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Load and performance monitoring in wheelchair court sports: A narrative review of the use of technology and practical recommendations.

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Running Head: Load & performance monitoring in wheelchair court sports

Abstract

Quantifying measures of physical loading has been an essential part of performance monitoring within elite able-bodied sport, facilitated through advancing innovative technology. In wheelchair court sports (WCS) the inter-individual variability of physical impairments in the athletes increases the necessity for accurate load and performance measurements, while at the same time standard load monitoring methods (e.g. heart-rate) often fail in this group and dedicated WCS performance measurement methods are scarce.

The objective of this review was to provide practitioners and researchers with an overview and recommendations to underpin the selection of suitable technologies for a variety of load and performance monitoring purposes specific to WCS.

This review explored the different technologies that have been used for load and performance monitoring in WCS. During structured field testing, magnetic switch-based devices, optical encoders and laser systems have all been used to monitor linear aspects of performance. However, movement in WCS is multidirectional, hence accelerations, decelerations and rotational performance and their impact on physiological responses and determination of skill level, is also of interest. Subsequently both for structured field testing as well as match-play and training, inertial measurement units mounted on wheels and frame have emerged as an accurate and practical option for quantifying linear and non-linear movements.

In conclusion, each method has its place in load and performance measurement, yet inertial sensors seem most versatile and accurate. However, to add context to load and performance metrics, position-based acquisition devices such as automated image-based processing or local positioning systems are required.

Keywords: Paralympics, physical preparation, technology, performance, monitoring, inertial measurement units

Highlights

- Objective measures of wheelchair mobility performance are paramount in wheelchair court sport support, since they enable quantification of workload across athletes of all classifications and in structured field testing, training and match play settings.
- Given the variety of methods for load and performance monitoring in wheelchair court sports, this review: identified and examined the technology available; provides meaningful insights and decision guidelines; describes applicability for different goals; and proposes practical recommendations for researchers and sports professionals.

- Wheelchair mounted inertial sensors are most reliable and versatile for measuring wheelchair mobility performance and estimates of workload, yet a combination with local position measurement via indoor tracking or image-based processing could be useful to add context.
- For wheelchair athletes bound to a wheelchair for daily use, workload monitoring on a regular basis, both on- and off-court, is crucial to avoid overuse injuries. Alternatively, in athletes with lower severity impairments often lack frequent exposure to optimal and progressive loading, reducing the likelihood of positive physiological adaptations.

1. Introduction

Performance monitoring is a fundamental part of a sport scientist's responsibilities, specifically workload quantification (Burgess, 2017). Work performed by athletes and concomitant physiological responses (external and internal load respectively) are measured constantly in elite sport to support periodised training prescription, monitor adaptations, and mitigate fatigue and injury (Bourdon et al., 2017). Technology has broadened the capacity for monitoring workload, with global positioning systems (GPS) integrated with microelectromechanical sensors (MEMS) offering quantification of location, volume, intensity and frequency of activities performed in a user-friendly manner (Cummins, Orr, O'Connor, & West, 2013). While GPS has been adopted widely in able-bodied sports, the technology is not universally practical.

Wheelchair basketball (WB), wheelchair rugby (WR) and wheelchair tennis (WT), collectively known as the wheelchair court sports (WCS), share unique characteristics which restrict application of mainstream technologies. First of all, mainstream measures for physiological cost are inadequate for the full breadth of Paralympic athletes, since heart rate responses might differ, with consequential underestimations of high intensity activity load (Paulson, Thomas AW, Mason, Rhodes, & Goosey-Tolfrey, 2015). Since in a wheelchair it is possible to coast with minimal effort, high intensity activities in WCS are characterized by multidirectional movement with intermittent linear and rotational high-speed activity (van der Slikke, Berger, Bregman, & Veeger, 2020) incorporating rapid accelerations and rotational movements (Van der Slikke, Berger, Bregman, & Veeger, 2015). For accurate load estimations, global metrics often used in mainstream technology (e.g. time in high speed zones) may inadequately represent WCS nuances. Furthermore, WCS are mostly played indoors (no GPS) and court dimensions are relatively small (WB & WR: 28.0 x 15.0m; WT: ~35.0 x 16.5m), so the level of detail and accuracy should be fitting (van der Slikke et al., 2020).

Whilst issues are clear, credible options for accurate and reliable quantification of WCS performance have not yet been popularised. In consequence, practitioners have limited evidence-based information pertaining to physiological load, performance capabilities, external demands and inter-individual differences. Training prescription inevitably involves estimations and is generic rather than individualised, such factors predispose to detrimental performance outcomes and injury (Paulson & Goosey-Tolfrey, 2017; Paulson et al., 2015). This approach is confounded by the considerable inter-individual variability in WCS athletes, whereby a spectrum of health conditions and impairments are involved. Exposure to optimal and progressive overload may be impossible in athletes with lower severity impairment (highest classification), reducing the likelihood of positive physiological adaptations. Alternatively, those with the most impairment (lowest classification) could overtrain, with resultant performance maladaptation coupled with heightened injury risk and associated concerns (Paulson & Goosey-Tolfrey, 2017). WCS load and performance monitoring requires alternative methods, with different approaches applied. Therefore, there is a requirement for synthesis of current methods, and an evaluation of scientific application in the WCS.

