The Ergonomics of Wheelchair Configuration for Optimal Performance in the Wheelchair Court Sports

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Contents

Abstract

Optimising mobility performance in wheelchair court sports (basketball, rugby and tennis) is dependent on a combination of factors associated with the user, the wheelchair and the interfacing between the two. Substantial research has been attributed to the wheelchair athlete yet very little has focused on the role of the wheelchair and the wheelchair-user combination. This article aims to review relevant scientific literature that has investigated the effects of wheelchair configuration on aspects of mobility performance from an ergonomics perspective.

Optimising performance from an ergonomics perspective requires a multidisciplinary approach. This has resulted in laboratory based investigations incorporating a combination of physiological and biomechanical analyses to assess the efficiency, health/safety and comfort of various wheelchair configurations. To a lesser extent, field based testing has also been incorporated to determine the effects of wheelchair configuration on aspects of mobility performance specific to the wheelchair court sports.

The available literature has demonstrated that areas of seat positioning, rear wheel camber, wheel size and hand-rim configurations can all influence the ergonomics of wheelchair performance. Certain configurations have been found to elevate the physiological demand of wheelchair propulsion, others have been associated with an increased risk of injury and some have demonstrated favourable performance on court. A consideration of all these factors is required to identify optimal wheelchair configurations. Unfortunately, a wide variety of different methodologies have immerged between studies, many of which are accompanied by limitations, thus making the identification of optimal configurations problematic. When investigating an area of wheelchair configuration, many studies have failed to adequately standardise other areas, which has prevented reliable cause and effect relationships being established. In addition, a large number of studies have explored the effects of wheelchair configuration in either able-bodied populations or in daily life or racing wheelchairs. As such the findings are not specific and transferable to athletes competing in the wheelchair court sports.

This review presents evidence about the effects of wheelchair configuration on aspects of mobility performance specific to the wheelchair court sports to better inform athletes, coaches and manufacturers about the consequences of their selections. It also provides

researchers with guidance on the design of future investigations into areas of wheelchair configuration, which are essential.

Significant developments have been witnessed in the wheelchair court sports (basketball, rugby and tennis) over the years. Performance levels have improved dramatically, which has been somewhat due to improvements in athlete's physical conditioning, technique and tactical awareness, all of which have been facilitated by science. Yet, there have also been substantial developments to the design and configurations of the wheelchairs used for these sports, which is also likely to have contributed towards improved performance. Despite these changes to wheelchair configuration and the numerous options that are now available to athletes when configuring a new sports wheelchair, little is known about the effects that these changes can have on aspects of mobility performance. Subsequently, athletes predominantly base their selections pertaining to wheelchair configuration on subjective perceptions and trial and error. There are obviously numerous other components that contribute towards successful performance in the court sports, such as ball handling in wheelchair basketball and rugby or stroke production in tennis. However, the aim of this review is to focus, where possible, on the effects of configuration on mobility performance specific to these sports to ultimately better inform athletes, coaches and manufacturers about the consequences of some of their decisions relating to configuration.

A comprehensive literature search was conducted via the Web of Knowledge, SPORTDiscus and PubMed databases. The following key words were included in the literature search in a number of combinations and variants: 'wheelchair configuration', 'wheelchair set-up', 'wheelchair athletes', 'wheelchair sport' and 'wheelchair propulsion'. Lists of articles published up to and including January 2012 are included in the review. The review is structured into three main sections, firstly addressing the issues concerning ergonomics in a wheelchair and sporting context. A brief background on the wheelchair court sports is then provided before the literature on areas of wheelchair configuration is critiqued. Although the focus of this paper is centred on wheelchair court sports and wheelchair athletes, given the scarcity of research in this area, papers that have investigated the effects of areas of wheelchair configuration in a daily life or wheelchair racing setting in non-athletic or able-bodied (AB) populations are also discussed.

1. Ergonomics of Sports Wheelchair Performance

Ergonomics describes the scientific study between man and his environment and has predominantly been used in an industrial context.[1] In a sporting context, ergonomics requires a multidisciplinary approach to optimise the interaction between the user and their equipment so that the efficiency, safety/health, comfort and performance of the resulting task are maximised.[2,3] In the context of this review, and elite sport in general, optimisation refers to the maximisation of area/s of performance, without significant detriment to other areas, in particular user safety/health. A conceptual model based on a previous model developed by Woude et al.[4] has been devised to demonstrate some of the key factors that can affect the ergonomics of sports wheelchair performance (figure 1). This figure demonstrates how performance is particularly dependent on a number of factors associated with the wheelchair, within the athlete and the interfacing between the two. It also reiterates the necessity for a multidisciplinary approach by highlighting some of the physiological and biomechanical factors associated with the wheelchair-user combination that need to be considered.

