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Short communication

# Obtaining wheelchair kinematics with one sensor only? The trade-off between number of inertial sensors and accuracy for measuring wheelchair mobility performance in sports

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ABSTRACT

In wheelchair sports, the use of Inertial Measurement Units (IMUs) has proven to be one of the most accessible ways for ambulatory measurement of wheelchair kinematics. A three-IMU configuration, with one IMU attached to the wheelchair frame and two IMUs on each wheel axle, has previously shown accurate results and is considered optimal for accuracy. Configurations with fewer sensors reduce costs and could enhance usability, but may be less accurate. The aim of this study was to quantify the decline in accuracy for measuring wheelchair kinematics with a stepwise sensor reduction. Ten differently skilled participants performed a series of wheelchair sport specific tests while their performance was simultaneously measured with IMUs and an optical motion capture system which served as reference. Subsequently, both a one-IMU and a two-IMU configuration were validated and the accuracy of the two approaches was compared for linear and angular wheelchair velocity. Results revealed that the one-IMU approach show a mean absolute error (MAE) of 0.10 m/s for absolute linear velocity and a MAE of 8.1°/s for wheelchair angular velocity when compared with the reference system. The two-IMU approach showed similar differences for absolute linear wheelchair velocity (MAE 0.10 m/s), and smaller differences for angular velocity (MAE 3.0°/s). Overall, a lower number of IMUs used in the configuration resulted in a lower accuracy of wheelchair kinematics. Based on the results of this study, choices regarding the number of IMUs can be made depending on the aim, required accuracy and resources available.

## 1. Introduction

In wheelchair court sports, kinematic variables like forward acceleration and angular velocity are important for the quantification of the athlete's wheelchair mobility performance (van der Slikke et al., 2018), which is an important aspect of overall game performance. In wheelchair racing, the relationship between wheelchair kinematics and overall performance is even more profound, with the highest average speed resulting in the best race time. Therefore, the ability to measure wheelchair kinematics using inertial sensors offers multiple opportunities for many wheelchair sports.

Van der Slikke et al. (2015) used inertial measurement units (IMUs) attached to the rear wheels and frame to measure wheelchair kinematics on the court. By using the gyroscope data of the wheel-mounted IMUs to obtain wheel speed, and those of the frame IMU to obtain frame rotation speed, wheelchair kinematics could be assessed with relative ease. To further increase accuracy in vigorous sports conditions, van der Slikke et al. (2015) developed a skid detection algorithm to correct for misinterpretations due to wheel skidding. This three-IMU configuration was validated using an optical motion capture system and provides accurate linear- and angular wheelchair displacement and speed (van der Slikke et al., 2015).

Although the three-IMU configuration might be considered optimal for accuracy, a two-IMU configuration (with IMUs attached to the frame

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and right wheel) is more accessible by reducing cost and enhance usability. A two-IMU configuration still allows for the same calculations as described by van der Slikke (2015), except for wheel skid correction. As wheel speed was initially determined by a weighted average of the two wheel-mounted IMUs, wheel speed may be less accurate in the two-IMU configuration.

Recently, Rupf et al. (2021) developed an IMU-based method that enables detection of wheelchair kinematics using only a single IMU. This method used a single IMU mounted on the wheel to derive both frame rotation and angular speed. Frame rotation was obtained by fusing the accelerometer and gyroscope data such that the attitude of the sensor was determined in a global reference frame. Although this one-IMU configuration is promising and was already tested and compared to the three-IMU configuration, validation with an optical motion capture system has yet to be performed.

The aim of this study is to quantify the decline in accuracy for measuring wheelchair kinematics using a stepwise sensor reduction. Errors in outcome parameters due to skidding may affect the results of one- and two-IMU configurations, whereas additional errors may be introduced in the one-IMU configuration as rotation is measured at the wheel instead of the frame center. It is therefore hypothesized that a lower number of IMUs would result in a lower accuracy of the measured wheelchair kinematics. To test this hypothesis, the one-IMU and two-IMU configurations were validated in a wheelchair sport specific test setting. Secondly, the accuracy of the two approaches was compared for linear and angular wheelchair velocity.

