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Current perspectives on profiling and enhancing wheelchair court-sport performance

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Abstract

Despite the growing interest in Paralympic sport, the evidence-base for supporting elite wheelchair sport performance remains in its infancy when compared to able-bodied (AB) sport. Subsequently, current practice is often based on theory adapted from AB guidelines, with a heavy reliance on anecdotal evidence and practitioner experience. Many principles in training prescription and performance monitoring with wheelchair athletes are directly transferable from AB practice, including the periodisation and tapering of athlete loads around competition. Yet, a consideration for the physiological consequences of an athlete's impairment and the interface between athlete and their equipment are vital when targeting interventions to optimise in-competition performance. Researchers and practitioners are faced with the challenge of identifying and implementing reliable protocols that detect small but meaningful changes in impairment-specific physical capacities and on-court performance. Technologies to profile both linear and rotational on-court performance are an essential component of sports science support in order to understand sport-specific movement profiles and prescribe training intensities. In addition, an individualised approach to the prescription of athlete training and optimisation of the *'wheelchair/user interface'* is required, accounting for an athlete's anthropometrics, sports classification and positional role on court. As well as enhancing physical capacities, interventions must also focus on the integration of the athlete and their equipment as well as techniques for limiting environmental influence on performance. Taken together, the optimisation of wheelchair sport performance requires a multi-disciplinary approach based on the individual requirements of each athlete.

Key words: Paralympic, wheelchair rugby, wheelchair basketball, wheelchair tennis, physical capacity, training monitoring.

Introduction

Since its inception at the Stoke Mandeville games in 1948, the Paralympic movement has experienced a dramatic growth as a platform for sport in individuals with a physical impairment.[1] At the Rio 2016 Paralympic games, ~~over~~ around 4350~~000~~ athletes from 176 countries are expected to compete for 528 medals in one of the world's largest sporting events. The rapid expansion in participation levels and public interest over recent decades has been matched by a continued advancement in the standard of elite competition. The latter is supported by the evolution of technical aids and equipment[2] and an increasingly specialised approach to sports science and sports medicine support.[3,4]

Despite the growing interest in Paralympic sport, the evidence-base for supporting wheelchair sport performance remains in its infancy when compared to able-bodied (AB) sport. A lack of resource as well as small, heterogeneous pools of elite athletes often inhibits the publication of scientific data collected in performance settings. Restrictions on data sharing within high performance systems also limit the availability of information detailing physiological capabilities and training practices of elite performers. Subsequently, current practice is often based on theory adapted from AB guidelines, with a heavy reliance on anecdotal evidence and practitioner experience.[5] Many principles in training prescription and performance monitoring are directly transferable between AB and wheelchair-based sport, including the periodisation and tapering of athlete training loads around competition. Yet, a consideration for the physiological consequences of an athlete's impairment and the interface between athlete and their equipment are vital when targeting interventions to optimise in-competition performance (see Figure 1 for overview).

The wheelchair sports currently receiving the most attention in the scientific literature are the 'court sports' (i.e. basketball, rugby and tennis). Wheelchair basketball (WB) is a team sport designed for athletes who have a lower limb physical impairment~~ that prevents running, jumping and pivoting~~, including paraplegia, ~~or~~ musculoskeletal conditions, spina bifida, amputation and poliomyelitis.[6] Wheelchair rugby (WR) is ~~a team sport~~ played by individuals with an impairment that affects all four limbs, including cervical spinal cord injuries (tetraplegia), multiple amputations, polio, cerebral palsy and other neurological disorders.[6] Wheelchair tennis (WT) is played in an open class (athletes with a range of impairments, such as amputations or thoracic/lumbar spinal cord injuries (paraplegia)) and the quad division (athletes with tetraplegia or upper extremity impairment)[6]. A wider discussion on the functional classifications systems within each sport is beyond the scope of this review and is provided elsewhere.[6] Importantly the aforementioned sports present similarities in terms of the intermittent movement dynamics of on-court performance and the need to optimise the interface between an individual athlete and their equipment.~~wheelchair configuration and sport specific movement dynamics~~. This review will outline scientific evidence and current perspectives on the profiling and enhancing physical performance in the court sports. Specifically, this review will focus on i) laboratory and field based assessments of physical capacity related to court-sport performance; ii) techniques and technologies available for profiling on-court physical performance and iii) the evidence base for targeted interventions aimed at enhancing physical performance, including training prescription, equipment innovations and thermoregulation.

Profiling physical capacity and performance

An athlete's impairment type and anthropometrics have a large influence on what physical attributes may be trainable in a sport-specific context (Figure 1). The functional classification systems within wheelchair sports are designed to minimise the impact of eligible impairment types on the outcome of competition and to promote equality in competition.[1,6] However, the heterogeneity in impairment types competing within the same classification and/or sporting discipline presents a unique challenge for coaches and practitioners when considering ‘benchmarks’ of physical performance (e.g. tetraplegia vs. cerebral palsy). Furthermore, wheeled sports performance requires the integration of both the athlete and their equipment into one functioning unit, known as the ‘wheelchair-user interface’. Researchers and practitioners are faced with the challenge of identifying and implementing reliable protocols that allow for differences in classification and detect small but meaningful changes in impairment-specific physical capacities and on-court performance.

