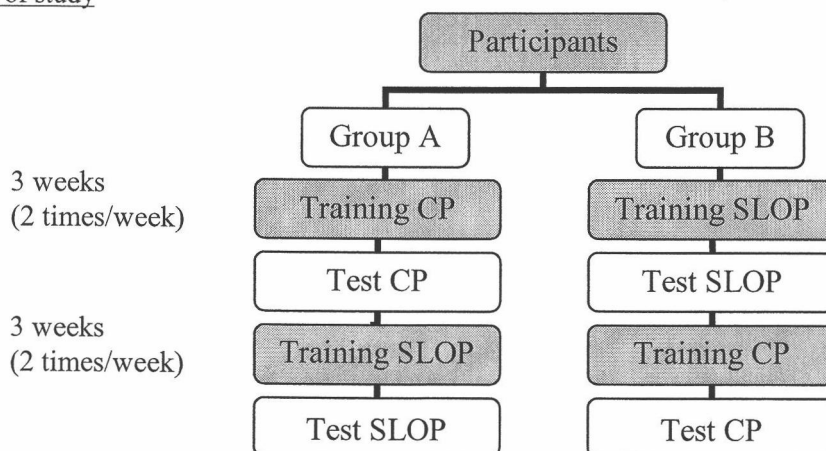
* At least one week brake after the first testing session

During the training phase, you will be randomly assigned to one of two training groups. The researcher will provide instructions on how to push a wheelchair (the circular pattern or the single-loop pattern). Your training sessions will be two times per week for 6 weeks. Each training session will be approximately 45 minutes long, including warm-up and resting times. Group A will be practicing the circular pattern for the first three weeks. Then, you will be instructed how to stroke a wheelchair with the single-loop pattern for the second three weeks. The other group will be instructed in stroke patterns in the opposite order of the first group. You will practice on the wheelchair roller with a speed meter to provide visual feedback of the setup speed (2 mile/hour) to you. The speed, 2 miles/hour, is half the typical walking speed. All training and testing sessions will be at the Sport Medicine and Disability Laboratory in the Women's Building at Oregon State University. You will arrange schedules for training and be able to rearrange them whenever you need to.

In testing sessions, movement analysis of your wheelchair pushing technique will be measured by 3-dimensional-cameras motion analysis system. Various body-parts including, your left shoulder, arm, elbow, forearm, hand, wrist and the back will be marked by reflective markers (diameter of 9mm). Your stroke pattern will be analyzed by the 3- dimensional motion camera system. Energy cost will be measured by the metabolic cart system and the heart rate monitor. You will be asked to wear a mouth piece to measure your oxygen consumption and to be attached a sensor of heart rate monitor to your chest. For testing trials, you will be asked on your own to prepare a black tank top and shoes without reflective materials, which may affect the motion capture system. The investigator will ask your gender, age, height and weight. Your demographic information will be recorded and used in the calculation of energy cost.

All testing will be conducted at the Biomechanics Laboratory in the Women's Building at OSU. You will be tested twice. The first test section will be after your first 3-week training session, and the second test section will be after your second 3-week training session. Each testing session will be approximately 30 minutes long. You will be asked to perform your assigned technique on the wheelchair roller in the 3-dimensional motion analyzing system. You will be asked to perform two trials at the setup speed. Each trial will be approximately 6 minutes long, and you will be asked to maintain the setup speed at least for 3 minutes. During your performance, biomechanical and energy cost data will be collected. The total time commitment expected for you will be approximately 8 weeks.

RISKS
Although the possible risks related to participating in this experiment are minimal, there are possible risks associated with participating in this research project. It is possible: (a) you may get tired and feel physical strain due to training or test trial, (b) you may have scratches or blisters on your hands or have some post-exercise muscle soreness, and (c) you may have some post-exercise muscle soreness in your upper-extremities. You are allowed to stop any activities and tests whenever you feel a problem in continuing them. Gloves or taping for your hands will be provided, if you would like to prevent blisters or scratches on your hands. The investigator and research staff will give you instructions to stretch your upper-body muscles before and after training and testing protocol. The researcher or assistants will supervise all training sessions.

BENEFITS
Outcomes from this study will contribute to managing the health status of existing wheelchair users. In addition, the researchers anticipate that, in the future, society may benefit from this study by learning how and what wheelchair users feel using this locomotion in their daily life. There are no direct benefits to participants (other than gaining some insight to some of the challenges that wheelchair users regularly face).