## 2. Methods

### 2.1. Procedure

Ten differently skilled participants (Table 1) performed a series of wheelchair sport-specific activities, while simultaneously being measured with two IMUs on their wheelchair and a marker-based optical motion capture system serving as reference. Calculated outcomes based on the one-IMU configuration, two-IMU configuration and reference system were compared to test the accuracy. Prior to the measurements, participants were informed about the aims and procedures of the study and provided written informed consent. The study was approved by the Human Research Ethics Committee of the Technical University of Delft (nr. 1530).

**Table 1**
Subject characteristics (mean ± standard deviation).

| Type | N | Age (years) | Class[1] | Wheel base | Camber angle | Wheel diameter |
|---|---|---|---|---|---|---|
| Elite wheelchair athlete[2] | 3 | 25.0 ± 3.0 | 3.2 ± 1.3 | 0.75 ± 0.05 | 18, 18 | 0.63 ± 0.02 |
| Active wheelchair user | 3 | 46.3 ± 11.0 | 2.5 ± 0.5 | 0.62 ± 0.23 | 18, 2, 3 | 0.62 ± 0.02 |
| Non-experienced user | 4 | 24.5 ± 0.6 | – | 0.62 ± 0.11 | 18, 4, 4, 4 | 0.61 ± 0.01 |

[1] The classes were indicated by the point scores as used in elite wheelchair basketball classification.
[2] Two wheelchair basketball players (premier league) and one wheelchair hockey player (Dutch national team).

### 2.2. System overview

Two IMUs (NGIMU, x-io technologies) were used to collect 3D inertial sensor data (100 Hz) of the right wheel and the wheelchair frame. A ten-camera optical motion capture system (OptiTrack Prime, National Point) with a frame rate of 100 Hz was used to record the 3D orientation and position of the wheelchair. The wheelchair marker cluster frame consisted of five retro-reflective markers attached to the front and back of the wheelchair frame.

### 2.3. Wheelchair sport-specific activities

The measurement session (see Table 2 and Fig. 1) included sprints and agility exercises that represent some main aspects of wheelchair basketball, tennis, and rugby games (Pansiot et al., 2011; van der Slikke et al., 2015; van Dijk et al., 2021). At the start and end of each session, participants were instructed to keep a static posture for 20 s. Wheelchair athletes performed the session in their own wheelchair if feasible, whereas untrained participants used an ADL (Progeo) or all court sports (Quickie) wheelchair and were instructed to familiarize themselves with the chair (Vegter et al., 2014).

### 2.4. Optical motion capture analysis

OptiTrack three-dimensional position data of the wheelchair markers were acquired in Motive 2.2.0 (Natural Point), converted to a

**Table 2**
All sport-specific tests, together with a description of each test and the speed at which the participants were instructed to perform the test (see also Fig. 1). All tests were carried out in immediate succession.

| Test | | Speed | Description |
|---|---|---|---|
| 1 | Straight 5 m | normal | 3x sprint with static trunk |
| | Straight 5 m | low | 3x |
| | Straight 5 m | normal | 3x |
| | Straight 5 m | high | 3x |
| 2 | Straight skid | high | 2x sprint (stop with skidding wheels) |
| 3 | Slalom | normal | around 3 cones (Fig. 1B) |
| | Slalom | high | around 3 cones (Fig. 1B) |
| 4 | Figure 8 | normal | (Fig. 1C) |
| | Figure 8 | high | (Fig. 1C) |
| 5 | U turn | normal | 180° clockwise turn (Fig. 1D) |
| | U turn | high | 180° clockwise turn (Fig. 1D) |
| | U turn | normal | 180° anti clockwise turn (Fig. 1D) |
| | U turn | high | 180° anti clockwise turn (Fig. 1D) |
| 6 | Turn on spot | normal | 360° clockwise turn |
| | Turn on spot | normal | 360° anti clockwise turn |
| | Turn on spot | high | 360° clockwise turn |
| | Turn on spot | high | 360° anti clockwise turn |
| 7 | Star twist | free | Star wise bi-directional rotation |
| | Star twist | free | As previous, combined with back-and-forth movement (Fig. 1E) |
| 8 | Collision | free | 2× 2 m sprint and collision against a block of 30 kg (Fig. 1F) |