INSERT FIGURE 1 HERE

2. Wheelchair Court Sports

The wheelchair court sports have been described as intermittent aerobic based activities that are interspersed with short bouts of high intensity work.[5-9] More specifically, the ability to accelerate, sprint, turn, brake and pull backwards have all been identified as key indicators of successful mobility performance in these sports.[10,11] One wheelchair configuration is clearly not going to be optimal for every aspect of mobility performance or indeed for each individual due to the large range of disabilities apparent within the wheelchair court sports. Therefore, athletes, coaches and manufacturers need to consider which aspect of mobility performance is most important to their role on court, which is often linked to their functional capacity.[12] Limited regulations exist with respect to the specifications of the wheelchairs used in each sport, which allows athletes and manufacturers a large number of options to choose from when configuring a new sports wheelchair.

2.1 Wheelchair Basketball

Wheelchair basketball is contested by two teams of five players, each classified according to the severity of their impairment on a points system ranging from 1.0 (most impaired) to 4.5 (least impaired) as determined by the International Wheelchair Basketball Federation. A total of 14 points per team is permitted on the court at any one time.[13] Legislations surrounding the configurations of the wheelchairs used state that wheel size must not exceed 0.69 m in diameter, and that a maximum seat height of 0.63 m exists for 1.0 – 3.0 point players and 0.58 m for 3.5 – 4.5 point players.

2.2 Wheelchair Rugby

Wheelchair rugby shares a number of similarities with wheelchair basketball in terms of the movement dynamics performed. The game is contested by two teams of four players, who are again classified on a point system governed by the International Wheelchair Rugby Federation, which ranges from 0.5 (most impaired) to 3.5 (least impaired). A total of 8 points are allowed on court at one time and both men and women can compete on the same team unlike basketball, where they compete separately. [13] Like wheelchair basketball there are a small number of specification criteria that a rugby wheelchair must adhere to. Seat height (to the midpoint of the seat) must not exceed 0.53 m. The main wheels shall be no greater than 0.70 m in diameter and must be protected by spokeguards. Akin to basketball, the use of anti-tip castor wheels are permitted, yet these must not extend beyond the rearmost part of the main wheels.

2.3 Wheelchair Tennis

No complex classification system exists for wheelchair tennis and instead players are purely classified in to two groups: a tetraplegic division and an open division.[13] To the authors knowledge and in contrast to wheelchair basketball and wheelchair rugby, there are no regulations concerning the specifications of the wheelchairs used for wheelchair tennis. Despite this, the wheelchairs used tend to be configured in a very similar manner to basketball and rugby wheelchairs. The only slight variation is that on very rare occasions nowadays, tennis wheelchairs may be configured with one front castor wheel as opposed to the more traditional two-wheeled varieties. A further difference to wheelchair basketball and rugby is that wheelchair tennis players are required to push their wheelchairs with the added constraint of a tennis racket.

3. Wheelchair Configuration

A court sports wheelchair is comprised of numerous individual components that can be configured in a variety of different ways (figure 2). Slight adjustments to the way in which each component is configured can affect the ergonomics of mobility performance during wheelchair propulsion. Of the evidence based research that exists, the majority of studies have been limited to assess the effects of seat positioning, rear wheel camber, wheel size and different hand-rim configurations, which will be addressed. Unfortunately the majority of these investigations have been conducted with a predominantly daily life focus and in addition to a number of methodological limitations that will also be discussed, translations to the wheelchair court sports are rarely possible.

INSERT FIGURE 2 HERE

3.1 Seat Positioning

The positioning of the seat in a vertical and horizontal direction (referred to as seat height and fore-aft position respectively) is a critical decision for wheelchair athletes. It is often desirable for athletes to sit as high as possible in order to aid ball handling skills in wheelchair basketball and rugby and stroke production in wheelchair tennis. However, there are numerous other factors worthy of consideration. The position of the seat influences the centre of gravity, the rolling resistance and the stability of the wheelchair-user combination.[14-17] Yet, the effects that such changes have on aspects of mobility performance specific to the court sports remains somewhat limited. Table I details the variety of methodological approaches that have been adopted when investigating the effects of seat positioning and highlights the fact that the majority of these studies have examined a combination of seat heights and fore-aft positions in daily life wheelchairs. Manipulating more than one area at a time prevents any direct cause and effect relationships between the influences of each individual area of configuration on mobility performance from being established.