{[Insert Figure 1 here]}

Impairment-specific characteristics

Physical capacity has previously been described as the ability of the musculoskeletal, neurological/cerebral, cardiovascular and respiratory systems to perform a level of physical work. Spinal cord injury (SCI) is the most widely researched impairment, with physiological measures of aerobic capacity (peak oxygen uptake ($\dot{V}O_{2peak}$) and aerobic power), anaerobic capacity (peak power) and strength inversely related to lesion level and injury completeness.[7] The lesion-level dependent loss of upper limb (<C7-8), respiratory and trunk (<T12) function determines the ability of muscle groups to contribute to physical work output. In some cases asymmetry in remaining upper-limb or trunk function may reduce bilateral force production and should be assessed during initial functional movement screenings. The redistribution of blood during exercise in individuals with a SCI is impaired due to the lack of sympathetic vasoconstriction in inactive tissue below the lesion level.[8] In athletes with paraplegia cardiac output ($\dot{Q}$) is maintained by elevations in resting and submaximal HR.[8] In athletes with complete tetraplegia, the redistribution of blood and ability to elevate $\dot{Q}$ is further limited due to the loss of autonomic control of vessels in the abdominal bed and cardiac tissue.[9] A SCI above T5 results in the loss of sympathetic outflow to the heart and maximal heart rates

(HRpeak) of 100-140 b·min^{-1} are achieved primarily by the withdrawal of parasympathetic tone.[8,9] Recently, the partial preservation of descending sympathetic control was found to be strongly correlated with indices of exercise performance, including 4-min push distance, HRpeak, and $\dot{V}O_{2peak.}$[9] These findings occurred in athletes neurologically motor and sensory complete spinal lesions, suggesting 'autonomic completeness' is an important factor in determining physical performance.[9]

From a medical perspective the loss of autonomic function following high thoracic and cervical level injury presents two distinct challenges to health and performance; namely *autonomic dysreflexia* and *impaired thermoregulation*. Autonomic dysreflexia is a potentially life-threatening bout of uncontrolled hypertension resulting from severe vasoconstriction and cardiac stimulation in response to a painful/noxious stimulus below the lesion level.[4] The voluntary inducement of autonomic dysreflexia to enhance performance, known as 'boosting' is regarded as violation of anti-doping regulations.[4] Reduced sympathetic input to the thermoregulatory centre also presents a loss of sweating capacity and loss of vasomotor control for redistribution of blood below the level of the spinal lesion.[4,8] This compromised thermoregulatory response provides a greater risk of heat illness when compared with AB athletes and requires specific interventions to maintain health and performance (discussed further later).[10,11]

In contrast, those with lower and/or upper limb deficiency (e.g. amputee) may remain neurologically and physiologically intact, with cardiovascular responses similar to those observed in AB athletes. Importantly, the preservation of trunk function provides stability and contributes to the generation of momentum when performing high intensity activities, including accelerations or rotations.[12] Athletes with cerebral palsy (CP) or central neurologic injury, such as stroke, have a variety of impairment in sensation, motor control and communication ranging from mild to severe.[4] From a motor control perspective, athletes typically present an increased muscle tone or spasticity and impaired co-ordination leading to muscle imbalance and reduced muscle power.[4,13] The inhibited lactate release from spastic muscle and aforementioned motor impairments may influence the reliability of protocols for assessing aerobic and anaerobic capacity, yet wheelchair ergometry-specific evidence is limited.[13] Greater focus is required on the role of impaired motor-co-ordination on wheelchair propulsion kinematics in athletes with CP.

Field vs. Laboratory assessments

In the assessment of an athlete's physical capacity there is a conflict between the higher reliability and lower ecological validity of laboratory compared to field-based protocols. Technological advances in treadmill and wheelchair roller design permit well established assessments of aerobic[14,15] and anaerobic[16] physiological parameters under standardised conditions. Recently, however, peak maximal cardiorespiratory responses during 4 and 40 min field-based, continuous push tests in WR athletes were found to exceed those observed during a treadmill-based, graded exercise to exhaustionmaximal exercise.[17] Further, Leicht et al.[15] reported a greater variability in $\dot{V}O_{2peak}$ in athletes with tetraplegia (Co-efficient of variation (CV) 9.3%) than paraplegia (4.5%) or non-SCI (3.3%) employing the same treadmill-based protocol. Wheelchair propulsion kinetics, including work per cycle (lower), and push frequencies (higher) are significantly altered during over-ground versus ergometer and treadmill-based propulsion at equivalent submaximal speeds (4, 6 & 8 km.h^{-1}).[18] No research has yet examined maximal push mechanics between laboratory and field-based scenarios. Anecdotal observations suggest WR athletes with tetraplegia adopt self-selected propulsion technique to compensate for impaired respiratory dynamics when performing high intensity activites.[17] Subsequently, the performance of verification stages is recommended for the confirmation of peak cardiorespiratory responses, particularly in athletes with low physical capacities or limited wheelchair propulsion experience.[15]

In the authors' experience ~~When testing inexperienced athletes,~~ both sub-optimal wheelchair configuration and a lack of wheelchair skills can significantly influence tests outcomes when testing inexperienced athletes. Improvements in physical performance over repeated testing sessions may result from habituation effects on propulsion technique and kinematics rather than improved cardiorespiratory capacity. Asynchronous, stationary arm crank ergometry (ACE) is a more mechanically efficient than wheelchair propulsion, resulting in higher levels of peak power output (PO_{peak}) during ACE (~30% higher) with little difference in $\dot{V}O_{2peak}$.[19] ACE protocols have limited specificity to wheelchair performance and gripping aids are required when testing individuals with high spinal lesions. However, ACE protocols may be ~~but are~~ advantageous when practitioners wish to establish the physiological capacities of an athlete in isolation from their equipment.