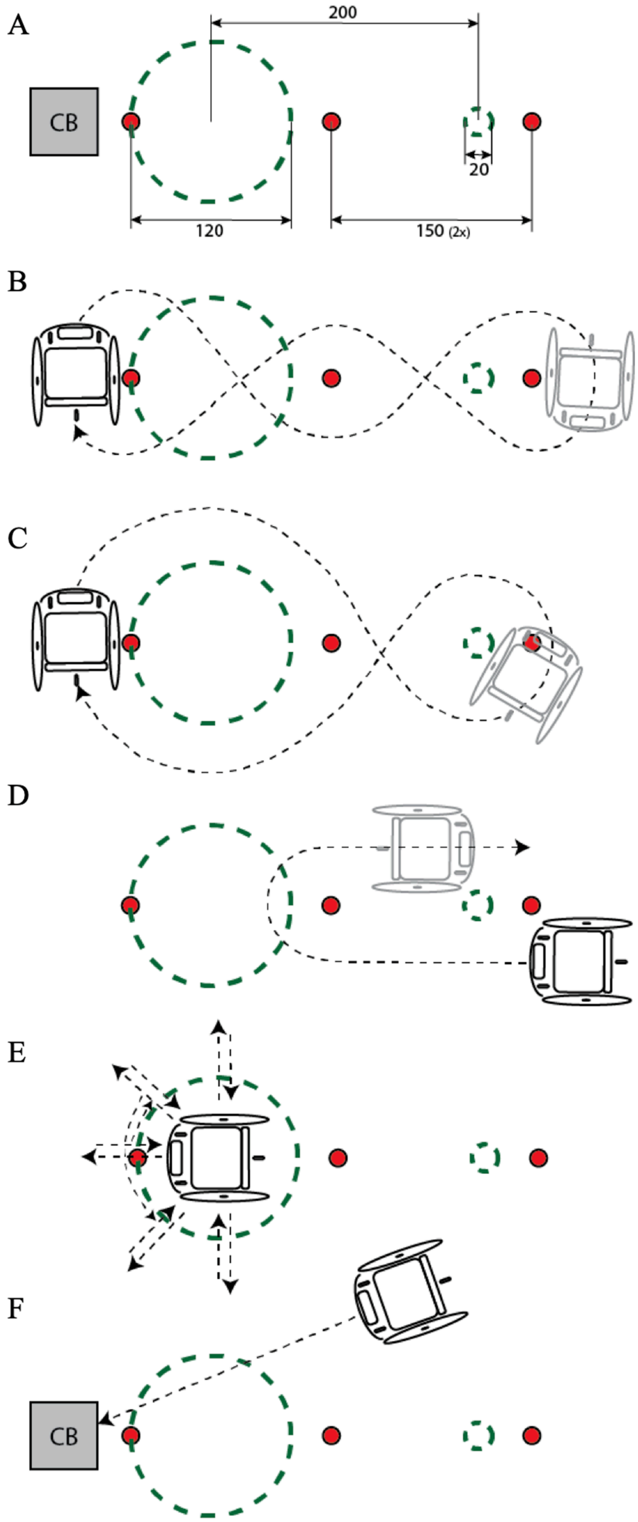


**Fig. 1. (A to F).** Track lay-out with dimensions in cm (A) corresponding to the tests as explained in Table 2. Cones and collision block (CB) were removed during test parts in which they were not used. This figure was adopted from Van der Slikke et al. (van der Slikke et al., 2015).

C3D format and imported in MATLAB (R2019b, The Mathworks Inc.). Missing values were interpolated if the duration of the gap was <1/6 of a second. Accordingly, the rotation matrix and translation vector of the wheelchair segment relative to the first (static) sample was determined using the singular value decomposition described by Söderkvist & Wedin (1993). This required position data of at least three markers at both time instants. The derivative of the angle in the sagittal plane was determined and low-pass filtered at 6 Hz (Cooper et al., 2002) to obtain wheelchair angular velocity. The translation vectors were filtered at 10 Hz (van der Slikke et al., 2015) to filter marker positioning noise. Linear wheelchair velocities were determined according to Eq. (1), with $x$ and $y$ being the positions in the horizontal plane.