Hence, the aims of the current narrative review were to i) identify and examine the technology within WCS literature for load and performance monitoring to identify the studies with meaningful insights; ii) establish the applicability of these technologies in sports practice, and ultimately iii) propose practical recommendations for WCS performance monitoring.

2. Methods

A comprehensive search of relevant databases (PubMed, Scopus, Google Scholar) was performed in January 2021 using the Publish or Perish tool (https://harzing.com/resources/publish-or-perish). Search terms associated with 'wheelchair', 'sport', 'performance' and 'technology' were used to assess suitability (full list of search terms, see Supplementary Material). Articles were included if a form of technology was used for quantifying performance load metrics in WCS, with no restriction on the year of publication. Articles that violated these criteria were excluded, alongside review articles or articles not available in English.

An initial search yielded 3,198 articles, with 1,166 remaining after removing duplicates and incomplete references. Two authors independently conducted stage-wise eligibility screening, with title- followed by abstract-screening for review relevance. Subsequently, reviewers selected 59 and 67 papers respectively, with consensus attained (n=72). Per method and research area, all selected papers were used but only the key references were included, to comply with journal review paper policy.

3. Technologies used to monitor field-based performance in WCS

Within the identified research, data were extracted according to technology type. Upon further inspection, a clear distinction was observed regarding how technologies acquired performance metrics. Technology was utilised to directly measure: a) *wheel speed* or *wheelchair* *acceleration* for determination of distance and speed ('*speed-based acquisition technologies'* - Table 1), or b) *wheelchair (field) position*, to derive distance and speed-based metrics ('*position-based acquisition technologies'* - Table 2). Moreover, technology was applied to monitor performance during '*structured field-based testing*' or during '*unstructured match-play scenarios*'. Subsequent sections describe the available technologies stratified by these distinctions and explain their application (Figure 1).

3.1 Speed-based acquisition technologies

3.1.1 Magnetic switch-based devices

The earliest speed-based technology used to measure WCS performance in a field-based environment were wheel-mounted magnetic switch cycle computers (MSCC) (Coutts, K. D., 1992). In this device two magnets are positioned on the spokes of a single wheel, 180° apart, with a reed-switch (1000 Hz) secured to the frame recording wheel rotation. Wheel diameter can then be used to estimate wheelchair speed.

MSCC were primarily used to determine linear sprint profiles of WB players during structured field-based testing (Figure 1), with speed traces used to predict drag characteristics and power output requirements (Coutts, 1992; Coutts, Kenneth D., 1994). Maximal linear sprinting capabilities were also reported, with sex-specific comparisons for WB players (Coutts, 1991; Coutts, 1994). Peak speeds up to 4.98 $m \cdot s^{-1}$ (male) and 4.54 $m \cdot s^{-1}$ (female) were observed, which was the first indication of speeds reached by WCS athletes during field-based testing (Coutts, 1991; Coutts, 1994). MSCC had also been trialled to explore WB demands (Coutts, 1994) during unstructured match-play (Figure 1). In a simulated game players attained peak speeds of ~4 m·s^{-1} and mean speeds of ~2 m·s^{-1}. Data extrapolation revealed that WB players could cover ~5 km during a match (Sporner et al., 2009).

Based on similar principles, miniaturised data loggers (MDL) were later used to monitor WCS performance (Sindall, Lenton, Tolfrey et al., 2013). MDLs are self-contained, long-life lithium battery-powered units, with three reed switches and a magnetic pendulum housed within. Similar to MSCC, wheel rotation is recorded with a reed switch, yet with higher accuracy (3 vs 2 switches). Although MSCC was never validated for WCS, MDL demonstrated excellent accuracy at speeds ≤ 2.5 m·s^{-1}, with coefficients of variation (CV) of ≤ 0.4 % reported. Yet at speeds > 2.5 m·s^{-1}, concerns were noted (~ 20 %) (Sindall, Lenton, Whytock et al., 2013). Given that speeds ≥ 4.0 m·s^{-1} have been reported for linear sprinting and WB match-play (Coutts, 1992; Coutts, 1994), limitations are noteworthy for wider application in WCS.

Early MDL studies only used one wheel-mounted unit during WB, WR (Sporner et al., 2009) and WT (Sindall et al., 2013) match-play (Figure 1) and in addition to peak speed, mean speed and distance data, also explored: starts and stops, propulsion direction (forwards vs. reverse), and time in speed zones. However, due to the multidirectional nature of WCS match-play, authors acknowledged likely over- or under-estimations dependent on the wheel selected and the turn direction (Sindall et al., 2013). Consequently, more recent MDL studies have favoured the use of two units, one on each wheel (Mason, Lenton, Rhodes, Cooper, & Goosey-Tolfrey, 2014; Sindall, Lenton, Cooper, Tolfrey, & Goosey-Tolfrey, 2015).