Extensive batteries of field-based tests have been validated for the assessment of anaerobic and manoeuvrability-related performance, including 20m sprint and sport-specific protocols (see Goosey-Tolfrey and Leicht[20]), and show a strong association with functional classification.[21]~~.~~ These are favoured by coaches due to ability to test large numbers of athletes with little specialised equipment and their direct representation of on-court performance.[19] In contrast, the validity of continuous[22,23] or shuttle-based[24,25,26] field tests of aerobic capacity adapted from AB protocols remains inconclusive. To date, only Vinet et al.[22] have performed direct comparisons between lab and field-based maximal cardiorespiratory responses during wheelchair ergometry. No differences were observed between $\dot{V}O_{2peak}$ measured during an adapted Leger Boucher~~ard~~ test on 400m track and on a wheelchair ergometer, although only moderate intra-class correlation coefficients (ICC) were reported.[22] Elsewhere, only low to moderate correlations (r = 0.39-0.58) have been observed between final test score during a multi-stage fitness test (MSFT) and $\dot{V}O_{2peak}$ identified during laboratory-based wheelchair ergometry.[25] Shuttle-based tests involve turning and acceleration and as such may under-predict specific aerobic capacity due to the anaerobic contribution and influence of wheel speed on hand-rim contact at high speed. However, MSFT test scores demonstrate a strong relationship (r = 0.80) with wheelchair tennis skills as determined by players ranking and therefore may provide a functional indicator of wheelchair-user combination.[24] Small standard errors of measurement have been confirmed for MSFT distance travelled (86 m, 95% CI: 59 to 157 m) and peak HR (2.4 $b.min^{-1}$, 95% CI: 1.7 to 4.5) suggesting that these variables can be measured reliably in a field-based setting.[25] Recently, Weissland et al.[23] reported higher $\dot{V}O_{2peak}$ but no difference in final test score during a figure of 8 compared to an octagonal-based MSFT protocol in a group of WB athletes. Provided the adapted tests deliver reliable results that are sensitive to changes in physical performance, practitioners can identify the most suitable protocol for their individual needs. Due to the influence of chair configuration, tyre pressure and floor surface on wheelchair rolling resistance, the standardisation of such factors across observations is required where possible.

Assessment of on-court performance

Currently, limited research has documented the physiological responses during actual or simulated competition in elite Paralympic athletes. Average $\dot{V}O_2$ during both basketball and tennis competitions have been observed around the ventilatory threshold with average heart rates (HR) of around 75-80% and 65-70% HR_{peak} respectively.[27,28,29] This is significantly lower than intensities of continuous, endurance based wheelchair racing (85% $\dot{V}O_{2peak}$) and nordic sit skiing competition (82% $\dot{V}O_{2peak}$).[28] A higher number and longer duration of breaks during wheelchair tennis competition result in a greater work to rest ratio (~1:5; 17% time spent active)[29] compared to basketball (~1:1).[27] Figure 2 provides an example of ~~Unpublished~~

~~data from our research group displaying~~ typical HR_{peak} and ~~external~~ distances covered ~~work completed during~~ during the same duration of WR competition and game-specific training in players of two different impairments and classifications. ~~groups is shown in Figure 2~~. The influence of impairment type on physiological responses and absolute intensities observed during on-court performance should be accounted for when benchmarking players both within and between classification groups. The ~~R~~reduced HR and active muscle mass in athletes with tetraplegia are associated with lower energy expenditures during WR (248.5 ± 69.4 $kcal.h^{-1}$) compared to athletes with paraplegia performing WT (325.8 ± 73.0 $kcal.h^{-1}$) and WB (374.8 ± 127.1 $kcal.h^{-1}$).[30]

{[Insert Figure 2 here]}

It has been shown that athletes cover distances that range between 3500 – 5000 m during WR and WB match-play.[31,32,33] Around 28% of active basketball match-play is spent performing high intensity work, including sprinting or contesting for the ball, with 22% of activity above ventilatory threshold and 50% resting.[33] Positional requirements and player classification must be also taken into account when identifying an individual athlete's performance profile as role-specific demands can influence movement profiles.[34] Recent data during WR match-play found that the majority of time spent (~75%) was performing low intensity activities (<50% peak speed) interspersed with short, frequent bouts of high intensity activity accounting for only 2-5% of total activity.[35] Specifically, defensive players spend a significantly greater amount of time performing very low speed activities (blocking, trapping) compared to offensive players whilst performing a greater number of high-intensity activities (n= ~13 vs. ~9 respectively).[35]

In contrast to many linear endurance sports, no single physiological parameter determines performance outcome in court-based sports. In competitive WT match-play, Sindall et al.[36]

observed higher average speeds and greater distances covered in high versus low ranking players. In addition, high ranked players also covered more distance at higher average HR than their opponents.[36] High ranking WR teams have been found to spend a greater time within high (>81-95% peak speed) (2.9 ± 1.6%) and very high (>95% peak speed) (0.7 ± 0.8%) speed zones compared to low (1.5 ± 1.1% and 0 ± 0.4%) and mid-ranked teams (2.0 ± 1.3% and 0.3 ± 0.5%) across all classifications.[35] Higher ranking teams also performed high intensity activities for greater distances and for a longer duration[35], although opposition characteristics, including style of play and ranking, clearly influence indices of game intensity~~.~~ As well as linear performance parameters, ~~international standard~~ WB players who represent national teams performed more frequent (+7 %) and longer duration (+0.2 s) rotational activities and fewer braking activities compared to club level counterparts during simulated match-play.[37] ~~national level counterparts[33].~~ Consequently, techniques for profiling linear and rotational performance are important to understand sport-specific movement profiles and prescribe training intensities to match or exceed the demands of the competition environment.