$$\left|\sqrt{(ds_x/dt)^2 + (ds_y/dt)^2}\right| \tag{1}$$

### 2.5. Two-IMU analysis

Wheelchair linear and angular velocity based on the two-IMU configuration were calculated as reported by van der Slikke et al. (2015). Wheelchair angular velocity was directly measured by the gyroscope signal around the vertical axis of the frame IMU, and low-pass filtered at 6 Hz. Wheelchair linear velocity was determined based on the gyroscope signal around the wheel axis of the wheel IMU (see Eq. 2.1–2.4 in Appendix A). Wheel angular velocity was low-pass filtered at a 10 Hz cut-off frequency, corrected for camber angle (Eq. (2.1); Pansiot et al., 2011; van der Slikke et al., 2015) and multiplied by the wheel circumference (Eq. (2.2)) to obtain linear velocity of the wheel. To obtain the linear velocity of the frame center instead, an additional correction was performed (Eq. (2.4)).

### 2.6. One-IMU analysis

To analyze the one-IMU configuration, only data from the wheel-mounted IMU were used. A Madgwick filter (Madgwick et al., 2011), with a tuning parameter set at 0.03 (Rupf et al., 2021), was used to derive the attitude of the sensor. The resulting Euler angles were differentiated with respect to time (Rupf et al., 2021) and low-pass filtered at 6 Hz. Wheelchair angular velocity was defined by the angular velocity in the horizontal plane. Since the sensor orientation was obtained relative to the global earth frame, no correction for camber angle was required. Wheelchair linear velocity was derived in the same way as for the two-IMU configuration (see Eq. 2.1–2.4 in Appendix A).

### 2.7. Comparisons

IMU data and reference data were synchronized with respect to time using a cross-correlation of the angular velocity. Mean error, mean absolute error (MAE), root mean squared error (RMSE), maximal error and the 95% confidence intervals of the difference between different sensor configurations and reference data were reported for linear (absolute linear velocity $> 0.1$ m/s) and rotational (angular velocity $>5^\circ$/s or $<-5^\circ$/s) wheelchair movements. Further, the start and end of each exercise of interest was selected manually based on the plots.

## 3. Results

Table 3 shows the error measures for the two different configurations compared to the reference system. Table 4 shows characteristics and error measures per subject group as defined in Table 1. Figs. 2 and 3

**Table 3**
Differences between the given sensor configuration and the reference system expressed as mean absolute error (MAE), root-mean-squared error (RMSE), mean error, maximal error, and upper and lower bound of the confidence interval (CI). The mean (SD) of the outcome measures over all participants was reported.

| Config. | MAE | RMSE | Mean error | Max error | CI lower bound | CI upper bound |
|---|---|---|---|---|---|---|
| | Angular velocity in deg/s | | | | | |
| One IMU | 8.1 (2.5) | 11.2 (3.3) | −0.1 (0.3) | 55.6 (22.1) | −0.2 (0.3) | 0.0 (0.3) |
| Two IMUs | 3.0 (3.3) | 4.6 (4.9) | −0.2 (0.3) | 23.9 (15.3) | −0.2 (0.3) | −0.1 (0.3) |
| | Linear velocity in m/s | | | | | |
| One IMU | 0.10 (0.06) | 0.19 (0.11) | −0.03 (0.05) | 1.55 (1.52) | −0.03 (0.05) | −0.03 (0.05) |
| Two IMUs | 0.10 (0.05) | 0.20 (0.10) | −0.02 (0.05) | 1.44 (1.47) | −0.02 (0.05) | −0.01 (0.05) |

show typical examples of the linear and angular velocities measured by the one-IMU configuration, two-IMU configuration and reference system.

## 4. Discussion

The aim of this study was to quantify the decline in accuracy for measuring wheelchair kinematics using a stepwise sensor reduction. Compared to the reference system, the one-IMU approach show a MAE of 0.10 m/s for wheelchair linear velocity and a MAE of 8.1°/s for angular velocity. The two-IMU approach showed similar differences for linear wheelchair velocity (MAE 0.10 m/s), and smaller differences for angular velocity (MAE 3.0°/s). Plots to compare the different approaches show a small sinusoidal deviation for the one-IMU approach which is mainly visible in angular wheelchair velocity.

