Upper Extremity Temporospatial Parameters and Kinematics of Filipino Track and Field Paralympians during Wheelchair Propulsion: an Analysis using a Kinect®-based Markerless Motion Analysis System

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ABSTRACT

Objective. The potential of a low-cost, novel Kinect®-based markerless motion analysis system as a tool to measure temporospatial parameters, joint and muscle kinematics, and hand trajectory patterns during the propulsion and recovery phase of wheelchair propulsion (WCP) was determined.

Methods. Twenty (20) adult male track and field paralympians, (mean age = 36 ± 8.47) propelled themselves on a wheelchair ergometer system while their upper extremity motion was recorded by two Kinect® cameras and processed.

Results. The temporospatial parameters, joint kinematics, and hand trajectory patterns during the propulsion and recovery phase of each participant's WCP cycle were determined and averaged. Average cycle time was 1.45s ± 0.19, average cadence was 0.70 cycles/s ± 0.09, and average speed was 0.76m/s ± 0.32. Average shoulder flexion was 30.99° ± 28.38, average elbow flexion was 24.23° ± 12.25, and average wrist flexion was 12.82° ± 26.78. Eighty five percent (85%) of the participants used a semicircular hand trajectory pattern.

Conclusion: The low-cost, novel Kinect®-based markerless motion analysis system had the potential to obtain measurable values during independent wheelchair propulsion.

Key Words: Kinect®, temporospatial, kinematics, ergometry, track and field, paralympians, wheelchair propulsion, markerless, motion analysis

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Introduction

Observable and quantifiable metrics of the upper extremities during wheelchair propulsion (WCP) affect efficiency and injury risk of manual wheelchair users (MWU).[1-5] One study showed that propulsion patterns employed by experienced MWU resulted in lesser forces on their joints compared to inexperienced users. It was shown further that inexperienced MWU can learn those propulsion patterns over time, and they can achieve increased mechanical efficiency and decreased metabolic cost similar to experienced MWU.[1] Determining which patterns are more efficient than others could be done by measurements obtained by motion analysis systems.[2-6] Another study showed that these motion analysis systems can measure individual muscle contributions during wheelchair propulsion and can allow clinicians to determine which muscles are at an increased risk for injury due to overuse fatigue.[7] Furthermore, objective measurements such as these may remove any bias which may over- or underestimate patients' abilities during monitoring of their progress when undergoing rehabilitation. Another potential benefit of objectively measuring WCP with a set of discrete data could be motivation of the patient or athlete by providing them quantitative feedback of their progress during rehabilitation or during a training program.[8] These objective and quantifiable determinants of efficiency and injury risk can be applied to improve the quality and safety of rehabilitation regimens and athletic training programs.

In other countries, motion analysis systems are used routinely to assess patients. These systems however, entail having expensive facilities and instruments (the gold standard Vicon camera costs USD 25,000.00 each, compared to a Kinect® camera, costing USD 400.00 each). Also, most systems use markers placed on patients which can restrict motion or add discomfort.[9]

To address these problems, studies have been conducted using Kinect® (Microsoft®, Washington, USA), a motion capture camera used for video games, to create markerless, inexpensive, accessible, and portable hardware. The use of this technology has been studied alongside kinematic evaluation of human movements.[10-13] A validated motion analysis platform was developed to measure upper extremity and hand function of pediatric patients using a Kinect®-based motion analysis system.[14] This was further developed into a motion analysis system that measures the following during WCP: joint and muscle kinematics, hand trajectory, and temporospatial parameters.[15] Pilot testing of this novel motion analysis system was done in this study.

Materials and Methods

Study design

This was a cross-sectional study design, approved by the University of the Philippines Manila Research Ethics Board (UPMREB). All patient information and collected data were kept confidential. Participants had access to their data during and after the study period.