Although the validity and reliability of using two MDLs has never been examined, it is considered preferable for estimation of overall external workload by mitigating the effect of turns (Sindall et al., 2014). As such, two MDLs have been used to provide a more comprehensive examination of WT demands, stratified by rank and sex (Sindall et al., 2015). Although not sensitive to small movements or higher (>2.5 m·s^{-1}) speeds, two MDL units have been used successfully to examine the effect of using low compression tennis balls on court-movement variables (Sindall et al., 2014) and the influence of tennis-specific mobility drills (Sindall et al., 2021) on WT skill development in novices.

3.1.2 Optical encoders

Optical encoders offer an alternative means for collecting speed-based metrics with one such device, the ‘velocometer’, developed specifically for wheelchair sports (Moss, Fowler, & Tolfrey, 2003). The velocometer houses an optical encoder fixed to the wheelchair frame and a Perspex disc attached to the inside of a single wheel. During a calibration trial, the number of pulses for one complete wheel revolution is recorded (1000 Hz), converted to speed data, and wirelessly transmitted to a local computer (<200 m range). However, at ~ 0.7 kg, the velocometer is considerably heavier than the MDL (~ 0.1 kg per unit), affecting handling.

Like the MSCC and early MDL iterations, the velocometer only collects data from one wheel, so performance measurements have focussed on linear sprinting capabilities, such as intra-push profiles of WT players, and the effect of racket-holding on propulsion (Goosey-Tolfrey & Moss, 2005). Propulsion while holding a racket, requires additional skill (Diaper & Goosey-Tolfrey, 2009), reduces acceleration from standstill (Moss et al., 2003), and therefore, increases physiological load (Diaper & Goosey-Tolfrey, 2009; Goosey-Tolfrey & Moss, 2005). The velocometer has also been used as a research tool to assess the effectiveness of different wheelchair configurations (Mason, Van Der Woude, Lenton, & Goosey-Tolfrey, 2012; Mason, Van Der Woude, Tolfrey, & Goosey-Tolfrey, 2012). Despite only being appropriate for linear performance assessments, average root mean square deviations (≤ 6.0 %) across a range of speeds in excess of typical WCS match-play values, confirm context-specific device applicability.

3.1.3 Inertial measurement units

Introduction of inertial measurement units (IMUs) into WCS has enabled practical and accurate measurement of multidirectional movements. While IMUs include accelerometers and gyroscopes (Chua, Fuss, & Subic, 2011; Usma-Alvarez, Chua, Fuss, Subic, & Burton, 2010), both functions are not always applied in parallel, with consideration of the metrics of interest and sensor location on the wheelchair determining operation.

Single frame-mounted IMUs initially utilised accelerometers from devices such as smart phones (Chua, Fuss, Kulish, & Subic, 2010) or GPS units (Chua et al., 2011) to measure wheelchair acceleration and derive temporal performance parameters. In this capacity IMUs have been used to profile aspects of linear sprinting performance in WB (Bergamini et al., 2015) and WR (Haydon, Pinder, Grimshaw, & Robertson, 2018a; Haydon, Pinder, Grimshaw, & Robertson, 2018b), alongside estimation of drag and power requirements (Chua et al., 2010). Although accelerometery data from a frame-mounted IMU has been used to examine turning performance, it is predominantly restricted to linear-based, field testing (Figure 1).

Wheel-mounted IMUs have utilised gyroscopes to measure wheel angular velocity, enabling determination of wheelchair speed. When one wheel-mounted IMU has been used, speed metrics and intra-push profiles can be examined during linear sprinting (Mason, Rhodes, & Goosey-Tolfrey, 2014). In such cases, the advantage of an IMU over a magnetic switch device, is the continuous signal with high sampling frequency (typically $\geq$ 50 Hz) and therefore greater accuracy, with low random errors in speed (< 0.06 $m{\cdot}s^{-1}$, up to speeds of 6.0 $m{\cdot}s^{-1}$) (Mason et al., 2014).

The addition of a second sensor (opposing wheel), alongside known wheelchair dimensions (i.e. wheel size, camber angle and wheelbase width) and calculation of between-wheel speed differential, enables estimation of turning direction and velocity during non-linear movements (Hiremath, Ding, & Cooper, 2013; Pansiot, Zhang, Lo, & Yang, 2011; Xu et al., 2010). From this, valuable information about chair orientation, direction and distance can be calculated. Pansiot et al. (2011) reported relative distance errors of < 0.7% when using two wheel-mounted sensors, which is less than the 3.1% reported from a single IMU sensor using a novel 'Attitude Heading and Reference System' sensor fusion algorithm (Shepherd, Wada, Rowlands, & James, 2016). Error reduction can be attributed to measurements being less prone to wheel skidding (Shepherd et al., 2016). That said, both these validation studies were conducted at very low speeds, and therefore lack validity for sports application (Hiremath et al., 2013; Shepherd et al., 2016). To confirm suitability of wheel-mounted sensors for WCS match-play, validation must involve typical movements and representative speeds.