To put the present results into perspective, the accuracy obtained for linear and angular velocity were compared with those previously

**Table 4**
Mean and maximal values of the angular and linear velocities, and differences between the one- and two IMU configurations and the reference system expressed as MAE and RMSE averaged for each subject group.

| Group* | Sensors | Angular velocity in deg/s | | | | Linear velocity in m/s | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean | Max | MAE | RMSE | Mean | Max | MAE | RMSE |
| EA | IMU1vsOpti | 17.5 | 450 | 7.1 | 9.8 | 0.41 | 3.51 | 0.15 | 0.28 |
| EA | IMU2vsOpti | – | – | 2.5 | 3.8 | – | – | 0.14 | 0.28 |
| EU | IMU1vsOpti | 18.2 | 328 | 8.8 | 12.5 | 0.41 | 3.15 | 0.10 | 0.21 |
| EU | IMU2vsOpti | – | – | 6.3 | 9.3 | – | – | 0.10 | 0.22 |
| NU | IMU1vsOpti | 15.0 | 272 | 8.3 | 11.2 | 0.36 | 2.75 | 0.07 | 0.12 |
| NU | IMU2vsOpti | – | – | 1.0 | 1.7 | – | – | 0.06 | 0.11 |

*EA = Elite Athlete, EU = Experienced wheelchair user, NU = non-experienced user

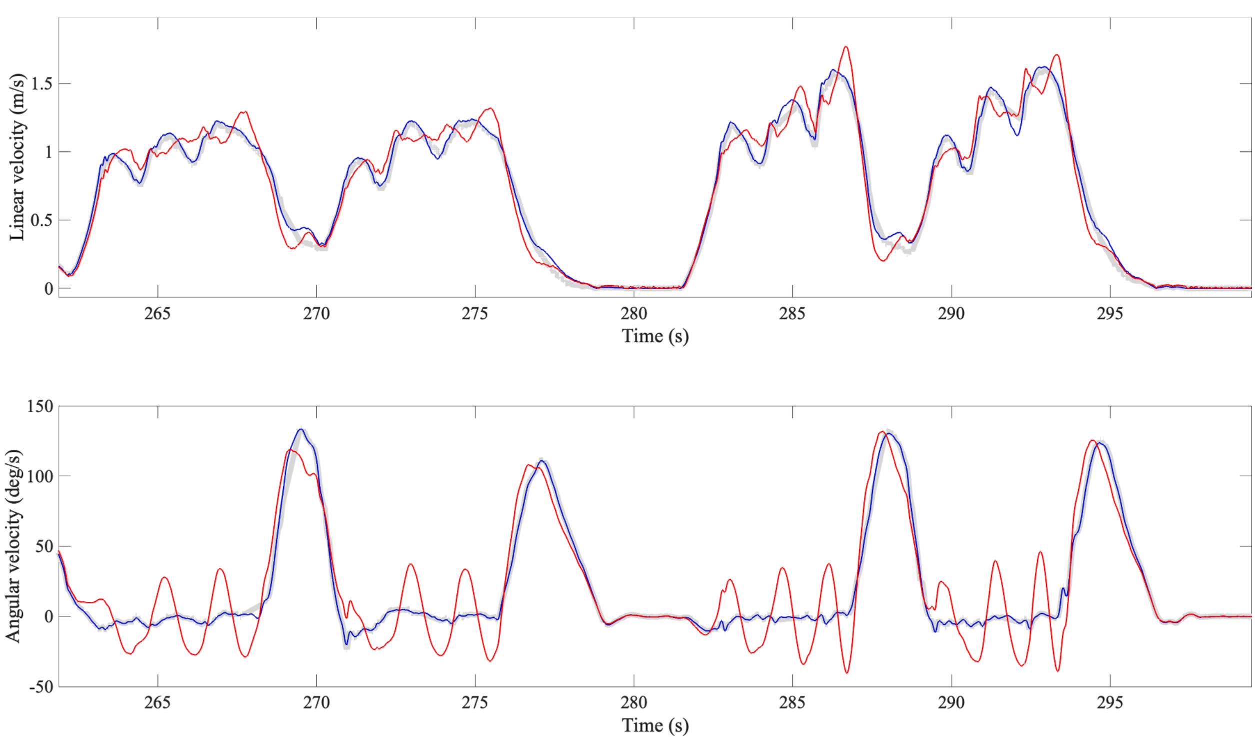


**Fig. 2.** Typical examples of the angular velocity and linear velocity during two linear sprints at low speed and two linear sprints at normal speed (see Table 2, test 1). The results from the two-IMU analysis are indicated in blue, One-IMU analysis are indicated in red, and those of the optical motion capture system were indicated in grey. Although both IMU configurations match the patterns of the reference system, striking differences for the one-IMU frame angular velocity show in sinusoidal deviations in straight forward motion. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