INSERT TABLE I HERE

3.1.1 Seat Height

From a physiological perspective the majority of investigations into seat positioning have focused on its relationship with mechanical efficiency (ME), with varying results reported.[18-22] Manipulating seat positions by making absolute adjustments in a vertical and horizontal direction, Brubaker et al.[18] and Samuelsson et al.[21] revealed no differences in ME between different seat heights. These changes only evoked a difference of 0.10 m[18] and 0.06 m[21] between the two extreme seat height settings, which may not have been sufficient to induce any physiological adaptations during sub-maximal propulsion. Alternatively, Woude and colleagues[9,22] identified a significant effect of seat height on ME when making standardised adjustments in relation to the anthropometrics of the user, using elbow angle at top dead centre of the wheel. Investigating seat heights ranging from 100° to 160° (whereby 180° represents full extension), Woude et al.[19] revealed that the higher seat heights (140° & 160°) increased oxygen uptake ($\dot{V}O_2$) and reduced ME in comparison with lower seat heights (100° & 120°). When evaluating a lower range of seat heights (70° to 90°), Woude et al.[20] revealed that seat height had no significant effect on power output (P_O) and also revealed that the lowest two settings (70° & 80°) increased $\dot{V}O_2$ in relation to the highest setting (90°). These two investigations suggested that a physiologically optimal seat height existed, since physiological demand was elevated in the extreme high[19] and low[20] settings. Unfortunately, optimal seat heights could not directly be proposed from these two investigations due to the combination of AB and wheelchair dependent participants. Caution must be exercised when using this approach given the inter-individual differences in physiological responses,[23,24] temporal parameters,[24] upper body joint kinematics[23,25] and force application patterns[25,26] that can exist between these groups.

More recently, Woude et al.[22] investigated wheelchair users with a spinal cord injury (SCI) across a larger range of seat heights (70° to 140°) to more reliably establish optimal seat heights. Improvements in $\dot{V}O_2$ and ME were observed between seat heights inducing 100° to 130° elbow extension, suggesting that this was the optimal range for daily life wheelchair users in the early stages of rehabilitation. Although this information could not be translated to a sporting population performing high intensity tasks, it demonstrated the importance of seat height optimisation. Woude et al.[22] revealed that an absolute change of 1.5% in ME was achievable through seat height manipulations, which reflected a potential relative improvement of 25 %.

Given that physiological demand was influenced by seat height and that P_O remained relatively constant suggests that changes in physiological demand may be the result of associated biomechanical adaptations, since these adjustments ultimately dictate how accessible the wheels are for users. A number of studies have identified that standardised seat height adjustments alter propulsion technique.[14,19,27-29] Woude et al.[19] revealed an increased trunk range of motion (RoM) with increasing seat height to compensate for the increased distance between the users and the wheels. A qualitative assessment of muscular activity also demonstrated that the muscles responsible for trunk flexion (rectus abdominis) and extension (erector spinae) remained active for longer periods at higher seat positions, which would not only explain the greater trunk RoM but may also account for the decreased ME.[19] The actions of the elbow[19,28] and wrist[29] are also said to be influenced by seat height. Woude et al.[19] identified increased elbow extension during propulsion at higher seat heights, which could explain the increase in elbow torque predicted by Richter.[28] This was reinforced by the qualitative electromyography data, whereby triceps activation commenced earlier during the propulsion cycle, over a prolonged period of time[19] and at a greater magnitude[14] in higher seat positions. As previously observed with the trunk, this was likely to be related to the increased necessity to reach in order to access the wheels at higher seat heights. Wei et al.[29] revealed that the wrist remained in more of an extended position during propulsion in higher seat positions (100° vs. 90°), which subsequently reduced the RoM. Like the wrist, shoulder motion also becomes restricted in higher seat positions.[19,28] Using mathematical modelling, Richter[28] predicted that decreases in shoulder torque result when the distance between the shoulder and the hub increases. This appeared to support the findings of Woude et al.[19] who revealed that shoulder abduction/adduction and flexion/extension RoM decreased and anterior deltoid and pectoralis major activity shortened with increasing seat height. Although these muscles were active for shorter periods, Masse et al.[14] established that the magnitude of activity was in fact greater at higher seat positions during racing wheelchair propulsion.

Despite all the resultant adaptations to propulsion technique inflicted by seat height manipulations, Woude et al.[19] revealed that peak angular velocities of upper body joints still occurred in sequence. A proximal to distal sequencing pattern was established from the trunk to the shoulder to the elbow and was evident for all seat heights investigated.[19]. Subsequently, all that appears to be influenced is the RoM permitted at each joint and the muscular activity of muscles associated with the movement, whereby higher seat positions increased the involvement of the trunk and elbow, whereas the shoulder and wrist seem to be inhibited.