More recently, three IMUs using gyroscope data from two wheel-mounted sensors in conjunction with accelerometer data from a frame-mounted sensor, have been adopted in WCS (van der Slikke, Berger, Bregman, & Veeger, 2016; Van der Slikke et al., 2015; Van der Slikke, Berger, Bregman, Lagerberg, & Veeger, 2015; Van der Slikke, Berger, Bregman, & Veeger, 2016). Here, the speed of both wheels is known, alongside the acceleration and rotational speed of the wheelchair frame, enabling detection and correction for cases of wheel skidding (Van der Slikke et al., 2015). Once corrected, errors < 0.8% have been observed for wheelchair and rotational speed during validation at speeds and movements consistent with WB match-play (Van der Slikke et al., 2015). The three-sensor IMU configuration enables more robust outcome measures for both linear and non-linear movements, which confirms appropriateness for both structured field-based testing and unstructured match-play scenarios (Figure 1).

Three IMU sensors have been used to profile WB players performance during structured field tests (van der Slikke et al., 2016), to validate field tests for profiling purposes in WT (Rietveld et al., 2019) and to explore wheelchair configurations effectiveness (Haydon, Pinder, Grimshaw, & Robertson, 2018c; Van Der Slikke, De Witte, Berger, Bregman, & Veeger, 2018). During unstructured scenarios, three IMUs have identified the external demands of WCS competition (Van der Slikke et al., 2016), provided further insight into evidence-based classification (van der Slikke, Bregman, Berger, & De Witte, 2018) and explored the effectiveness of specific training interventions (van der Slikke et al., 2020). In addition to global measures of peak speed, mean speed and distance data previously provided by magnetic switch devices, IMUs offer detailed information about linear and rotational speed and acceleration performance. These accelerations, decelerations and rotations are important aspects of performance from a physiological perspective, since they closely relate to exerted force. In global metrics, these important nuances are missed. Frequent 'coasting' (i.e. wheelchair movement without internal input) may result in overestimation of workload, whereas frequent rotations might be ignored, resulting in workload underestimations. Therefore, the combined global and discrete measures provided by the three IMU configuration offers the most complete solution for practitioners in terms of the speed-based acquisition technologies.

3.2 Position-based acquisition technologies

3.2.1 Laser systems

Laser systems operate via the time-of-flight principle; systems emit a laser beam at frequencies up to 2,000 Hz, which reflects off an object and returns to the laser. The time difference between signal-emission and -return determines the laser-to-object distance and thereby, distance and speed profiles. Systems are frequently used in sprint analysis, including WCS (Ferro, Villacieros, & Pérez-Tejero, 2016). As the beam is typically aimed at a fixed component on the wheelchair-user system, no instrumentation of the wheelchair or athlete is required, making it practicable for testing of multiple athletes in straight line field testing, as seen in WB players (Ferro et al., 2016; Villacieros et al., 2020). Yet, the system is neither able to quantify non-linear performance, or the dynamic movement associated with match-play or training situations (Figure 1).

3.2.2 Image-based processing

Image-based processing techniques, typically relying on low-speed (10 to 25 Hz), stationary, overhead video cameras to capture 2D player movements, have been utilised during WT (Filipčič & Filipčič, 2009) and WR (Sarro, Misuta, Burkett, Malone, & Barros, 2010). Measured court locations can be used to calibrate the surface volume, with athlete movement digitised and processed to quantify speed and distance parameters (Filipčič & Filipčič, 2009; Sarro et al., 2010). Like laser systems, image-based processing offers a non-invasive and instrumentation-free approach. The added benefit of image-based processing is collection of basic speed and distance measurements during non-linear movements and as such, quantification of global aspects of workload during match-play (Filipčič & Filipčič, 2009; Sarro et al., 2010). However, low frame rates and lack of wheelchair instrumentation preclude measurement of acceleration or rotational performance.

Other limitations also exist with this technique. Firstly, the automated image-based tracking system adopted by Sarro et al. (2010) was originally developed for soccer, whereby automated tracking was possible for 95% of the time (Barros et al., 2007). Unfortunately, when applied to WR, automated tracking was only possible ~ 20% of the time, and therefore, considerable manual digitising was required (Filipčič & Filipčič, 2009). Such an approach is highly time consuming, prone to error, limits the amount of data analysis, and delays feedback. Although technological advancements have increased accuracy and ease-of-use in marker-less tracking in a general sporting context, no recent validation studies in WCS are available.

3.2.3 Local positioning systems

Radio-frequency-based local positioning systems have also been used to monitor workload metrics in soccer (Barros et al., 2007) and within WCS (Rhodes, James, Mason, Perrat, Smith, & Goosey-Tolfrey, 2014). These systems function similarly to GPS but in an indoor environment, with satellites represented by fixed sensors positioned around the court perimeter. Sensor position is calibrated to known court dimensions and fixed reference points. Lightweight, athlete-worn tags communicate via ultra-wideband signals to the sensors for determination of position. Numerous local positioning systems exist, however only the Indoor Tracking System (ITS; Ubisense) was developed and validated for WCS (Rhodes et al., 2014). ITS is a wired system, utilising angle-of-arrival and time-difference-of-arrival of the ultra-wideband signals to provide positional coordinates of tags in three dimensions with respect to time. This enables speed metrics, time spent in speed zones, and distance to be derived.