Participants

Inclusion criteria included Filipino adult, male, track and field paralympians who are members of the Philippine Sports Association of the Differently Abled (PhilSPADA), between 21 to 55 years old (mean = 36 ± 8.47) who have competed in the Association of Southeast Asian Nations (ASEAN) Paralympic Games or in local paralympic track and field competitions. These athletes use a personalized sports-type wheelchair for everyday use. They have normal upper extremity function with absent or limited lower extremity function. The degree of disability of each participant was described using the classification system created by the International Paralympic Committee (IPC),[16] and not based on their diagnosis. The IPC uses an alphanumeric classification system based on the sport the Paralympian competes in. Athletes who compete in track events are assigned one of the following classification codes: T51, T52, T53, or T54. These athletes differ with regard to their arm and shoulder functions. Athletes from classes T51-52 have activity limitations in both upper and lower extremities. Those from class T53 have normal upper extremity function, with preserved or limited trunk function, and absent lower extremity function. T54 paralympians have normal upper extremity function, and partial trunk and leg function. The participants in this study were among those classified under the T53 and T54 classification. Twelve (12) participants fell under the T53 classification, and eight (8) fell under the T54 classification.

Exclusion criteria included athletes who did not wish to participate in the study, those who had upper extremity impairments or medical conditions that hinder the participant from manually propelling a wheelchair during the time of the study, or those who had injuries during the time of the study.

Methods

Each participant was seated on a manually propelled customized sports-type wheelchair mounted on an ergometer roller system. This ergometer roller system consists of two separate roller units wherein drive wheels will be situated to accommodate the wheelchair used by the participants. It allows "freewheeling", or continuous rolling of the wheelchair wheels without having to stop after each stroke. Metal weights in increments of 0.57 kilogram are placed in correlation with the wheel diameter of the wheelchair to be used, and with the weight of the participant. This is done in order to lower the resistance of the roller system to simulate actual WCP on level surface. These values are based on a mathematical model described by the designers of the ergometer.[15]

The wheelchair used in the study was similar to the participants' everyday-use wheelchair. All participants used the same customized wheelchair. Two Kinect® cameras, each connected to an individual computer, were positioned on the left and on the right of the participant. The mounted wheelchair and the Kinect® cameras set-up are shown in Figure 1.

Figure 1. Photograph of the Kinect®-based motion analysis system.

Each participant then faced the camera on the right with outstretched arms for ten seconds. Their position in space was captured, and was recorded in the computer as the static trial. Next, each participant propelled the wheelchair 30 times while both cameras simultaneously captured the motion, and recorded it as the dynamic trial. There were no practice sessions prior to this.

Statistical analysis

The temporospatial parameters and kinematics of the participants were analyzed using the licensed free trial version of the International Business Machines Statistical Package for the Social Science (IBM SPSS) and Microsoft Excel using descriptive statistics.

Results

Total enumeration of all twenty (20) members of the Philippine Sports Association of the Differently Abled

(PhilSPADA) were recruited as study participants. Anthropometric data of each participant and the wheelchair tire diameter were then taken and saved in the computer. The data were used to automatically generate their upper extremity kinematics and temporospatial parameters. The anthropometric data collected were the following: participant's weight, bilateral hand length in centimeters (measured from the middle finger to the wrist crease), bilateral forearm length in centimeters (measured from the radial styloid to the olecranon process), and bilateral arm length in centimeters (measured from the olecranon process to the acromion). Sixteen (16) participants were right-handed, and 4 were left-handed.