COMPENSATION

Participants will be compensated for participation in this research project. They will receive a total amount of $75, and refreshment will be provided during the practice and test sessions. If a participant does not complete a whole research procedure, they will be only allowed to receive a portion of compensation. Participants will be paid for $4 for each practice and testing session. The remaining, $43, will be paid as incentive for completion of this study.

CONFIDENTIALITY

Records of your participation in this project will be kept confidential to the extent permitted by law. However, federal government regulatory agencies and the Oregon State University Institutional Review Board (a committee that reviews and approves research studies involving human subjects) may inspect and copy records pertaining to this research. It is possible that these records could contain information that personally identifies you. After completing the informed consent process, you will be assigned an identification number. Only numbers will be used in the analysis to preserve anonymity and confidentiality. In the event of any report or publication from this study, your identity will not be disclosed. Results will be reported in a summarized manner in such a way that you cannot be identified.

VISUAL RECORDING

By initialing in the space provided, you verify that you have been told that visual recordings will be generated during the course of this study. Your motion during testing sessions is needed to record for analysis purposes. Images of records are presented as stick figure and participants will not be identified by these records. Only research staff can access your records and identify them with anonymous identification numbers. _____Participant's initials.

RESEARCH RELATED INJURY

In the event of research related injury, compensation and medical treatment is not provided by Oregon State University.

VOLUNTARY PARTICIPATION

Taking part in this research study is voluntary. You may choose not to take part at all. If you agree to participate in this study, you may stop participating at any time. If you decide not to take part, or if you stop participating at any time, your decision will not result in any penalty or loss of benefits to which you may otherwise be entitled. You will not be forced to continue participation in this study once you decide not to take part. If you withdraw prior to completing the study, any of your records will be eliminated from the study. The compensation given for early withdrawal will be pro-rated, based on the number of training and testing sessions completed.

QUESTIONS

Questions are encouraged. If you have any questions about this research project, please contact: Sanae Asahara at (541) 737-5927, e-mail: asaharas@onid.orst.edu or Joonkoo Yun at (541) 737-8584, email: jk.yun@oregonstate.edu. If you have questions about your rights as a participant, please contact the Oregon State University Institutional Review Board (IRB) Human Protections Administrator, at (541) 737-3437 or by e-mail at IRB@oregonstate.edu.

Your signature indicates that this research study has been explained to you, that your questions have been answered, and that you agree to take part in this study. You will receive a copy of this form.

Participant's Name (printed): _____

_____   _____
(Signature of Participant)   (Date)

RESEARCHER STATEMENT

I have discussed the above points with the participant or, where appropriate, with the

participant's legally authorized representative, using a translator when necessary. It is

my opinion that the participant understands the risks, benefits, and procedures

involved with participation in this research study.

_____   _____
(Signature of Researcher)   (Date)

APPENDIX E: INSTITUTIONAL REVIEW BOARD APPROVAL

INSTITUTIONAL REVIEW BOARD

OREGON STATE UNIVERSITY

Office of Sponsored Programs and Research Compliance
312 Kerr Administration Bldg.
Corvallis, Oregon
97331-2140

TO: Joonkoo Yun,
Exercise and Sport Science

RE: Proper Technique for Manual Wheelchair Propulsion
(Student Researcher: Sanae Asahara)

IRB Protocol No. 2438

The referenced project was reviewed under the guidelines of Oregon State University's Institutional Review Board (IRB). The IRB has **approved** the application. This approval will expire on 2/19/2005. This new request was reviewed at the Expedited level. A copy of this information will be provided to the full IRB committee.

Enclosed with this letter please find the approved informed consent document for this project, which has received the IRB stamp. This information has been stamped to ensure that only current, approved informed consent forms are used to enroll participants in this study. <u>All participants must receive the IRB-stamped informed consent document.</u>

- Any proposed change to the approved protocol, informed consent form(s), or testing instrument(s) must be submitted using the MODIFICATION REQUEST FORM. Allow sufficient time for review and approval by the committee before any changes are implemented. Immediate action may be taken where necessary to eliminate apparent hazards to subjects, but this modification to the approved project must be reported immediately to the IRB.
- In the event that a human participant in this study experiences an outcome that is not expected and routine and that results in bodily injury and/or psychological, emotional, or physical harm or stress, it must be reported to the IRB Human Protections Administrator within three days of the occurrence using the ADVERSE EVENT FORM.
- If a complaint from a participant is received, you will be contacted for further information.
- Please go to the IRB web site at:
  http://osu.orst.edu/research/RegulatoryCompliance/HumanSubjects.html to access the MODIFICATION REQUEST FORM and the ADVERSE EVENT FORM as needed.