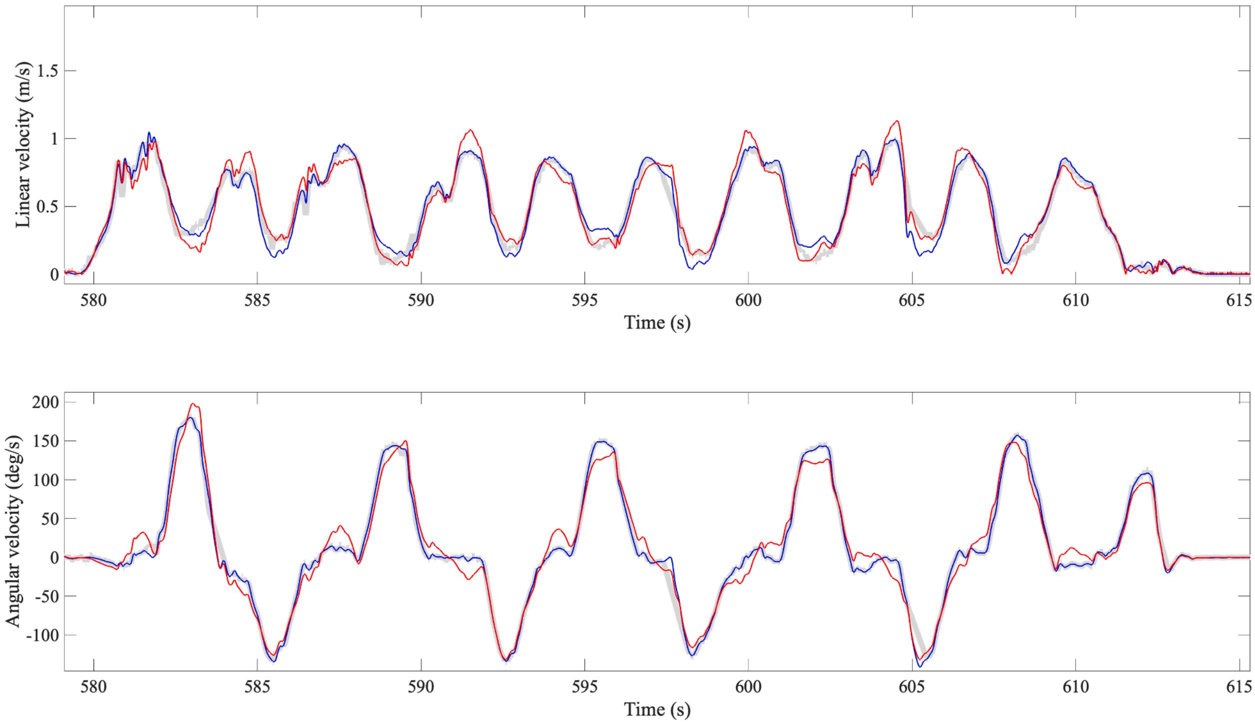


**Fig. 3.** Typical examples of the angular velocity and linear velocity during a bidirectional star twist (see Table 2, test 7). The results from the two-IMU analysis are indicated in blue, one-IMU analysis are indicated in red, and those of the optical motion capture system were indicated in grey. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

reported for wheelchair sports. Van der Slikke et al. (2015) validated the three-IMU configuration with an optical motion capture system and reported an average RMSE of 0.07 m/s (ranging from 0.03 to 0.27 m/s) for linear velocity, which is smaller than the 0.19 and 0.20 m/s for the one and two-IMU configurations in this study, respectively. The increased accuracy of the three-IMU configuration is likely due to skid-correction. As skidding causes a mis-match between wheel rotation and frame displacement, larger errors in frame displacement occur when skidding is not identified. Since the skid-detection algorithm is based on two wheel-mounted sensors, this can only be applied in the three-IMU algorithm. However, further development of IMU analyses in the global reference frame may enable skid correction with less than three IMUs as well.