The indoor tracking system (ITS), as used by Rhodes et al.[35], has been proved to be a valid and reliable tool for the assessment of distance/speed during a range of tasks specific to the wheelchair court sports.[38] Importantly, the ITS has shown good reliability reliable even at maximal speeds (>4 m·s^{-1}), where random errors of <0.10 m·s^{-1}, with <2% CV were observed.[38] Unfortunately, from a practical perspective, the ITS requires considerable set-up/calibration time and to date no acceleration or angular velocity data has been reported using this system. Image-based processing techniques have also previously been employed for the quantification of WR match-play movement.[32] However, these techniques are heavily reliant on manual tracking digitisation which introduces accuracy and reliability issues and are not suitable if athletes/coaches require timely feedback post training or competition.

Devices (e.g., wheel mounted magnetic –reed-switch devices) originally designed to measure the daily life activity patterns of wheelchair uses have recently been assessed for their suitability in sporting environments.[36,39] These compact devices attach near the axle of the main wheels and, powered by long life batteries, enable data to be collected and stored over extended periods (~3 months).[39] Yet, substantial errors in measurement reliability (19.9% CV) have been reported when determining peak speed, resulting in large random errors in time and distance spent in speed zones relative speed zones.[39] Therefore, the interest in measurement tools continues, with wireless inertial measurement units (IMU) reported to be reliable for assessing wheelchair kinematics once corrected for wheel skidding during vigorous activity.[40] Average test outcomes for linear speed (ICCs>.90) and rotational speed (ICCs>.99) showed high correlations between IMU and a 'gold-standard' 24 camera optical motion analysis system.[40] More research is required to validate the use of IMU's during competition match-play rather than standardised environments and refine adaptations to apply/remove devices from the sports wheelchair in a timely manner.

Interventions to enhance physical capacity and performance

When initiating interventions to enhance physical performance, consideration must be made to both an athlete's impairment-specific physiological responses and sport-specific movement and energetic demands. The accurate quantification and longitudinal monitoring of prescribed training load (TL) is essential to provide a scientific explanation for changes in performance and manage illness/injury risk. As well as enhancing physical capacities, interventions also focus on the integration of the athlete and their equipment as well as techniques for limiting environmental influence on performance (Figure 1). Recent interest has been paid to the nutritional supplement habits of Paralympic athletes, with recommendations made for a greater education for athletes on appropriate information sources and dosage requirements.[5] Limited evidence exists supporting the ergogenic properties of carbohydrate[41] and caffeine[42] on endurance and sprint-based performance in wheelchair court-sport athletes, respectively. However, a wider discussion regarding the influence of impairment type on the efficacy of nutritional supplements, including side-effects (e.g., increased spasms), optimising fluid intake (e.g., preventing dehydration and urinary infection risk) and impaired absorption rates (e.g., reduced gastric motility), is beyond the scope of this review.[43] The subsequent sections will discuss literature regarding training prescription practices, adaptations to the wheelchair/user interface and cooling strategies to enhance physical performance.

Training prescription and monitoring

The quest for optimal performance requires practitioners to continuously balance strategies to support and improve physical capacities alongside coach-led on-court technical/tactical training demands. Remaining function can be trained through programs that involve specific on-court and over-ground wheelchair propulsion, non-specific arm-crank ergometer training, hand cycling and resistance training (Table 1). These must be balanced with technical and tactical requirements prescribed by coaches. Due to the relatively small muscle mass of the upper limb and the high mobility but low stability of the shoulder girdle, wheelchair propulsion is a mechanically inefficient exercise modality.[19] The associated large load and the instability of the shoulder complex provide a risk factor for chronic over-use injuries in manual wheelchair users.[4] Interventions should first ensure the robustness of athletes shoulder by re-enforcing positive functional movement patterns and symmetry in scapula kinematics through strength (e.g., elastic bands) and coordination (e.g., visual stimuli) exercises.[44] In athletes with CP passive stretching of the shoulder is recommended to provide proprioceptive training of joint movement and increase joint range of motion.

Several studies conducted with elite wheelchair athletes have reported favourable changes in functional performance[3,45,46] or body composition[46,47] when following a periodised program during a competitive season. To the author's knowledge, only two studies have intervened with specific strength and resistance training programmes of wheelchair athletes.[44,48] Turbanski and Schmidtbleicher[48] found that wheelchair athletes demonstrated significant improvements in strength and power as a result of 8 weeks resistance training which incorporated heavy bench press exercises. It was noted that the velocity and acceleration associated improvements of the bench press throw contributed to a 6.2% improvement in 10m sprinting performance.[48] Moreover, while no direct strength improvements were noted following the 3 month elastic band and visual coordination training of Bergamini et al.[44] significant improvements in wheelchair propulsion kinematics (e.g. reduced asymmetry) were noted. No studies have yet differentiated between responses in SCI athletes or those with limb deficiency or neurological impairments.