A computer program called Mathworks MATLAB generated formatted plots of each of the participants' temporospatial parameters, joint kinematics, muscle kinematics, and hand trajectory based on their static and dynamic trials, anthropometric data, and wheelchair tire diameter. Figure 2 shows an example of the generated formative plot of one participant. The red lines correspond to the right upper extremity, and the blue lines correspond to the left. The shapes the lines form indicate how the extremities or trunk moves in space. The Y-axis shows the range of motion of the joint in degrees as it moves along the propulsion cycle. The X-axis shows how many percent of one propulsion cycle has been completed. In this example, at 40 percent of the cycle, the elbow is at 100 degrees of flexion (red rectangle). The red curved lines represent the right extremity, and blue represents the left. One thin curved line represents one stroke out of the 30 strokes the participant did during the motion analysis, and the thick curved lines represents the average of the 30 strokes. The vertical line delineates the propulsion phase from recovery phase of wheelchair propulsion. The propulsion phase starts at the moment the arms move away from the wheel and ends as soon as the arms go toward the wheel; the recovery phase of the cycle is the opposite.

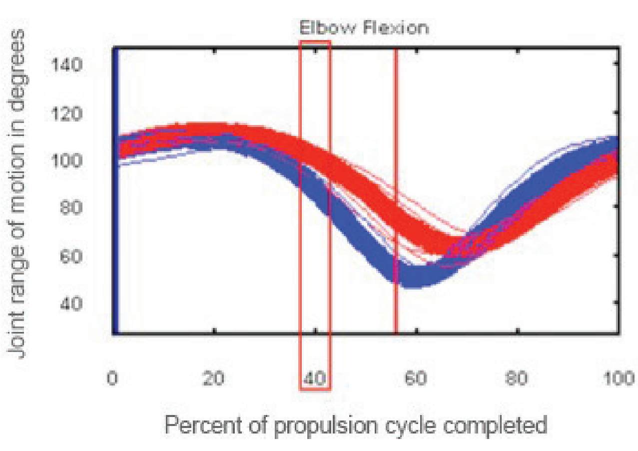

Figure 2. Enlarged view of an elbow flexion formative plot of one of the participants.

A three-dimensional video model during the wheelchair propulsion was also generated for each participant using a computer program called Open Sim, developed by the National Center for Simulation in Rehabilitation Research, Stanford University, California, USA. Screen captured images of the three-dimensional musculoskeletal model generated by Open Sim, juxtaposed to actual pictures of the participant's arm during WCP, are shown in Figure 3.

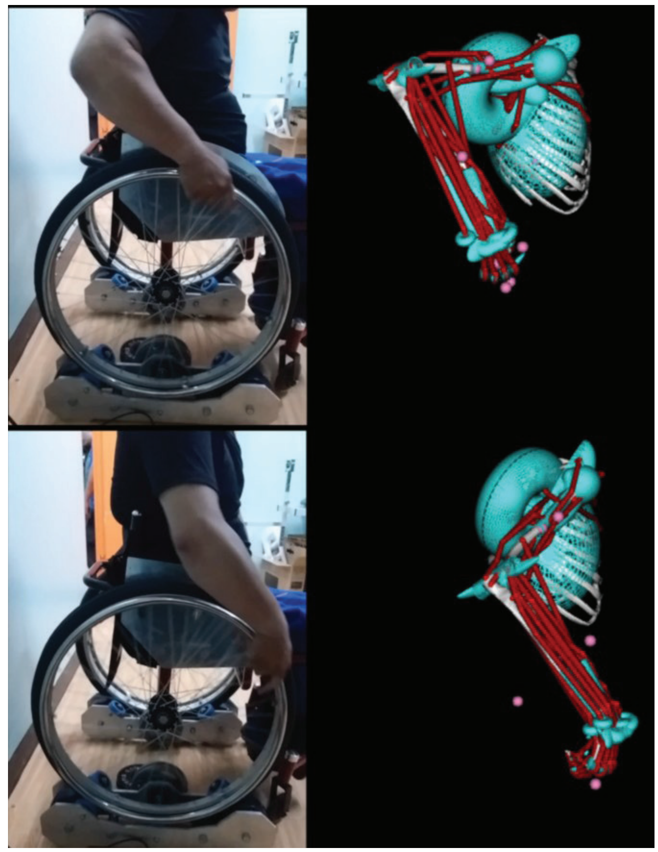

Figure 3. Three-dimensional model generated by the Open Sim program, juxtaposed to actual pictures of the participant's arm.

