Wheel Skid Correction is a Prerequisite to Reliably Measure Wheelchair Sports Kinematics Based on Inertial Sensors

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Abstract

Accurate knowledge of wheelchair kinematics during a match could be a significant factor in performance improvement in wheelchair basketball. To date, most systems for measuring wheelchair kinematics are not suitable for match applications or lack detail in key kinematic outcomes. This study describes the construction of wheel skid correction algorithms when using a three inertial measurement unit (IMUs) configuration for estimating wheelchair kinematics. The reliability of the skid corrected outcomes was assessed in wheelchair basketball match-like conditions. Twenty participants performed a series of tests reflecting different motion aspects of wheelchair basketball. IMU based estimations were compared to the outcomes of a 24-camera optical motion analysis system serving as gold standard. Once the skid correction algorithms were applied, estimation errors were reduced up to 4% of their original magnitude. Calculated Root Mean Square Errors (RMSE) showed good estimates for frame displacement (RMSE \leq 0.05 m) and speed (RMSE \leq 0.1 m/s) except for three truly vigorous tests. Estimates of horizontal frame rotation (RMSE < 3°) and rotational speed (RMSE < 7°/s) were very accurate in all conditions. Differences in calculated instantaneous rotation centers (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. Results indicate that wheel skid correction is a prerequisite to reliably measure wheelchair kinematics in sports conditions. Once applied, this method using cheap and affordable sensors, might enable prospective research in wheelchair basketball match conditions and contribute to individual support of athletes in everyday sports practice.

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Keywords: Wheelchair kinematics; Wheelchair Basketball; Reliability; Inertial Measurement Unit; Instrumented wheelchair

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1. Introduction & Objectives

Increased professionalism in wheelchair basketball has raised the need for scientific input into optimizing performance. Knowledge of wheelchair kinematics during a match is prerequisite for this performance improvement [1]. A method for measurement of wheelchair kinematics in match play would allow for applied research into athlete-wheelchair interaction by determining the relation between wheelchair settings, 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.

In the past, well controlled experiments were performed determining the effect of propulsion techniques [2], seat height [3] and axle position [4] on performance during wheeling. With key biomechanics explored, several researchers took the subsequent step moving their research from a lab setting to the sports hall with actual Paralympic athletes. With a miniature data logger, Sporner et al. [5] explored distances travelled and speeds achieved during wheelchair basketball and rugby matches. Usma et al. [6] used an inertial measurement unit (IMU) instrumented wheelchair to explore performance differences between athletes of different classification levels. Fuss et al. [7] also used IMUs to identify differences in activity patterns based on fractal dimension analysis of frame acceleration during rugby match play. Rhodes et al [8] and Sarro et al [9] used an external reference frame to determine wheelchair kinematics, with iGPS and video tracking respectively in wheelchair rugby matches.

The reliability of IMU configurations for measuring wheelchair kinematics was tested by several researchers. Pansiot [10] tested the performance of gyro/accelerometers in both rear wheelchair wheels during a lab based figure 8 trajectory test. The system proved reliable in estimating velocity, heading, distance covered and motion trajectory. Hiremath [11] compared their outcomes of a gyroscope on the spokes with several other systems (tape measures, smart wheel and a motion capture system) and found an overall accuracy above 95%.

The use of IMUs enables cheap and user friendly measurements, but the reliability of such a method is highly dependent on the algorithms used to process the sensor output. This study describes the basis for an algorithm to significantly reduce errors in IMU based estimation of wheelchair kinematics. Elaborating on prior IMU methods, it was intended to establish a method that accurately and reliably determines key wheelchair kinematics even in the most brutal sports conditions. In court sports, wheelchair basketball is one of the most demanding sports with respect to speeds and maneuverability [5], so typical basketball movements were selected to access the reliability. IMU based kinematics like displacement, speed, rotation (speed) and curvature of the path were compared to outcomes of a 3D optical motion analysis system.