Before the expiration date noted above, a Status Report will be sent to either close or renew this project. It is imperative that the Status Report is completed and submitted by the due date indicated or the project must be suspended to be compliant with federal policies.

If you have any questions, please contact the IRB Human Protections Administrator at IRB@oregonstate.edu or by phone at (541) 737-3437.

Redacted for privacy

Date: 2/20/04

Drs. Courtney Campbell and Wayne Kradjan
Institutional Review Board Co-Chairs

pc: 2438 file

Telephone
541-737-3437

FAX
541-737-3093

Email
IRB@oregonstate.edu

APPENDIX F: KINEMATICS

The following information describes the kinematic methods used for the data analysis in this study.

Calculations of Kinematics

Propulsion Velocity

The equations were derived from the changes of positions of the axis of the wheel and the spokes.

Positions of the axis: (A_x, A_z), Positions of the spoke: (S_x, S_z)

1) $? = \tan^{-1}(A_x - S_x / S_z - A_z)$

2) $\omega = (?_{(i+1)} - ?_{(i-1)}) / (2*dt)$

3) revolution (rev.) $= \omega *(1/360)$

4) $v = 1.87*(rev.)$

   where $? =$ changes in degrees in radians
   $dt = 1/60$ sec.
   1.87: the circumference of the wheel in meter

Ratio of push time to recovery time (Push-to-recovery ratio)

Formula: push-to-recovery ratio $=$ pushing time / recovery time

A curve of the wheel velocity vs. time was used to identify the push and recovery phase (Figure F.1). A phase of increasing velocity indicates a pushing phase (hand contact on the wheel), while a phase decreasing velocity indicates recovery time

(hand release from wheel). The points of the hands coming on and off the wheel were checked with the 3D picture data.

Figure F.1: Ratio of push time to recovery time
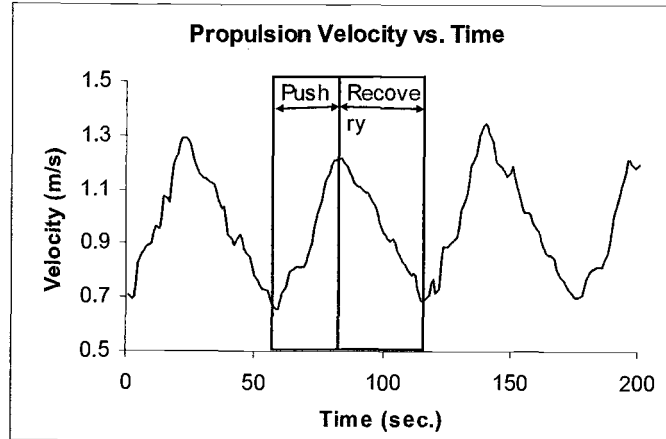
Filtering

All of the markers were examined in a residual analysis (Winter, 1990), using cutoff frequencies of 4, 5, 6, 7, 9, 11, 13, 15, 17, and 19 Hz in a 4th order recursive Butterworth digital filter. Table F.1 summarizes the cutoff frequency determined for each marker used for computing joint motion of the shoulder, elbow and trunk.

Table T.1: Cutoff Frequencies

Markers' position	Cutoff frequency (Hz)
C7	9
Thorax	6
Acromion process	10
Arm under Deltoid	10
Elbow epicondyle	10
Forearm	9
Ulnar styloid	9

Sample frequency: 60Hz

Kinematic model for Body Builder Program

A kinematic model was created to define joint centers and segment coordinate systems, which were used to compute joint angles.

Static parameter

The following physical data was measured for the static parameters in a static trial: a) shoulder depth, b) elbow width, c) wrist depth, and d) wrist width. The sitting position during static trials was to hold the left arms straight down to the side, the elbow flexed 90 degrees, the forearm straight forward, the palm facing, and the head and trunk erect.

Joint center

Three joint centers were defined in a static trial: shoulder joint center (SJC), elbow joint center (EJC), and wrist joint center (WJC). SJC was determined as a point of a half shoulder depth plus a half marker's diameter below the left acromion (LSHO). EJC was defined as a point of a half elbow width plus a half maker's diameter inside from the left elbow epicondyle (LELB). WJC was defined as a point of a half wrist width minus a half marker's diameter inside from the left ulnar styloid (LWRI), and then it was defined again as a point of a half wrist depth and a half marker's diameter below the ulnar styloid.