The ITS has an overall bandwidth of 137 Hz, typically resulting in a sampling frequency of 8 Hz per athlete for WR and WB (Mason, van der Slikke, Hutchinson, Berger, & Goosey-Tolfrey, 2018; Rhodes, James M. et al., 2015), whereas during WT, where fewer athletes compete at once, 16 Hz has been adopted (Mason, van der Slikke, Hutchinson, & Goosey-Tolfrey, 2020). Whilst sampling frequency, number of sensors and positioning of the tags can affect measurement accuracy (Perrat, Smith, Mason, Rhodes, & Goosey-Tolfrey, 2015; Rhodes et al., 2014), ITS validity and reliability is comparable with other proven technologies. During standardised and sport-specific validation trials, errors for distance, mean and peak speed never exceeded 2.0% with excellent inter session reliability (≤ 2.7% CV) across a range of sampling frequencies (4 – 16 Hz) (Rhodes et al., 2014).

ITS accuracy, coupled with practicality, suggests appropriateness for training and match-play data collection (Figure 1). ITS has been used to quantify workload in WR and WT match-play according to athlete classification (Mason, Altmann, & Goosey-Tolfrey, 2019; Mason et al., 2020; Rhodes et al., 2015) and applied during competition to examine demands according to rank and outcome (Mason et al., 2020; Rhodes, James M., Mason, Malone, & Goosey-Tolfrey, 2015). This has enabled assessment of the training environment, comparing current external training loads with competitive demands (Rhodes, James M., Mason, Paulson, & Goosey-Tolfrey, 2017), with training manipulated according to characteristics such as drill type (i.e. conditioning, skill-based etc.), timing method (i.e. shot-clock manipulations), court size, and number of players, with effects on workload investigated (Rhodes et al., 2017; Rhodes, Mason, Paulson, & Goosey-Tolfrey, 2018). These outcomes are of considerable practical value to coaches in devising and evaluating the effectiveness of training regimes. ITS also has efficacy as a research tool. Previous studies have attempted to quantify the internal load (Paulson et al., 2015) and the thermoregulatory responses (Griggs, Havenith, Price, Mason, & Goosey-Tolfrey, 2017) of WR match-play, utilising ITS based workload metrics to interpret findings.

Akin to image-based processing, a limitation with ITS is that global measures of workload are reported, without identification of rotational measures. Although ITS is valid and reliable for reporting speed and distance, with only minor differences in speed and distance (< 1%) compared to IMUs (Van der Slikke, Mason, Berger, & Goosey-Tolfrey, 2017), the absence of rotational acquisition measures could underestimate load measures. Despite potential limitations, a clear advantage to local positioning systems over speed-based acquisition technologies is inclusion of positional data. This information could be used tactically to link court-location with desired outcomes. Such a feature increases appeal, both to coaches and athletes, adding context and value to the metrics.

4. Practical Applications and Conclusions

A range of devices have been implemented within WCS to monitor load and performance, each with practical advantages and limitations (Figure 2). To underpin recommendations concerning potential applications, key considerations have been summarised (Figure 2), since no single device can satisfy all scenarios currently.

For appropriate selection of technology, due consideration of movement path (i.e. linear or multidirectional) and context (i.e. structured field testing or unstructured match-play scenarios) is required. Straight sprint tests are often applied to determine maximal aerobic performance, which could be achieved by laser systems or single wheel-mounted devices such as the MSCC. To measure physiological match load, all sports related aspects need to be included, so multidirectional performance, with the testing environment becoming a related factor. During unstructured match-play settings, where movements and intensities are random, global measures of workload are sufficient where, pending further considerations, two MDL units, IMUs, image-based processing or local positioning systems are possibilities. If player-location metrics are paramount, image-based processing or local positioning systems are required.

To further streamline decision-making, consideration must also be afforded to why performance is being monitored. The rationale can be expansive yet classified into two categories; athlete support or research, both of which involve structured and / or unstructured data collection environments. If conducting structured field-based testing, whether validating new tests or for longitudinal performance profiling, the accuracy and practicality of the technology is imperative, since large random errors inherent within performance monitoring technology could lead the practitioner or coach to advocate inappropriate training recommendations. Subsequently for linear sprint testing, IMUs or laser devices are preferable.

During unstructured match-play / training environments, accuracy will also be important for research-based interventions, meaning that the ITS and IMUs are best suited. If the purpose of monitoring is to establish the external demands of match-play or training, sport-specific considerations must be at the fore. Will the venue be constant, or are changes in court / venue anticipated? If multiple locations are involved, speed-acquisition devices represent the best option as these are wheel-mounted and can remain on a wheelchair or be promptly re-installed between venues. Alternatively, position-based acquisition devices such as the ITS or automated image-based processing cannot realistically be transferred, reinstalled or calibrated between multiple locations, restricting their application to single sites. That said, and to reiterate, if positional data is needed to supplement workload, position-based acquisition devices are necessary. In this instance, local positioning systems are advocated ahead of image-based processing devices due to the lack of automated tracking experienced during WCS applications currently (Sarro et al., 2010). The most effective solution for quantifying workload during match play or training scenarios could be a combination of speed- and position-based acquisition devices. Such 'hybrid' solutions have been adopted recently which incorporated IMU and ITS in unison (Mason et al., 2018; Mason et al., 2020). This solution allows for the accuracy and detail of both linear and non-linear movements provided by IMUs alongside the positional data and the context afforded by the ITS (Van der Slikke et al., 2017).

