ARTICLE IN PRESS

Journal of Biomechanics ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Opportunities for measuring wheelchair kinematics in match settings; reliability of a three inertial sensor configuration

R.M.A van der Slikke [a,b,*], M.A.M. Berger [a], D.J.J. Bregman [b], A.H. Lagerberg [a], H.E.J. Veeger [b,c]

[a] Human Kinetic Technology, The Hague University of Applied Sciences, Johanna Westerdijkplein 75, 2521EN The Hague, The Netherlands
[b] Department of Biomechanical Engineering, Delft University of Technology, The Netherlands
[c] Research Institute MOVE, VU, Amsterdam, The Netherlands

ARTICLE INFO

Article history:
Accepted 2 June 2015

Keywords:
Wheelchair kinematics
Wheelchair basketball
Reliability
Inertial measurement unit
Instrumented wheelchair

ABSTRACT

Knowledge of wheelchair kinematics during a match is prerequisite for performance improvement in wheelchair basketball. Unfortunately, no measurement system providing key kinematic outcomes proved to be reliable in competition. In this study, the reliability of estimated wheelchair kinematics based on a three inertial measurement unit (IMU) configuration was assessed in wheelchair basketball match-like conditions. Twenty participants performed a series of tests reflecting different motion aspects of wheelchair basketball. During the tests wheelchair kinematics were simultaneously measured using IMUs on wheels and frame, and a 24-camera optical motion analysis system serving as gold standard. Results showed only small deviations of the IMU method compared to the gold standard, once a newly developed skid correction algorithm was applied. Calculated Root Mean Square Errors (RMSE) showed good estimates for frame displacement (RMSE ≤ 0.05 m) and speed (RMSE ≤ 0.1 m/s), except for three truly vigorous tests. Estimates of frame rotation in the horizontal plane (RMSE < 3°) and rotational speed (RMSE < 7°/s) were very accurate. Differences in calculated Instantaneous Rotation Centres (IRC) were small, but somewhat larger in tests performed at high speed (RMSE up to 0.19 m). Average test outcomes for linear speed (ICCs > 0.90), rotational speed (ICC > 0.99) and IRC (ICC > 0.90) showed high correlations between IMU data and gold standard. IMU based estimation of wheelchair kinematics provided reliable results, except for brief moments of wheel skidding in truly vigorous tests. The IMU method is believed to enable prospective research in wheelchair basketball match conditions and contribute to individual support of athletes in everyday sports practice.

1. Introduction

Wheelchair sport events have become more and more competitive, and winning a Paralympic championship nowadays requires a professional approach. Increased professionalism in wheelchair basketball has raised the need for scientific input into the optimization of the wheelchair-athlete interaction. Wheelchair-athlete optimization requires not only insight into the general relation between wheelchair settings and performance, it also requires knowledge of individual performance characteristics of athletes during a match (Mason et al., 2013). A method for measurement of wheelchair kinematics in match play would allow for applied research into the relation between kinematics and performance. That knowledge could provide basis for more precise and faster optimization of individual wheelchair settings and thereby support existing experience-based expertise.

Wheelchair related performance in court sports is strongly determined by linear and rotational accelerations (Mason et al., 2013). Albeit, these acceleration data only provide performance insight if situated within the overall movement patterns, so that accurate determination of derivatives is required as well. Accelerations and rotational speed are well measured with inertial measurement units (IMU), but for reliable derivatives more complex algorithms are required. Once available, this will allow the application of IMUs for measuring kinematic aspects in sport specific situations.

While research on the effect of wheelchair settings and propulsion techniques on wheeling performance is available, data were mainly obtained with able-bodied individuals in artificial circumstances and hardly ever sport specific. The effect of propulsion techniques (van der Woude et al., 1998), seat height (Masse et al., 1992) and axle position (Boninger et al., 2000) on performance during normal wheeling is well investigated. The apparent subsequent step in research is the introduction of

* Corresponding author at: Human Kinetic Technology, The Hague University of Applied Sciences, Johanna Westerdijkplein 75, 2521EN, The Hague, The Netherlands. Tel. +31 70 4458704.
E-mail address: r.m.a.vanderslikke@hhs.nl (R.M.A van der Slikke).

http://dx.doi.org/10.1016/j.jbiomech.2015.06.001
0021-9290/

ambulatory methods, measuring *individual* sports performance in an *easy* and affordable manner.

No methods are yet applicable and validated for measuring all wheelchair kinematics in court sports. Mason and Rhodes (Mason et al., 2014; Rhodes et al., 2014) presented an accurate iGPS system for measuring field position, but the available sample frequencies (max. 16 Hz) do not allow for detailed analysis of speed and acceleration. Other more detailed measurement systems are often restricted to lab based settings on a treadmill or ergometer, and thereby have limited ecological validity for wheelchair related performance research (Mason et al., 2013). Ambulatory measurement systems, like IMUs mounted on a wheelchair, can provide good estimates of distance covered, average speed and duration of movement (Sonenblum et al., 2012; Coulter et al., 2011). However, this has only been tested at moderate speeds. Pansiot et al. (2011) found reliable results at moderate performance speeds for estimating velocity, heading, distance covered and trajectory, using gyro/accelerometers in both rear wheelchair wheels during a lab based figure 8 trajectory test. Inspired by this method, this research was dedicated to develop and test an IMU based measurement method that also enables reliable measurement of the more dynamic aspects of wheelchair use, as seen in elite level wheelchair sports.