{[Insert Table 1 here]}

The outcome of any training intervention is the consequence of both the work completed ('External load' = distance, speed, power) and the resultant stress on the athlete's physiological systems ('Internal load' = $\dot{V}O_2$, HR). On-court training in the team sports is frequently prescribed on a squad-basis to develop sport-specific, technical and tactical competences. The large heterogeneity in athlete impairment and conditioning within a squad may result in a range of internal TL responses to the same dose of external load (see Figure 2). The use of ratings of perceived exertion (RPE) is preferable to HR methods, the intermittent nature of court sports mean HR may not be directly associated with external work performed, including high intensity accelerations and decelerations.[49] Further, wheelchair athletes with a high spinal lesion may have a blunted HR response, whilst RPE displays a linear response with VO_2.[50] Leicht et al.[14] reported the same RPE responses at fixed relative exercise intensities across athletes with tetraplegia, paraplegia and non-SCI.

Therefore RPE may be considered a useful tool for the prescription and monitoring of athlete training. While the use of session RPE provides a valid alternative to HR-based methods for assessing distance covered and low to moderate intensity activity, the intra-individual relationships between external TL measures and session RPE should be assessed for each athlete prior to performing any systematic longitudinal monitoring.[50] It is recommended that external TL data are considered within the context of the training environment and a combination of internal and external load employed to accurately quantify across training modes.[50]

Respiratory muscle training and cardiorespiratory function

As mentioned earlier, persons with a SCI suffer from a lesion-level dependent impairment in respiratory muscle function and cardiovascular function. Both can contribute to the delivery of oxygenated blood to active muscles during upper limb exercise. Consequently, there has been an interest in establishing effective respiratory training programmes or cardiorespiratory aids (e.g. use of abdominal binders or strapping) to support aerobic capacity in wheelchair athletes. Previously, only positive indicators of quality of life (i.e. reduced scores of breathlessness) had been found following six weeks of inspiratory muscle training (IMT) in trained WB players of mixed physical disabilities.[51] Elsewhere, more encouraging improvements have been reported by West and co-workers[52] who examined a more homogeneous group of athletes (i.e. highly trained WR players with tetraplegia) and found a 15% increase in PO_{peak} following a 6 week period of IMT training. Accordingly, IMT may provide a useful adjunct to training in this population but current literature is inconclusive.

Other physiological interventions aimed at augmenting cardiorespiratory function in athletes with tetraplegia include the use of compression socks[53] and abdominal binders[54] during acute exercise. Both may act to enhance venous return and consequently improve ventricular filling pressure, stroke volume and cardiac performance in those with compromised vascular function.[53,54] Lower limb compression may be associated with an augmentation of upper limb blood flow and increased submaximal exercise performance.[53] As well as providing stability around the trunk, the use of abdominal binders has been associated with: i) reductions in minute ventilation and blood lactate accumulation during submaximal exercise; and ii) improvements in acceleration/ deceleration profiles and distance covered during a repeated maximal 4-min push.[54]

{[Insert Table 2 here]}

Equipment/User interface

The athlete and their individualised sports wheelchair must be considered as 'one'; becoming the *'wheelchair-user interface'*. The configuration of a wheelchair, including alterations to hand rim diameter, tire pressure, wheel size, camber, seat height, has a substantial influence on performance. While some aspects of configuration may be advantageous for one aspect of sport (e.g., increasing wheel camber to increase manoeuvrability), they may impair other aspects of performance (e.g, this may reduce linear speed due to increase rolling resistance).[55] Despite the abundance of research with an ergonomic interest on wheelchair configuration, very few studies have utilised wheelchair games players and measured sports performance specific outcomes of functional capacity (see Mason et al.[55]).

Trunk function has been identified as a central component determining sports performance (e.g., wheelchair sports classification).[12] Reducing the contribution of trunk to sprinting performance via manipulations in seat angles has been shown to significantly reduce acceleration and sprinting capability.[12] The combined impact of strapping/ seating position and the individual fit to the sports wheelchair must therefore be considered collectively whenever possible to maximise trunk contribution to performance (see Table 2).

Interventions of the interface between user and equipment have also been sought, including the use of neoprene belts to increase range-of-reach by stabilizing the chest to the wheelchair using a belt.[56] Elsewhere, Mason et al.[57] found glove type to impact sprint measures such as acceleration and 15m sprint times improving the hand rim user interface. However, a large number of individual glove types are available and elite athletes seem to perform best in their custom-made gloves.[57]

Cooling strategies

The scientific literature is well versed regarding the problems of exercise in the heat, the effects of dehydration and the benefits of acclimatisation for the AB athlete. However, there are a ~~variety~~ number of considerations for athletes with disabilities exercising in the heat where thermo-regulatory impairment increases the risk from heat-related illness.[10,11] There have been a variety of studies examining the effects of pre-cooling prior to exercise in athletes with tetraplegia[58] and as well as those aiming to reduce heat storage during exercise in athletes with paraplegia who compete outdoors in events such as wheelchair tennis [3,59] which may last between 1-3 h.[36] These selected studies shown in Table 2 replicated the exercise of a similar duration or intensity of that undertaken in wheelchair tennis or rugby. In brief, key findings suggest that i) wearing an ice vest ~~during~~ prior to intermittent sprint exercise both reduces thermal strain and enhances performance and ii) hand cooling is effective as a cooling aid. Wearing an ice vest during on-court training may not attenuate the rise in core temperature in athletes with paraplegia and tetraplegia, although the influence on performance remains equivocal .[60] ~~Yet, T~~The practicality of cooling must be considered as wheelchair athletes would not wish to experience feelings of numbness of the hands when hand dexterity in court sports is of paramount importance. Prior heat acclimation protocols may provide one method of improving thermoregulatory stability and reducing heat stress when competing in challenging environments for prolonged periods e.g. tennis competition.[61]

Practical applications

The present brief review has outlined current practical perspectives and scientific literature regarding the profiling and enhancement of physical performance in wheelchair-court sports. A range of physical impairments demand a fully individualised approach to supporting wheelchair athletes. However, a number of key principles exist which provide the foundation upon which bespoke sport science and medicine programmes can be implemented.