Temporospatial parameters

During wheelchair propulsion (WCP), one cycle is divided into 2 phases: propulsion and recovery. The propulsion phase of one cycle is composed of all the moments the participant's hands are moving away from the wheelchair. Recovery is composed of all the moments the participant's hands are moving toward the wheelchair. Propulsion was described in this study in terms of the time in seconds the propulsion moment lasted during one cycle (s), how many percent of the cycle was propulsion (%), and the distance the hand moved during the propulsion moment in millimeters (mm). Recovery was also described the same way. The ratio of propulsion over recovery was also described. Propulsion was characterized further by

Table 1. Summary of temporospatial parameters during WCP

Temporospatial parameter	Minimum	Maximum	Mean
Propulsion phase %	30.00	61.00	49.75 ± 8.03
Recovery phase %	39.00	70.00	50.25 ± 8.03
Propulsion/Recovery	0.43	1.56	1.03 ± 0.31
Propulsion time (s)[1]	0.54	0.88	0.71 ± 0.11
Recovery time (s)	0.51	1.32	0.73 ± 0.19
Hand movement during propulsion (mm)[2]	185.98	888.18	531.11 ± 209.20
Hand movement during recovery (mm)	42.67	483.87	205.86 ± 127.74
Wheel rotation (°/cycles)[3]	35.52	169.63	101.43 ± 40.00
Cycle time(s)	1.16	1.89	1.45 ± 0.19
Cadence(cycles/s)	0.53	0.86	0.70 ± 0.09
Speed (m/s)	0.26	1.22	0.76 ± 0.32
Contact angle (°)	-160.96	150.61	-3.15 ± 99.60
Angular velocity (°/s)	50.16	233.56	145.86 ± 60.56

[1]s = second
[2]mm = millimeter
[3]° = degrees

measuring the rotation of the wheelchair wheel during the propulsion phase in one cycle (°/c). Cycle time is defined as the time (in seconds, s) it takes for a participant to complete one cycle. Cadence is the number of cycles a participant can make in one second (c/s). Speed was also recorded in meters per second. Contact angle is described as the angle of the elbow (in degrees, °) at the start of the propulsion moment. Angular velocity of the wheelchair wheel (°/s) during propulsion was also measured. Measurement of the wheel's motion is intended as a metric to describe propulsion efficiency. For instance, longer strokes (more rotation) at similar angular velocity would be more efficient propulsion and lower strain on the shoulder. The temporospatial parameters of the participants during WCP are summarized in Table 1.

Joint kinematics

Minimum, maximum, average, and standard deviation values of range of motion (ROM), peak velocity (PV), and peak acceleration (PA) of left and right shoulder flexion, shoulder abduction, forearm pronation, elbow flexion, wrist flexion and wrist deviation during the propulsion and recovery phase of wheelchair propulsion were measured and recorded. Range of motion (ROM), measured in degrees (°), was greatest during wrist flexion, with a mean of 52.96° ± 31.93, followed by shoulder flexion (mean = 51. 25° ± 35.62) on the left upper extremity. On the right, ROM was greatest during shoulder abduction (mean = 48.28° ± 9.95), followed by elbow flexion (mean = 46.14° ± 11.54). Peak velocity, measured by ROM per second (°/s), was greatest during shoulder flexion, with a mean of 112.13°/s ± 77.87, followed by shoulder abduction (mean = 111.42°/s ± 25.80) on the left upper extremity. On the right, peak velocity was greatest during shoulder abduction (mean = 105.15°/s ± 26.87), followed by wrist flexion (mean = 93.57°/s ± 53.05). Peak acceleration, measured as ROM per second squared (°/s^2), was greatest during shoulder flexion, with a mean of 924.37°/s^2 ± 743.84, followed by wrist flexion (mean = 700.76°/s^2 ± 443.72) on the left upper extremity. On the right, peak acceleration was greatest during shoulder abduction (mean = 880.32°/s^2 ± 1062.14), followed by elbow flexion (mean = 709.78°/s^2 ± 173.15).