Factors relating to the participant and profiler is the final consideration. If elite athletes are implicated, higher speeds will be realised (Rhodes et al., 2015). A more expansive array of metrics may be required to gain sufficient insight to prompt marginal gains in performance; the technology must be capable of meeting these requirements. During structured field-based testing, three IMUs are recommended to maximise insight into linear and multidirectional performance with an excellent degree of accuracy (Van der Slikke et al., 2015). In contrast, IMU's combined with a local positioning system may currently be most appropriate during unstructured match-play scenarios. Alternatively, in novice or developmental athletes, costs and ease of use might be more decisive factors than detail and accuracy, making MSCC or MDL an acceptable option.

Resources may also dictate which personnel are available to monitor performance, and in turn, influence suitability and applicability. If performance monitoring is undertaken by an athlete or coach, simplistic approaches to collection and analysis are required, for example, reed switches. That said, commercially available IMUs are constantly becoming cheaper, with long lasting battery life and Bluetooth connections to mobile devices. Mobile phone popularity has enabled cost-effective solutions for data logging, data analysis, cloud storage, analysis and feedback. With the arrival of Bluetooth 5, the range is quadrupled and the data transfer rate highly increased; the mobile device can be placed court-side, receiving data from multiple IMUs at high sample frequencies. Most importantly, mobile devices allow athletes to autonomously monitor their own performance. With dedicated apps, athletes can access instant feedback in a user-friendly format.

The overview of methods and recommendations provided by this review could be used to support informed decision-making in WCS load and performance measurement. In general, the flexibility afforded by IMUs, which functions accurately with detailed performance metrics available in both structured and unstructured settings, makes this device the most universally suitable. Ease of use and affordability add to the appeal. Technological advancements will further improve IMU performance, leaving only the absence of position data as its principal limitation. Thus, future research in unstructured collection environments should seek to combine IMUs with either local positioning systems and / or image-based processing techniques. Both options would benefit from development before optimal 'hybrid' solutions are advocated. Considering the ITS, current features require extended set-up and calibration times and thereby limit practicality. However, accuracy and set-up time could be enhanced via new technologies, such as wireless two-way ranging-based local positioning systems. Regarding image-based processing systems as supplementary to IMUs, deficiencies have been demonstrated with automated tracking for WCS purposes, but this technology has continued to rapidly improve in able-bodied sports, with deep learning techniques implemented to facilitate automated tracking and action identification. Accessing video data that provides additional tactical insight alongside the IMU and local positioning system metrics most likely represents the gold standard feedback package to facilitate coach and athlete development in unstructured WCS settings. Finally, next to an optimised measurement setup, the challenge remains to ensure that complex data can be translated into a more 'coach and athlete friendly' format, yet with improvements to data analysis and real-time feedback platforms becoming available, this will soon become a reality.

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6. Declaration of interest statement

There is no conflict of interest.

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Note: numbers are added for Figure 1 and Tables reference

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Figure Legends

Figure 1 – A summary of the practical applications from studies using each performance monitoring device in WCS. Numbers represent the reference of each study. Two-colour circles represent a hybrid solution whereby the study included two devices together.

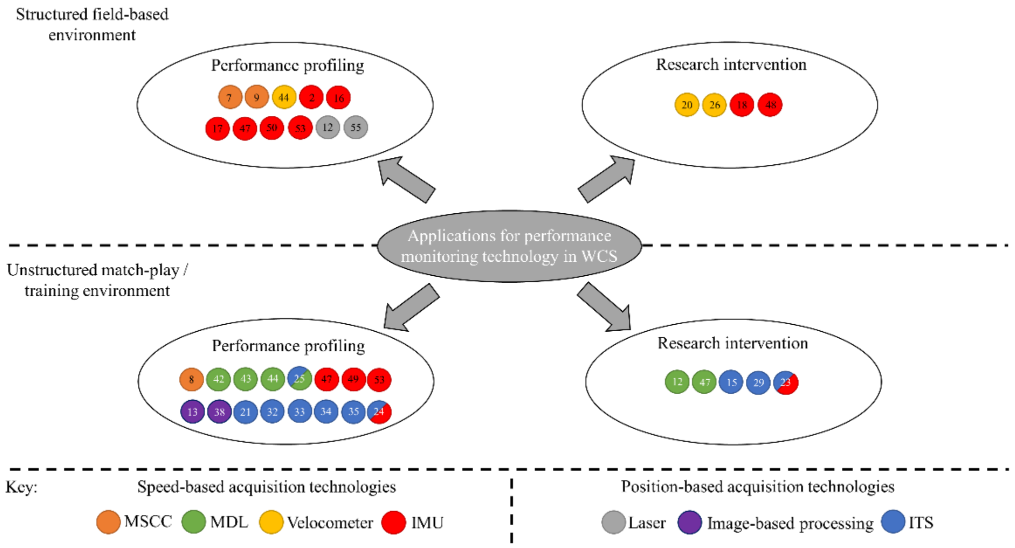

Figure 2 – Upper: A summary of the characteristics, advantages and limitations of performance monitoring technology currently used in WCS. Lower: Considerations and recommendations for performance monitoring technology in WCS.