- An understanding of the individual wheelchair athlete is vital, including a full medical diagnosis of physical impairment, screening of current functional movement pattern and previous illness/injury history.
- Profiling protocols must show good reliability and demonstrate specificity to the movement or energetic demands of competition. The battery of protocols available to practitioners will be dependent on available resource (lab vs. field assessments), the experience of athletes being profiled (novice vs. experienced wheelchair user) and contact time available with athletes.
- A range of technologies are available for examining the movement and physiological demands of performance, including HR monitoring, motion capture, ITS and IMU. However, the limitations of each technique must be acknowledged and considered when supporting coaches in the training and competition environment.
- A multi-disciplinary approach to the preparation and assessment of interventions aimed at enhancing physical performance is essential. Interventions may increase one element of performance (linear speed) but be detrimental to other parameters of athlete health or performance.

Conclusion

Despite the growing interest in Paralympic sport, the evidence-base for supporting wheelchair sport performance remains limited. Current practice is often based on theory adapted from AB guidelines, with a heavy reliance on anecdotal evidence and practitioner experience. Where possible this practitioner experience should be supplemented with impairment and sport-specific applied research. The optimisation of wheelchair sport performance requires a multi-disciplinary approach based on the individual requirements of each athlete in their sporting environment.

Table 1 Longitudinal training strategies designed to improve the physical capacity of competitive wheelchair games players

Author	Sport	Number/ sex (impairment)/ playing standard	Age (yr.) Mean ±SD	Training methods	Measures of physical capacity and body composition	Outcomes
Usual Training Practices						
Goosey-Tolfrey[45]	Basketball	12 Male, Mixed (1.0-4.0 IWBF) International	30.5 ±4.5	Three year longitudinal observation. Twenty hours of physical and skill training per week. Sport-specific game play and club training	Peak aerobic capacity and sprint performance using treadmill and wheelchair ergometer. Athletes tested in their own sports wheelchairs	Aerobic capacity improved by 6.8% while all other fitness prerequisites, including sprint performance, were maintained
Iturricastillo et al.[46]	Basketball	8 Male, Mixed 1st Division Club	26.5 ±2.9	Longitudinal observation across one competitive club season (of 16 matches and training twice per week). Training sessions included 1 hr of technical and tactical drills. Each session always ended with real game situations	Handgrip, body composition (skinfold; triceps, subscapular, suprailiac and abdominal), medicine ball throw, on-court sprinting (5 and ~~10~~ 20 m sprints) and completion of the Yo-Yo level 1 test of 10 m. Athletes tested in their own sports wheelchairs	Improvements in body composition (decreased fat mass of upper limb) and physical performance, particularly in acceleration over 5 and 20 m sprint with the ball, handgrip strength and the total distance covered in the Yo-Yo level 1 endurance test. No differences were observed in acceleration capacity without the ball, change of direction ability or explosive strength.
Gorla et al.[47]	Rugby	13 Male, TP 1st Division Club	26.6 ±6.0	Longitudinal observation across one season (8.1 ±2.5 months). Four sessions per week of aerobic and anaerobic sport specific (inc. technical and tactical) aspects of wheelchair rugby	Body composition using dual-energy x-ray absorptiometry (DXA)	Regular wheelchair rugby training results in an increase in lean mass and decreased total body fat mass.
Diaper and Goosey-Tolfrey[3]	Tennis	1 Female, PP (L1) International	33	2 years observational study. Twenty hours of physical and skill training per week. Sport-	Aerobic capacity and repeated sprint performance (10 s x 10	Aerobic capacity reduced by 21%, yet the submaximal physiological variables such as

				specific game play and club training	sprints with 30 s recovery) using a wheelchair ergometer. Athlete tested in their own tennis wheelchair	lactate profile and pushing economy improved. Maintenance of peak speed and improvement found in the fatigue profile across the repeated sprint performance
Strength and Conditioning Training						
Bergamini et al.[44]	Basketball	10 Male, 2 Female Mixed Junior Club	17.1 ±2.7	n=6 control group and n=6 training group (TG). Both groups undertook, 2 times a week, 90 min sessions aimed to improve wheelchair propulsion, wheelchair manoeuvrability and ball handling skills. The TG also completed twice a week for three months strength (elastic bands) and coordination (inc. visual stimuli) exercises lasting 30-35 mins	20 m sprint test. Wearable inertial measurement units (IMUs) devices to measure biomechanical parameters in wheelchair sports	No improvement in 20 m sprint[*] after the TG. Athletes modified their propulsion technique following training by increasing the push cycle frequency, the force expressed to accelerate their wheelchair and adopting a more symmetrical pushing mode
Turbanski and Schmidtbleicher[48]	Basketball and Rugby	8 Male 8 PP/ 2TP 1st and 2nd Division	33.2 ±10.6	Eight week resistive training regimen. Exercises were performed twice per week with program variables of 70 to 85% intensity of 1 repetition maximum (1RM) and 5 sets not exceeding 12 repetitions.	10 m sprint test. Strength and power measures included the bench throw - maximal velocity, maximal acceleration, and time intervals representing the initial acceleration (t1 and t2) of the barbell. Maximal strength (Fmax) and maximal rate of force development (MRFD) was measured in the static condition. Dynamic bench press 1RM and strength endurance (SE) were also measured.	Improvements were noted for all tests. With improvements in 10 m sprints of 1.8% and as large as 39.3% in the 1RM (kg)
Respiratory muscle training						
Goosey-Tolfrey et al.[51]	Basketball	16 Male, Mixed (1.0-3.0 IWBF) 1st Division	NS	Six weeks inspiratory muscle training (IMT) – Two Groups IMT group - 30 dynamic breaths	Repetitive sprint test (RST) comprised of 15 x 20 m sprints. Total test	IMT - MIP and MEP improved (17% and 23%, respectively). Sham-IMT also resulted in 23%