To enable applied research and optimization of athlete-wheelchair interaction, this study seeks to provide a reliable, robust and easily applicable system to measure wheelchair kinematics during matches. To determine whether this goal is met, the IMU configuration is tested against an optical 3D system, with variedly skilled athletes in a series of tests reflecting all kinematic aspects of a wheelchair basketball match.

2. Methods

Twenty participants (Table 1) performed a series of tests in an IMU instrumented wheelchair, while measured simultaneously with a 3D optical motion analysis system as gold standard. Calculated outcomes of wheelchair kinematics based on IMU and gold standard were compared to test the reliability of the IMU sensor configuration.

2.1. System overview

A Celeritas 300 wheelchair was equipped with 3 markers and 3 battery powered inertial measurement units (x-IMU; x-io Technologies) measuring 3D linear acceleration, angular velocity and magnetic field orientation at a sampling rate of 256 Hz. Sensors were placed on the frame's rear axis slightly right from the centre and on each wheel axis (Fig. 1). Data were collected on micro-SD cards, with initial factory registry-settings used (± 8 g for the accelerometers and $\pm 2000°$/s for the gyroscopes). The selected IMU measurement set in this study was configured to provide duplicate information for all measured wheelchair kinematics, to allow for higher accuracy and robustness of developed algorithms.

Marker positions were recorded with a 120 Hz, 24 infrared camera 3D motion capture system (Flex 13 Optitrack, Natural Point), serving as 'gold standard'. To enhance visibility range and to prevent disturbing reflections, battery powered infrared light emitting diodes markers were used instead of standard retro reflective markers. The markers were mounted on the wheelchair frame (two on the bumper bar and one on a rod at the front of the frame, see Fig. 1). IMU units and optical motion analysis were synchronized by hardwiring all IMU sensors to a pulse generator.

2.2. Participants

Differently skilled participants were recruited to test the system over a wide performance range, with 6 elite wheelchair basketball athletes, 3 players of second division teams and 11 participants without extensive wheelchair experience. Wheelchair athletes were allowed to use their custom supports and straps. Prior to the test, participants received written instructions and viewed an example video of the agility track. The study was approved by the ethical committee of the faculty of Human Movement Sciences (ECB-2014-2). All participants signed an informed consent after being informed on the aims and procedures of the experiment.

2.3. Agility track

Participants performed an agility track consisting of 21 tests covering key aspects of wheelchair basketball (track lay-out in Fig. 2). To allow for comparison, certain tests were similar to ones used in prior research (de Groot et al., 2003; Pansiot et al., 2011), but some slightly modified to meet the capture volume dimensions. Others were designed based on consultation with wheelchair basketball experts to ensure inclusion of all critical kinematic patterns. This resulted in more vigorous tests combining bi-directional translations and rotations. To differentiate between the reliability at different performance speeds, most tests were performed at normal and high speed. The tests were performed in a motion lab with a linoleum flooring.

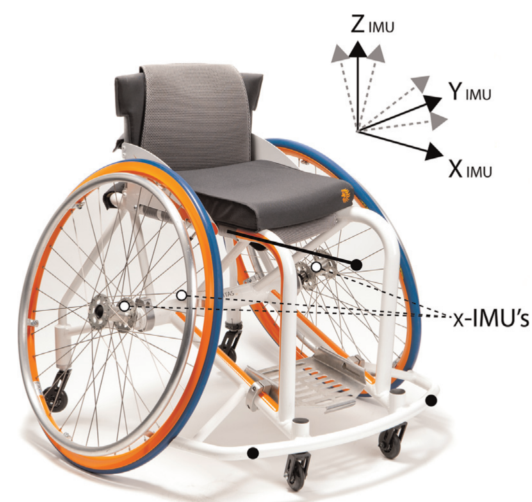

Fig. 1. Celeritas 300 wheelchair used in the experiment. Black dots indicate the position of the IR-LED markers (one on a rod). White dots show the locations of the x-IMU sensors. Orthogonal axes indicate x-IMU orientation at starting position for all x-IMUs, with the dashed arrows indicating the slightly rotated orientation of the wheel x-IMUs due to the wheel camber angle. Mind the effect of wheel rotation around the *Y*-axis on x-IMU orientation.

Table 1
Subject characteristics (mean and standard deviation).

Subjects	N	Age	Sex (m/f)	Weight (kg)	Height (cm)	Play hist.	Class
nonWBB	11	25 (5.7)	10/1	76.7 (8.6)	181.0 (9.2)		
Elite WBB	6	25 (6.7)	5/1	69.5 (15.7)	175.8 (16.0)	6.6 (5.8)	3.7 (1.0)
Am WBB	3	31 (9.2)	2/1	84.0 (29.1)	175.8 (16.0)	1.8 (0.7)	3.6 (0.2)
Total	20	26 (6.6)	17/3	75.7 (14.7)	178.1 (13.6)		

nonWBB = Nonwheelchair basketball players.
Elite WBB = Premier league wheelchair basketball players.
Am WBB = Second division wheelchair basketball players.
Play hist. = Mean years of playing in WBB competition.
Class = Mean players competition classification (handicap score).

Please cite this article as: van der Slikke, R.M.A, et al., Opportunities for measuring wheelchair kinematics in match settings; reliability of a three inertial sensor configuration. Journal of Biomechanics (2015), http://dx.doi.org/10.1016/j.jbiomech.2015.06.001