Muscle kinematics – propulsion phase

Kinematics of the following muscles were measured: anterior, lateral, and posterior deltoids, supraspinatus, infraspinatus, subscapularis, teres minor, pectoralis major (clavicular, sternal, and costal heads), latissimus dorsi (superior, middle, and inferior portions), lateral, long, and short heads of the triceps brachii, supinator, long and short heads of the biceps brachii, brachialis, brachioradialis, pronator teres, and pronator quadratus. For each muscle, the motion analysis system measured resting muscle length (RML) in millimeters (mm), as well as the change in length (CIL) during the motion, and then divided CIL by RML (CIL/RML). The CIL/RML quotient is recorded as the muscle activity; a higher quotient indicates a higher muscle activity. The posterior deltoid showed the highest muscle activity with a mean of 0.48 ± 0.19, followed by the teres major (mean = 0.28 ± 0.09) on the left upper extremity. On the right, the posterior deltoid (mean = 0.42 ± 0.21) showed the highest muscle activity, followed by the teres major (mean = 0.30 ± 0.09).

Hand trajectory

Hand trajectory is the movement of the hand in space as it undergoes one propulsion cycle. The different types were described based on a study by Boninger et al, which describes four main patterns of hand trajectory shown in Figure 4.[16]

The hand trajectories of the participants are shown in Table 2. Seventeen (17) of the twenty (20) participants exhibited a semicircular pattern for both hands. One participant exhibited arcing on both hands. Another participant exhibited arcing on the left, and semicircular on the right. Another exhibited arcing on the right, and single looping over propulsion on the left. One participant exhibited double looping over propulsion on the right and semicircular on the left.

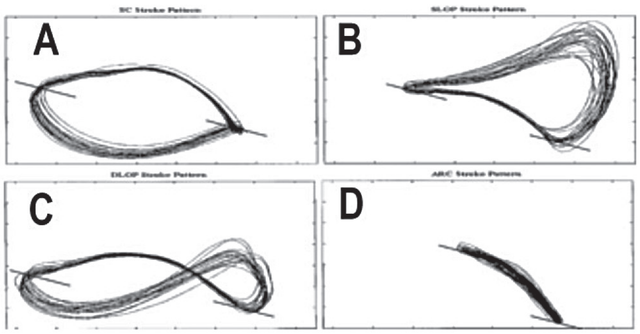

Figure 4. Different types of hand trajectory: Semi-circular (A), Single looping over propulsion (B), Double looping over propulsion (C), and Arcing (D).[16]

Table 2. Summary of hand trajectory patterns of participants

Type	Left hand	Right hand
Semicircular	17	17
Single looping over propulsion	1	0
Double looping over propulsion	0	1
Arcing	2	2

Discussion

The system was able to accurately determine the location of the upper extremities in space for each participant during the propulsion and recovery phase of WCP and plot the temporospatial parameters, joint and muscle kinematics, and hand trajectory patterns.

Conclusion

Results showed that the low-cost, novel Microsoft® Kinect®-based markerless motion analysis system was able to measure the temporospatial parameters and kinematics of upper extremity motion during wheelchair propulsion of Filipino adult male track and field paralympians. The system had the potential to be a viable tool to improve rehabilitation and training programs for patients and athletes. Further clinical research with a bigger sample size is recommended to obtain more uniform results and standardized values. This would allow correlation studies to determine which temporospatial parameters and kinematic profiles translate to better, safer, and more efficient wheelchair propulsion. Furthermore, studies comparing novice and elite wheelchair users may be done to investigate which aspects of the wheelchair propulsion need to be improved during rehabilitation programs of first time manual wheelchair users. This would enable physiatrists to formulate more quantitative and outcome-based rehabilitation protocols aimed at obtaining targeted values. The same principles can be applied to wheelchair-borne athletes to improve their training programs.