	Price	Time	Speed	Rotation	Position	Push	Ease	FoM	Advantages	Limitations
	Ratings									
	Costs		**Accuracy**				**Usage**			
MSCC	++	o	o				+	++	Simple and cheap	Limited accuracy, and no distinction between forward and backward movements
MDL	+	+	o			-	+	++	Well documented and tested, suitable for many purposes	Low top speed, and no distinction between forward and backward movements
Velocometer	o	o	+			-	o	o	Well documented and tested	Heavy and outdated technology. Awkward calibration
IMU (single)	++	+	+			+	+	++	Wheel mounted IMUs are cheap, easy to use and provide detailed outcomes.	Limited rotational information, but maybe in near future (AHRS-algorithm)
IMU (multiple)	+	+	++	++		+	+	++	More IMUs enrich performance output and accuracy, new user friendly apps developed	No position information
Laser	-	+	+			o	o	++	Simple and often already available in athletics setting	Only data in straight line sprinting
Image based processing	-	-	o	o	+		-	++	Least athlete interference	Not optimized for WCS yet, but strong development potential from AB sports
ITS	-	o	+	o	++	o	o	++	Best field position, in AB sports: cost reduction, improved ease of use and accuracy	No acceleration data, rotational information or push characteristics

Price ++ €10 - €50; + €50 - €100; o €100 - €500; - €500 - €2500; -- €2500+
Time of data processing ++ available (sport specific); + available (unstructured); o no comercial WCS solutions yet; - only available for non WCS
Speed ++ accurate (incl. skid); + single wheel (bi-directional); o single wheel (low freq./ resolution); - low accuracy
Rotation ++ acurate rot. speed and derevatives; '+ accurate rot. speed; o rot. estimates; - rot. detection
Field position ++ <0.1m; + 0.1 - 0.5m; o 0.5 - 1m; - 1m+
Push characteristics ++ push characteristics (straight and turn); + push characteristics (straight); o push times; - number of pushes
Ease of use ++ automated report; + athlete operated; o requires support; - requires data processing support; -- only research setting
Freedom of movement (FoM) ++ completely unobstructed; + unobstructed, some additional weight; o significant additional weight; - significant obstruction

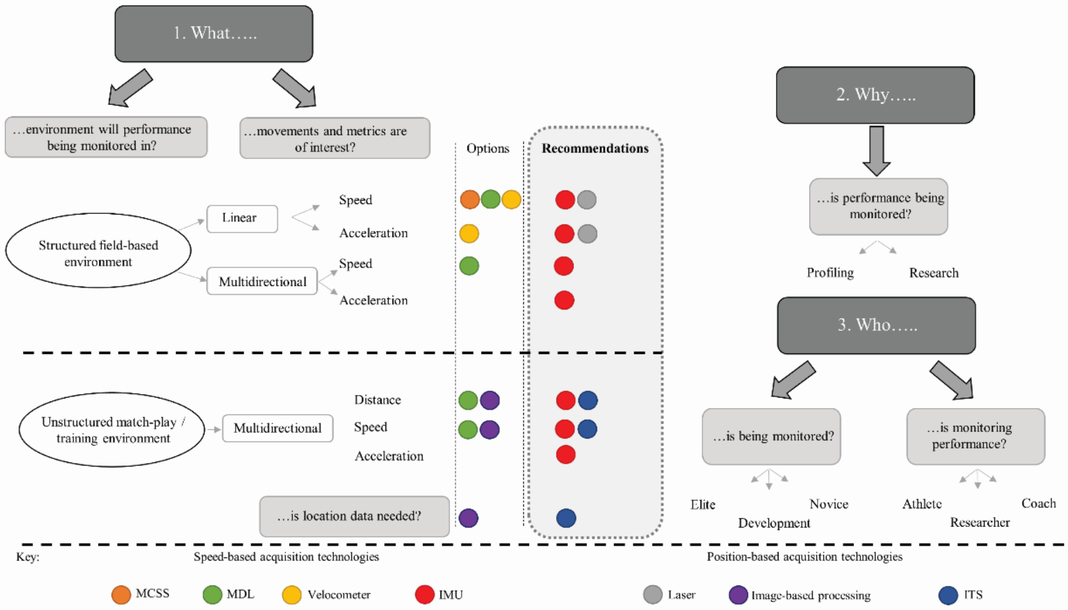

Table 1 – Description of speed-based acquisition technologies used to monitor field-based performance in WCS.