2. Methods

2.1. Setup and participants

Twenty participants (Table 1) performed a series of 21 tests reflecting different motion aspects of wheelchair basketball, such as a straight 5m sprint; a slalom; a U-turn; moving back and forth while rotating; collide and spin (see Figure 1). During these tests wheelchair kinematics were simultaneously measured using IMUs on wheels and frame, and a 24-camera optical motion analysis system serving as gold standard. Wheelchair kinematics like frame displacement, speed and rotation based on IMU outcomes were compared to gold standard outcomes, to test the reliability of the IMU sensor configuration [12].

Table 1: Subject characteristics (mean and standard deviation), with Non Wheelchair basketball players (non WBB), Premier league Wheelchair basketball players (Elite WBB), Second division (amateur) Wheelchair basketball players (Am WBB), Mean years of playing in WBB competition (Play hist.) and Competition Classification (Class).

<table>
<thead>
<tr>
<th>Subjects</th>
<th>N</th>
<th>Age</th>
<th>Sex (m/f)</th>
<th>Weight (kg)</th>
<th>Height (cm)</th>
<th>Play hist.</th>
<th>Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>non WBB</td>
<td>11</td>
<td>25 (5,7)</td>
<td>10/1</td>
<td>76,7 (8,6)</td>
<td>181,0 (9,2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elite WBB</td>
<td>6</td>
<td>25 (6,7)</td>
<td>5/1</td>
<td>69,5 (15,7)</td>
<td>175,8 (16,0)</td>
<td>6,6 (5,8)</td>
<td>3,7 (1,0)</td>
</tr>
<tr>
<td>Am WBB</td>
<td>3</td>
<td>31 (9,2)</td>
<td>2/1</td>
<td>84,0 (29,1)</td>
<td>175,8 (16,0)</td>
<td>1,8 (0,7)</td>
<td>3,6 (0,2)</td>
</tr>
<tr>
<td>total</td>
<td>20</td>
<td>26 (6,6)</td>
<td>17/3</td>
<td>75,7 (14,7)</td>
<td>178,1 (13,6)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.2. Inertial Measurement Unit

Wheelchair linear displacement, speed and curvature of the path was calculated based on rotation of the wheels, which in turn was based on the combined signal of the wheel acceleration sensor and gyroscope. After application of a correction for camber angle [10, 12, 13] wheel rotation times wheel circumference produced displacement and derivatives. Rotation and rotational speed of the wheelchair frame in the horizontal plane were directly derived from the frame sensor gyroscope.

2.3. Wheel Skid Correction Algorithms

The measurement configuration was chosen allowing for multiple ways of calculation of the same kinematics. Frame forward acceleration for example was measured directly by the frame acceleration sensor, but also calculated based on measured wheel rotation. These different sensor estimations were used to construct skid correction algorithms.

To correct for concurrent wheel skidding, low pass filtered (20Hz) forward acceleration derived from the wheels (average of left and right WhAG) was compared to the low pass filtered (20Hz) measured forward frame acceleration. For occasions with acceleration differences over 2.5 m/s², the corrected frame speed was calculated based on the frame sensor acceleration signal. This corrected frame speed signal was used for further kinematic calculations.
A second skid correction was developed to correct for single wheel skidding, typically occurring in a sharp turn (Figure 3). During turns, frame centre displacement was calculated twice, based on both wheels individually combined with the measured frame rotation. For each wheel, frame displacement was calculated as the wheel displacement (WhAG) plus or minus the tangent of the frame rotation (FrG) times half the wheelchair wheel base (WB, Figure 2). These two estimates were equal if both wheels are rolling, but deviated when one wheel was skidding. To assure the estimate of the least skidding wheel was used, a weighted average of the estimates was applied with less weight for the wheel with the lowest rotation speed (SpeedFactor) or highest rotational deceleration (AccFactor). Equation 1, 2 and 3 show the calculations for the right wheel based estimations:

\[ \text{SpeedFactor}_R = \frac{\text{WhAG}_R}{(\text{WhAG}_R + \text{WhAG}_L)} \]  
\[ \text{AccFactor}_R = \frac{\text{diff}(\text{WhAG}_R)}{\text{diff}(\text{WhAG}_R + \text{WhAG}_L)} \]  
\[ \text{Factor}_R = \frac{\text{SpeedFactor}_R \times \text{AccFactor}_R}{\text{SpeedFactor}_R \times \text{AccFactor}_R + (1 - \text{SpeedFactor}_R) \times (1 - \text{AccFactor}_R)} \]

The overall factor is the ratio between the factor multiplications:

\[ \text{FrC} = (\text{FrC}_R \times \text{Factor}_R) + (\text{FrC}_L \times (1 - \text{Factor}_R)) \]

2.4. Reliability analysis

Reliability of the IMU method with and without wheel skid correction, was determined by analysis of the IMU-based deviation from gold standard derived data, expressed in overall difference and RMSE values. Additionally, for relevant outcomes (speed, rotational speed and IRC) ICC between mean test averages of the IMU method and gold standard was calculated (ICC, two way mixed single measures, absolute agreement).