		Club		performed by the twice daily at a resistance equivalent to 50% maximum inspiratory pressure (MIP). sham-IMT group - 60 slow breaths performed once a day at 15% MIP	time and recovery time were recorded. HR and post blood lactate concentration measured. Respiratory muscle strength; (MIP and MEP)	and 33% improvements. There were no significant changes in pulmonary function at rest and any of the performance parameters associated with the RST
West et al.[52]	Rugby	10 TP 9 Male and 1 Female (C4-C5 COM to C6-C7 INC) International	29.2 ±5.5	Six weeks IMT - 30 dynamic breaths twice daily IMT group (n=5) or placebo (n=5)	Incremental arm crank exercise test to determine peak aerobic work rate and diaphragm thickness	IMT resulted in significant increase by 8 W (+15%) in incremental test peak aerobic work rate. IMT also showed significant increase in diaphragm thickness vs. placebo

Note. PP – Paraplegic; TP – Tetraplegic; NS – not stated; * - hand timing

Table 2 Studies examining influence of wheelchair/user interface, compression garments and cooling and respiratory interventions on sport-specific performance of trained wheelchair games players.

Author	Sport	Number/ Sex (Impairment)	Method		Modality/ Protocol	Performance Gains
STRATEGIES *Wheelchair-user interface*						
Curtis et al.[56]	Basketball	7 Mixed, 6 Male/ 1 Female (1.0-2.0 IWBF)	Strapping techniques	Without a belt, with a neoprene chest belt and with a webbing thigh belt	Participants were in a static seated position. They held a basketball in either the transverse or sagittal plane and reached within the limits of their stability. The area circumscribed by each participant's functional reach was processed using the Motion Analysis Expert Vision Flextrak program	Sagittal plane - high and low thoracic level athletes increased the area of their functional reach with the chest belt when compared with the thigh or no-belt condition. However, in the transverse plane, only lower level thoracic paraplegics (T8 to L1) benefited from chest strapping, increasing the area of their functional reach by a mean of 24%
Mason et al.[57]	Rugby	10 TP, Male – 9 Male/ 1 Female	Gloves	Own, American football, building and new prototype gloves	Overground propulsion (indoor) – Own court sports chair. Tests involved 3 drills that measured acceleration, braking and sprinting	Better acceleration and sprint performance wearing own gloves. Subjective data also identified that players favoured their own gloves
STRATEGIES *Cardiovascular hemodynamics*						
Vaile et al.[53]	Rugby	10 TP Male (C5-C6 COM – C7 INC)	Compression Socks (~~COMP~~CS)	~~COMP~~ CS worn during exercise vs. control (CON)	Overground propulsion (indoor) – Own court sports chair. 4 x 8 min submaximal exercise with full court sprint	Significant average lap time was better maintained in ~~COMP~~CS
West et al.[54]	Rugby	10 TP - 8 Male and 2 Female (C5-C7 COM)	Abdominal binder	Binding worn during 17 field-based performance measures vs. control (CON)	Wheelchair propulsion (indoor) – Own court sports chair. Tests included measures of agility, acceleration/ deceleration, repeated sprint, submaximal efficiency, Wingate test and repeated 4 min push efforts	Six tests demonstrated performance gains with binding. Improvements were noted with the acceleration/ deceleration profiles and distance covered during the repeated 4 min push. Reductions in minute ventilation during

						submaximal test as well as blood lactate accumulation and ratings of perceived exertion (RPE) during the second set of the repeated 4 min push test
Cooling Interventions						
Goosey-Tolfrey et al.[59]	Tennis	2 TP Male, 5 Male/ 1 Female (Open tennis class)	Hand cooling (HC) versus non-cooling control condition (CON)	HC vs. CON following 60-min steady-state intermittent exercise prior to 1km time-trial	Wheelchair ergometer – own court sports chair. 60-min exercise consisting of five 10-min blocks at 50% peak power output, separated by 2 min passive rest at 30.8°± 0.2° and 60.6% ± 0.2% relative humidity for both conditions.	1 km time-trial performance reduced by 20.5 s after HC
Diaper and Goosey-Tolfrey[3]	Tennis	1 PP Female (L1)	Cooling Garments	Precooling for 30min wearing an ice vest followed by head/neck cooling vs. CON during exercise	Wheelchair ergometer – own tennis sports chair. 60 min intermittent sprint protocol at 30.4 ± 0.6°, 54 ± 3.8% relative humidity for two conditions	Mean speed was maintained as a result of cooling across the 5 x10-min blocks of exercise
Webborn et al.[54]	Tennis & Rugby	8 TP Male (C5/C6-C6/C7, 2 INC)	Ice vest	20 min before start of exercise (PRE), during exercise (DUR) vs. CON	Arm crank Intermittent Sprint Protocol (ISP) – 28 min duration ISP consisting of 10 s of passive rest, a 5-s maximal sprint followed by 105 s of active recovery at 35% aerobic capacity	The cooling strategies appeared to lower the perceived exertion of the exercise, which may translate to improved function capacity
Webborn et al.[58]	Tennis & Rugby	8 TP Male (C5/C6-C6/C7, n=2 INC)	Ice vest	20 min before start of exercise (PRE), during exercise (DUREXE) vs. CON	Arm crank Intermittent Sprint Protocol (ISP) - up to thirty 2-min periods consisting of 10 s of passive rest, a 5-s maximal sprint followed by 105 s of active recovery at 35% aerobic capacity	PRE - 4 athletes completed the full duration, with all athletes completing 16 sprints (32 min). All athletes in DUR EXE were able to sprint longer than the other conditions, completing 22 sprints (44 min). Mean exercise duration was improved by both PRE and DUR EXE when compared with CON. The cooling strategies also