Device	Reference	Brief description	Position	Number	Weight	Frequency	Acquisition	Validated	Metrics
Magnetic switch-based devices:									
MSCC	Coutts[7]	Wheel velocity measured via two magnets and a switch	Spokes	1	3.5 kg	Variable, depends on wheel velocity	Wired	No	Speed
MDL	Sporner et al.[8]	Reed switch activated by magnetic pendulum measures wheel velocity.	Spokes	1	~0.1 kg		Wireless stored	Yes[43]	Speed Distance Starts / stops
Optical encoders:									
Velocometer	Moss et al.[44]	Optical encoder wheel in contact with perspex disc measures wheel velocity	Spokes & camber bar	1	~0.7 kg	≤ 1000 Hz	Telemetry	Yes[27]	Speed Push profile
Inertial Measurement Units (IMU):									
Accelerometer	Chua et al.[6]	Apple iPhone; Triaxial piezoelectric accel	Frame	1	~130 g	60 Hz	Wireless	No	Speed Push profile Acceleration
	Chua et al.[5]	Catapult GPS	Foot plate	1	67 g	100 Hz		No	
	Haydon et al.[16]	Gulf data concepts	Foot plate	1	~17 g	100 Hz		No	
Gyroscope	Xu et al.[56]	3D gyro & GPS	Axle	2	n.s	100 Hz		No	Rot. speed

Accel & gyro	Pansiot et al.[28]	3D gyro & 2D accel		Axle	2	10 g	30 – 50 Hz		Yes[51]	Rot. speed Distance
	Shepherd et al.[53]	SABELSense	3D gyro & 3D accel	Axle	1	23 g	n.s		Yes[48]	
	van der Slikke et al.[51]	xIMU		Axle & camber bar	3	49 g	256 Hz		Yes[23]	Speed
										Rot. speed
	van der Slikke et al.[50]	Shimmer			3	24 g	200 Hz		No	Distance
										Acceleration
	Haydon et al.[18]	iMeasureU			3	10 g	500 Hz		No	Rot. accel
										Push profile

MSCC magnetic switch cycle computer, *MDL* miniaturised data logger, *GPS* global positioning system, *Accel* accelerometer, *Gyro* gyroscope, *Rot.* rotational.

Table 2 – Description of position-based acquisition technologies used to monitor field-based performance in WCS.

Device	**Reference**	**Brief description**	**Calibration**	**Weight**	**Frequency**	**Acquisition**	**Validated**	**Metrics**
Laser:								
	Ferro et al.[12]	Jenoptik laser sensor	n/a	n/a	2000 Hz – position	Wireless	Not in WCS	Speed Distance

		interfaced with a BioLaserSport kinematic analysis system. Operate by time-of-flight principle with laser directed at backrest of wheelchair			200 Hz - velocity			Push profile
Image-based processing:								
	Filipcic & Filipcic[13]	Two low-speed overhead cameras used to automatically (and manually) digitise athletes' movements	Time and space reconstructed from known court locations	n/a	25 Hz	Wireless	No	Speed Distance Position
	Sarro et al.[38]			n/a	10 Hz		Not in WCS	
Local positioning systems:								
ITS	Rhodes et al.[36]	Wired ultra-wideband radio frequency system, utilising 4-8 sensors to track tag positioning worn by athletes via angle-of-arrival and time-difference-	Sensor position calculated via laser measurements and calibrated to known court locations	25 g	4 – 16 Hz (dependent on number of athletes tracked)	Wireless	Yes[36, 31]	Speed Distance Position

		of-arrival signals. 137 Hz bandwidth.						

WCS wheelchair court sports, *ITS* Indoor Tracking System

Search terms used:

All searches were performed once for keywords (KW) and once for titles (TI), and included once the term “wheelchair” and once the term “wheelchairs”, combined with one or more of the following terms: “sport”, “sports”, “rugby”, “basketball”, “tennis”, “mobility”, “performance”, “measurement”, “gps”, “tracking”, “inertial”, “sensor”, “sensors”, “gyroscope”, “gyro”, “accelerometer”, “wearable”, “training”, “classification” and “configuration”.

- The final search was performed on the 16th of November 2020.
- No limitation regarding year of publication
- The following searches were conducted (both for KW and TI):

Wheelchair AND GPS

Wheelchair AND Accelerometer

Wheelchair AND Basketball AND Classification

Wheelchair AND Basketball AND Configuration

Wheelchair AND Basketball AND Performance

Wheelchair AND Basketball AND Tracking

Wheelchair AND Basketball AND Training

Wheelchair AND Gyro

Wheelchair AND Gyroscope

Wheelchair AND Inertial AND Sensor

Wheelchair AND Inertial AND Sensors

Wheelchair AND Mobility AND Performance

Wheelchair AND Performance AND Measurement

Wheelchair AND Rugby AND Classification

Wheelchair AND Rugby AND Configuration

Wheelchair AND Rugby AND Performance

Wheelchair AND Rugby AND Tracking

Wheelchair AND Rugby AND Training

Wheelchair AND Sport AND Classification

Wheelchair AND Sport AND Performance

Wheelchair AND Sport AND Training

Wheelchair AND Sports AND Classification

Wheelchair AND Sports AND Configuration

Wheelchair AND Sports AND Performance

Wheelchair AND Sports AND Training

Wheelchair AND Tennis AND Classification

Wheelchair AND Tennis AND Performance

Wheelchair AND Tennis AND Tracking

Wheelchair AND Tennis AND Training

Wheelchair AND Tracking

Wheelchair AND Wearable

Wheelchair AND Wearables

Additional references for technology described in the main text not WCS specific:

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