These parameters were defined in local coordinate systems and used in dynamic trials.

Segment coordinate system

In the laboratory coordinate system, the global X and Y axes were horizontal, with Z axis was vertical. X axis was in the rightward direction, while Y axis was in the anterior-posterior direction. Four segments, the thorax, the torso, the arm, and the forearm, were modeled as rigid bodies, and their coordinate systems were created to obtain joint angles.

Trunk segment coordinate system:

The trunk segment was defined by makers over the C7 (C7), the thorax (THOR), and the left acromion process (LSHO). The origin of the trunk coordinate system is the C7. The first defining line was defined as a line between C7 and THOR. The second defining line was defined as a line between LSHO and C7. The segment z axis was the same as the first defining line. The x axis was perpendicular to both the first and second defining lines, and was computed by a cross product of vectors. The y axis was perpendicular to both the z axis and the x axis. Then, this coordinate system was rotated about its axes by the computed the thorax offset to align it with the anatomical axes. The thorax offset was defined as a parameter by calculating angles between the each axis of the global and segment coordinate system during a trial of static sitting.

Torso segment coordinate system:

The torso segment coordinate system was created to obtain flexion – extension angles of the trunk. The Torso segment was defined by the markers over C7, THOR and the global X axis. The origin of the segment was the THOR. The first defining

line was defined as a line between THOR and C7. The second defining line was defined as the global X axis. The segment z axis was the same as the first defining line. The y axis was perpendicular to both the z axis and the global X axis. The x axis was the same as the global X axis.

Arm segment coordinate system:

The arm segment coordinate was defined by the markers over the left arm (LARM) and the left humeral epicondyle (LELB), and the SJC defined in the trunk coordinate system. The origin of the segment was SJC. The first defining line was defined as a line from LELB to SJC. The second defining line was defined as a line from LELB to LARM. The first segment axis, the z axis, was as the same as the first defining line. The second segment axis, the y axis, was defined as the axis perpendicular to the first and second defining lines. The segment x axis was defined as the axis perpendicular to the z and y axes. The elbow joint center (EJC) was defined from this coordinate system, using the computed parameter of the elbow offset.

Forearm segment system:

The forearm segment coordinate system was defined by the markers over the left forearm (LFOR) and the left ulnar styloid (LWRI), and EJC. The origin of the segment coordinate system was LWRI. The first defining line was defined as a line from LWRI to EJC. The second defining line was defined as a line from LWRI to LFOR. The first segment axis, the z axis, was the same as the first defining line. The second segment axis, the y axis, was defined as the line perpendicular to the first and the second defining lines. The third segment axis, the x axis, was defined as the line

perpendicular to the first and the second segment axes. The wrist joint center (WJC) was defined by this coordinate system and the parameters of the wrist offset. Then, the first segment axis (z axis) was defined again as the line from WJC and EJC. The final forearm coordinate system was defined by rotating about the segment z axis by the offset angles between the global Z axis and the forearm coordinate system during the initial static trial.

Joint angle output

The shoulder angle was defined as a rotation angle of the torso to the arm segment. The elbow angle was defined as a rotation angle of the arm and forearm segment. The trunk angle was defined as a rotation angle of the global coordinate system to the torso segment. All joint angles were computed based on Cardan rotation's convention by Grood and Suntay (1983). The flexion and extension axis was rotated about the medio-lateral axis as the first rotation axis in the proximal segment. The abduction-adduction axis was rotated about the floating axis as the second rotation axis.