Statement of Authorship

All authors have approved the final version submitted.

Author Disclosure

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References

1. Robertson RN, Boninger ML, Cooper RA, Shimada SD. Pushrim forces and joint kinetics during wheelchair propulsion. Arch Phys Med Rehabil. 1996; 77(9):856-64.
2. Boninger ML, Koontz AM, Sisto SA, et al. Pushrim biomechanics and injury prevention in spinal cord injury: recommendations based on CULP-SCI investigations. J Rehabil Res Dev. 2005; 42(3Suppl 1):9-19.
3. Mercer JL, Boninger M, Koontz A, Ren D, Dyson-Hudson T, Cooper R. Shoulder joint kinetics and pathology in manual wheelchair users. Clin Biomech. 2006; 21(8):781-9.
4. de Groot S, Veeger HE, Hollander AP, van der Woude LH. Effect of wheelchair stroke pattern on mechanical efficiency. Am J Phys Med Rehabil. 2004; 83(8):640-9.
5. de Groot S, de Bruin M, Noomen SP, van der Woude LH. Mechanical efficiency and propulsion technique after 7 weeks of low-intensity wheelchair training. Clin Biomech. 2008; 23(4):434-41.
6. Rankin JW, Richter WM, Neptune RR. Individual muscle contributions to push and recovery subtasks during wheelchair propulsion. J Biomech. 2011; 44(7):1246-52.
7. Coutino AC, Neto FR, Perna CE. Determination of normative values for 20min exercise of wheelchair propulsion by spinal cord injury patients. Spinal Cord. 2013; 51(10):755-60.
8. Starrs P, Chohan A, Fewtrell D, Richards J, Selfe J. Biomechanical differences between experienced and inexperienced wheelchair users during sport. Prosthet Orthot Int. 2012; 36(3):324-31.
9. Rao SS, Bontrager EL, Gronley JK, Newsam CJ, Perry J. Three-dimensional kinematics of wheelchair propulsion. IEEE Trans Rehabil Eng. 1996; 4(3):152-60.
10. Paolini G, Peruzzi A, Mirelman A, et al. Validation of a method for real time foot position and orientation tracking with Microsoft Kinect technology for use in virtual reality and treadmill based gait training programs. IEEE Trans Neural Syst Rehabil Eng. 2014; 22(5):997-1002.
11. Galna B, Barry G, Jackson D, Mhiripiri D, Olivier P, Rochester L. Accuracy of the Microsoft Kinect sensor for measuring movement in people with Parkinson's disease. Gait Posture. 2014; 39(4):1062-8.
12. Clark RA, Bower KJ, Mentiplay BF, Paterson K, Pua YH. Concurrent validity of the Microsoft Kinect for assessment of spatiotemporal gait variables. J Biomech. 2013; 46(15):2722-5.
13. Rammer JR, Krzak JJ, Riedel SA, Harris GF. Evaluation of upper extremity movement characteristics during standardized pediatric functional assessment with a Kinect®-based markerless motion analysis system. Conf Proc IEEE Eng Med Biol Soc. 2014; 2014:2525-8.
14. Rammer J, Riedel S, Harris G. A portable, low-cost wheelchair ergometer design based on a mathematical model of pediatric wheelchair dynamics. Rehabilitation Engineering and Assertive Technology Society of North America (RESNA), 2015 RESNA Annual Conference.
15. International Paralympic Committee. Explanatory Guide to Paralympic Classification. Adenauerallee, Bonn, Germany: International Paralympic Committee; 2015. pp. 8-10.
16. Boninger ML, Souza AL, Cooper RA, Fitzgerald SG, Koontz AM, Fay BT. Propulsion and pushrim biomechanics in manual wheelchair propulsion. Arch Phys Med Rehabil. 2002; 83(5):718-23.