Regarding angular velocity, van der Slikke et al. (2015) reported an average RMSE of 4.8°/s (ranging from 3.1 to 6.8°/s) among different wheelchair specific tests. This error is smaller than the 11.2°/s RMSE for the one-IMU configuration and similar to the 4.6°/s RMSE for the two-IMU configuration which were found in our study. One explanation for the larger error and the sinusoidal deviation (see Fig. 2), found for the one-IMU configuration, may come from the way the IMU was mounted around the wheel axle. Due to the wheel camber angle and a non-zero axle diameter, a small lateral displacement relative to the frame center was induced with each wheel rotation. Since the one-IMU algorithm determines the IMU attitude with respect to the global reference frame (Rupf et al., 2021), these lateral displacements may be interpreted as small wheelchair rotations. Better results might be obtained by attaching the IMU to the lateral side of the wheel axle or by correcting for the lateral displacement induced by wheel rotation. Another possibility is to lower the cut-off frequency of the low-pass filter as done by Rupf et al. (2021). Eventually, optimization of the sensor fusion tuning parameter may further enhance the potential of one-IMU analyses (van Dijk et al., 2021).

### 4.1. Practical implications and limitations

Overall, the hypothesis that a lower number of IMUs would result in less accurate wheelchair kinematics was confirmed by this study. Given the mean error (0.03 m/s) with regard to linear wheelchair velocity for the one-IMU configuration, this configuration may well be used to determine average velocity or distance covered over a certain time interval (e.g., over a 3-minute interval at 1.4 m/s [low-point player], the distance covered deviates approximately 2%, or 5 m, over 250 m). However, to assess wheelchair (angular) velocity at the push level or to accurately determine field position, the three-IMU configuration is advised. Depending on the intended accuracy and resources available, fewer than three sensors may be used to obtain wheelchair kinematics.

Although this study provides a clear overview on the trade-off between number of sensors and accuracy regarding wheelchair kinematics, a few limitations should be noted. The number of wheelchair athletes was relatively low and top speeds that were achieved during the measurements were lower than during wheelchair sports matches due to the limited measurement area. Still, the results of this study are expected to be well transferable to wheelchair match settings since all subject groups showed similar trends, most participants performed the measurements in their own wheelchair and a wide variety of wheelchair sport-specific situations were included.

### 4.2. Conclusion

The present study aimed to quantify the trade-off between the number of sensors and accuracy for measuring wheelchair kinematics in wheelchair court sports. Results revealed that a lower number of IMUs used in the configuration would result in a lower accuracy of wheelchair kinematics. While one IMU seems sufficient to determine average wheelchair velocity, three IMUs are advised to analyze wheelchair kinematics on a push level. Based on the present results, choices regarding the number of IMUs can be made depending on the aim, required accuracy and resources available.

## CRediT authorship contribution statement

**Marit P. van Dijk:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft, Visualization. **Rienk M.A. van der Slikke:** Conceptualization, Software, Writing – review & editing. **Rob Rupf:** Software, Writing – review & editing. **Marco J.M. Hoozemans:** Conceptualization, Supervision. **Monique A. M. Berger:** Conceptualization, Supervision. **DirkJan H.E.J. Veeger:** Conceptualization, Supervision.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A

$$AV_{wheel,corrected} = AV_{wheel} + \tan(\varphi_{camber})*AV_{frame}*\cos(\varphi_{camber}) \tag{2.1}$$

$$LV_{wheel} = AV_{wheel,corrected}*WheelCircumference \tag{2.2}$$

$$d_{axle,center} = WheelBase/2 - \sin(\varphi_{camber})*0.5*WheelDiameter \tag{2.3}$$

$$\mathrm{LV_{frame}} = LV_{wheel} - \left(\tan\left(\mathrm{AV_{frame}}/\mathrm{fs}\right)*d_{axle,center}\right)*\mathrm{fs} \tag{2.4}$$

In which, $AV_{wheel}$ the angular wheel velocity, $\varphi_{camber}$ is the camber angle of the wheels, $LV_{wheel}$ is the linear wheel velocity and $d_{axle,center}$ is the distance from the wheel axle to the frame center. For clarity purposes, wheelchair angular and linear velocity (as indicated in the text) are referred to as $AV_{frame}$ and $LV_{frame}$. The calculations are based on the approach as described by van der Slikke et al. (2015).

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