appeared to lower the perceived exertion of the exercise, which may translate to improved function capacity

Note. IWBF – International Wheelchair Basketball Federation; C – cervical;~~ SB – spina bifida~~; SCI – spinal cord injury; TP – tetraplegic; PP~~PARA ~~– paraplegic; INC – incomplete; COM – complete; ~~FHF – French Handisport Federation.~~

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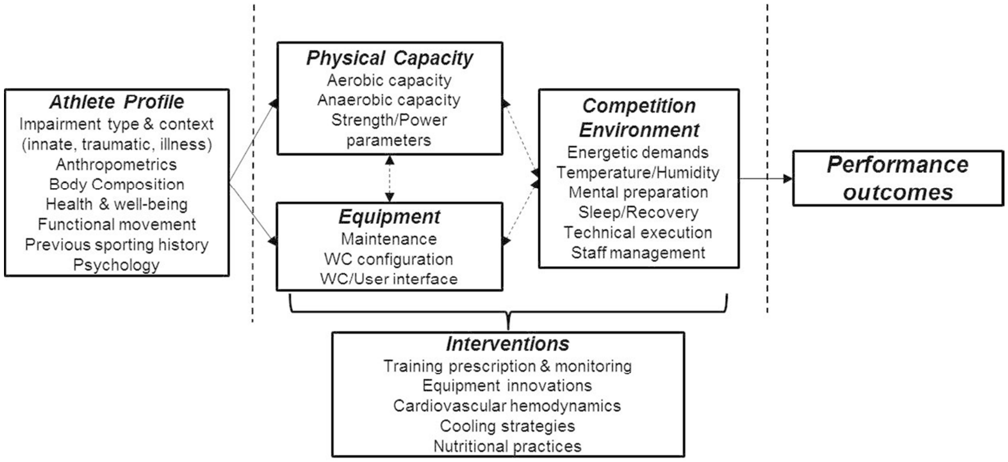

Figure 1 Key components of wheelchair court-sport performance. (WC = Wheelchair).
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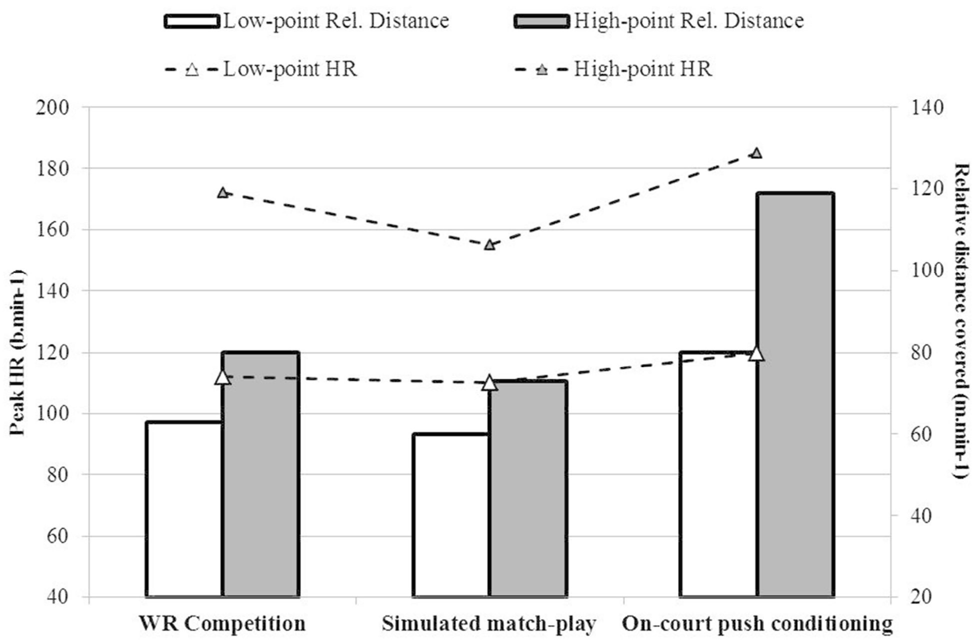

Figure 2 Example heart rate response and distances covered during the same duration wheelchair rugby competition and sport-specific conditioning training for n=1 athlete with tetraplegia (classification = 0.5; low-point player) and n=1 athlete with cerebral palsy (classification=3.0; high-point player). (HR = heart rate, Rel. Distance = distance covered per minute) (Paulson et al. Unpublished data).
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