3. Results

As expected, kinematics derived from wheel rotation (WhAG) showed increased errors during wheel skidding conditions. Detailed analysis of test signals showed deviations of linear displacement estimations (and derivatives) once some speed was build up and one or two wheels were blocked, resulting in a wheel skid (Figure 3).

Rotations and rotational speed of the frame in the horizontal plane were directly derived from the frame sensor gyroscope (FrG), thus not affected by any wheel skidding. Deviations of the IMU configuration estimations towards the gold standard are shown in Table 2. Calculated Root Mean Square Errors (RMSE) showed good estimates for frame displacement (RMSE ≤ 0.05m) and speed (RMSE ≤ 0.1m/s), except for three truly vigorous tests (during collisions and an evoked skidding stop). Estimates of frame rotation in the horizontal plane (RMSE<3°) and rotational speed (RMSE<7°/s) were very accurate in all tests.

Differences in calculated instantaneous rotation centers (IRC) were small, but somewhat larger in tests performed at high speed. At normal speed the error in calculated distance between IRC and frame centre stayed below an RMSE of 0.10 m, but at high performance speeds it reached up to an RMSE of 0.19 m. For linear speed (ICC’s > 0.90), rotational speed (ICC>0.99) and IRC (ICC> 0.90) average outcomes showed high correlations between IMU estimates and gold standard. So, even estimates with higher RMSE values, showed small errors once averaged per test.

4. Discussion and Conclusions

Results indicate that in most match like conditions skid correction algorithms are needed to reliably measure wheelchair kinematics. Using skid corrections, low RMSE values and high correlations (ICC) to gold standard outcomes were found.

As expected, skidding wheels were the main source of error in calculating wheelchair displacement (and derivatives) and IRC estimations. In tests with evoked wheel skidding, most of the errors of the IMU based
estimations were effectively reduced via the use of duplicate sensory information, reducing RMSE values up to 4% of the non-corrected RMSE values. Occasionally wheel skid corrections were not effective or even reduced accuracy, such as in tests performed at normal speeds or during collisions. Even after correction, in tests at higher speeds and of a truly vigorous nature, RMSE values turned out to be considerable higher than tests performed at normal speed.

Figure 3: Example plot of the calculated kinematics during a right U turn performed at high speed, with (a) displacement, (b) speed and (c) distance between frame and rotation centre (IRC). The black dotted line shows the Optitrack (Opti) gold standard outcomes, the blue dashed line the IMU calculations without skid corrections (WhAG) and the red solid line IMU outcomes with both skid corrections applied (WhAGc). The dashed O marks the start and the triangle the end of the actual turn (with 2.5m straight before and after). Mind the deviation towards Opti at the start of the turn for the outcomes without corrections (WhAG) and the effective reduction of error due to the skid correction algorithm (WhAGc). Due to the application of a threshold for the linear skid some minor signal jumps occur (see speed and IRC plot). Positive IRC values at 1s indicate a minor left deviation, to swirl around the cone at the turning point.
The proven reliability of the developed method enables wheelchair athletes, coaches and researchers to perform ambulant measurements and applied research in the field of wheelchair sports. Wheelchairs can easily be equipped with cheap lightweight IMU sensors, providing wheelchair kinematics if wheel diameter and track width are known and skid correction is applied. In future research, the use of this method might allow for a more detailed profile of wheelchair kinematics during a match. Combined with measurement of additional quantities, such as exerted force or observed game performance information, this allows for composition of an athlete specific performance profile. Such a profile could be used to determine the effect of sport specific training or wheelchair setting adjustment.

### References