APPENDIX G: COMPUTER PROGRAMS

```
{*Vicon BodyLanguage*}
{*copyright Oxford Metrics 1997*}

{*issued:          *}
{*Model  *wheelchair.MOD*}
{*Use only with *Wheelchair*.MP parameter file*}

{*This file is supplied to illustrate the normal operation of BodyLanguage.
Oxford Metrics and Vicon Motion systems accept no responsibility for its correct
operation*}

{*The model uses a total of 13 markers:

Clavicle                CLAV
C7                      C7
Thorax                  THOR
Right Back              RBAC
Left Acromion process   LSHO
Left Arm                LARM
Left Elbow              LELB
Left Forearm            LFOR
Left Ulner Styloid      LWRI
Left Thumb              LHAN
Left Wheel axis         LWHA
Left Wheel spoke1       LWH1
Left Wheel spoke2       LWH2

1) collect static and motion trials, using above markers
2) set $Static = 1 in .MP file and process static trial
3) set $Static = 0 in .MP file and process motion trial
4) write output angles to 3CD or ASCII file*}


{*Initializations*}
{*===============*}

Gorigin = {0,0,0}
Global = [Gorigin, {1,0,0}, {0,0,1}, xyz]

    mm = $MarkerDiameter/2

{*KINEMATICS*}
{*==========*}

{*Thorax*}
{*======*}
{*This segment uses 3 markers in static trials (C7, THOR, LSHO), with Global in static
trials*}

Thorax = [C7, C7-THOR, LSHO-C7, zyx]

If $Static == 1 Then
    SJC = LSHO + {0,0,-$ShoulderOffset/2-mm}
    $SJCOffset = (SJC-LSHO)/Attitude(Thorax)
    PARAM($SJCOffset)
EndIf

SJC = LSHO + $SJCOffset*Attitude(Thorax)
OUTPUT(SJC)

Torso = [THOR, 1(Global),C7-THOR,xyz]

If $Static == 1 Then
    $TorsoOffset = -<Torso,Global,xyz>
```

```
        PARAM($TorsoOffset)
    EndIf

    Torso = ROT(Torso,1(Torso),$TorsoOffset(1))

    TRXO = {0,0,0}*Torso
    TRXL = {100,0,0}*Torso
    TRXA = {0,100,0}*Torso
    TRXP = {0,0,100}*Torso

    OUTPUT(TRXO,TRXL,TRXA,TRXP)

    {*Arm*}
    {*===*}
    {*This segment uses 2 markers (LELB, LARM), with Global in static trials*}

    Arm = [SJC, SJC-LELB, LELB-LARM, zxy]

    If $Static == 1 Then
        ElbowOffset = $ElbowWidth/2
        EJC = LELB + {ElbowOffset+mm, 0,0}
        $EJCOffset = (EJC-LELB)/Attitude(Arm)
        PARAM($EJCOffset)
    EndIf

    EJC = LELB + $EJCOffset*Attitude(Arm)
    OUTPUT(EJC)

    Arm = [EJC, SJC-EJC, LELB-EJC, zyx]

    ARMO = {0,0,0}*Arm
    ARML = {100,0,0}*Arm
    ARMA = {0,100,0}*Arm
    ARMP = {0,0,100}*Arm

    OUTPUT(ARMO,ARML,ARMA,ARMP)

    {*Forearm*}
    {*=======*}

    Forearm = [LWRI, EJC-LWRI, LFOR-LWRI, zxy]

    If $Static == 1 Then
        WristOffsetW = $WristWidth/2
        WristOffsetD = $WristDepth/2

        WJC = LWRI + {WristOffsetD+mm,0,WristOffsetW-mm}
        $WJCOffset = (WJC-LWRI)/Attitude(Forearm)
        PARAM($WJCOffset)
    EndIf

    WJC = LWRI + $WJCOffset*Attitude(Forearm)
    OUTPUT(WJC)

    Forearm = [WJC,EJC-WJC,WJC-LWRI,zyx]

    If $Static == 1 Then
        ForearmAnat = [WJC, EJC-WJC, 3(Global), zyx]

        FOffsetAngles = -<Forearm, ForearmAnat,zxy>
        $FOffsetAng = 1(FOffsetAngles)
        PARAM($FOffsetAng)
    EndIf

    Forearm = ROT(Forearm, 3(Forearm), $FOffsetAng)

    FORO = {0,0,0}*Forearm
    FORL = {100,0,0}*Forearm
```

```
FORA = {0,100,0}*Forearm
FORP = {0,0,100}*Forearm

OUTPUT(FORO,FORL,FORA,FORP)

{*Joint Angles*}
{*============*}

SHOA = -<Torso, Arm, xyz>
SHOA = <1(SHOA), 2(SHOA), -3(SHOA)>

ELBA = -<Arm, Forearm, xyz>
ELBA = <1(ELBA), 2(ELBA), -3(ELBA)>

THOA = -<Global, Torso, xyz>
THOA = <-1(THOA), -2(THOA), 3(THOA)>

OUTPUT(SHOA, ELBA, THOA)
```