The changes in upper body joint kinematics and muscular activity observed with seat height have also affected parameters within the propulsion cycle. Lower seat heights have also been associated with increases in push angle and push times[14,16,19,21,29-31] and reductions in push frequency.[14,21] Given the increased push frequency associated with increasing seat height and the smaller RoM of the shoulder, a greater force may be necessitated in order to maintain a given wheelchair velocity. This was supported by the only previous force application investigation into seat height, whereby increases in the total force applied to the hand-rims existed in higher seat heights.[22] This may have implications on user safety/health at higher seat positions given the relationship between increased force magnitude, push frequency and injury risk.[32-34]

Unfortunately all of the physiological and biomechanical responses to changes in seat height that have been observed by previous studies are specific to either daily life or wheelchair racing propulsion, as demonstrated by the type of wheelchairs, participants and intensities investigated (table I). Subsequently, investigations into the effects of seat height during propulsion conditions that are more specific to the wheelchair court sports have been extremely limited. Only Walsh et al.[35] have considered different seat positions during maximal effort bouts of propulsion and revealed that no significant effect existed for the maximal velocities reached. However, a combination of seat heights and fore-aft positions were investigated together in a racing wheelchair, so again the findings cannot be directly translated to the court sports.

3.1.2 Fore-aft Position

As with seat height, adjustments in fore-aft position also directly influence the centre of gravity of the wheelchair-user combination.[14] Although, fore-aft position can affect the stability of the user in a daily life wheelchair,[15] the introduction of anti-tip castor wheel/s prevents this from being an issue in court sport wheelchairs. Fore-aft position can also influence the rolling resistance of the wheelchair-user combination, with less resistance experienced when the centre of gravity is positioned directly above the main wheels.[17] However, its effect on mobility performance has not been well documented, which is also largely due to the variety of methodological approaches employed between previous studies (table I). In particular, only Gutierrez et al.[36] and Mulroy et al.[37] have investigated fore-aft seat positions in isolation. In addition to this, standardisation methods have only been employed by two investigations.[27,29] Hughes et al.[27] and Wei et al.[29] both quantified changes in fore-aft position to the anthropometrics of the user by using arm length percentiles as a means for adjusting the seat base/backrest intersect position in relation to the axle.

The physiological responses to changes in fore-aft position have received limited empirical research attention, with conflicting findings again revealed.[18,21,38] Samuelsson et al.[21] observed no significant changes in $\dot{V}O_2$, heart rate (HR) or ME in two different seating positions, which was unsurprising given that these settings were un-standardised and only differed in fore-aft position by 0.01 m. Despite the absence of statistical analyses, Brubaker et al.[18] reported strong trends for the posterior position at all three seat heights to increase $\dot{V}O_2$ and reduce ME. Yet in contrast, a follow up study revealed trends for the posterior position at all three seat heights to improve ME.[38] Unfortunately, no associations can be made between these two investigations due to a lack of standardisation in relation to users anthropometrics and the fact that differences between the absolute positions of the seat in relation to the axle existed. The posterior position examined by Brubaker et al.[38] was only approximately 0.20 m behind the axle, whereas this position was 0.40 m behind the axle in the earlier investigation.[18]

Fore-aft seat position can also influence propulsion technique. More posterior seat positions have been suggested to permit a greater push angle.[14,21,31] Unfortunately, each of these studies investigated a combination of vertical and horizontal seat positions, so it cannot be reliably established whether increases in push angle were the direct result of fore-aft changes, seat height changes or a combination of both. Boninger et al.[30] investigated 40 manual wheelchair users in their own daily life wheelchairs and documented the horizontal positioning of the shoulder in relation to the axle of the main wheel. More anterior seat positions were shown to be significantly correlated with decreased push angle and frequency. Therefore, being positioned slightly behind the main wheels seemed to increase the portion of hand-rim available for propulsion. It also decreased the need for such a frequent stroke rate, which could offer support to the efficiency trends suggested by Brubaker et al.[38] since lower push frequencies have been associated with reduced physiological demand.[39-42]

The effects of fore-aft position on upper body joint kinematics during propulsion has also been investigated.[14,27,29] Unlike adjustments to seat height, changes in fore-aft position have not been shown to affect trunk[14,27] or wrist RoM.[29] Alternatively, elbow RoM has been affected by fore-aft position, with a reduced RoM observed in the standardised posterior seat positions (seat base/backrest intersect 20% of arm length behind axle) investigated by Hughes et al.[27] Masse et al.[14] revealed that triceps activity was reduced in their posterior setting, which was likely to be due to a greater contribution from the biceps during the ‘pulling’ motion in this position. Although testing was conducted in a racing wheelchair and the fore-aft adjustments were un-standardised, this type of information may be of relevance to wheelchair rugby players. Due to the severity of their SCI these players often lack triceps function and therefore a more posterior seat position may enable them to more effectively utilise their biceps in a pulling motion.

Shoulder motion seems to be the most significantly affected joint through adjustments to fore-aft seat positions. Hughes et al.[27] identified a larger shoulder RoM in the sagittal plane during the posterior fore-aft seat positions. This increase in RoM coincided with a reduction in muscular activity of the muscles surrounding the shoulder joint, with reduced muscular activity observed for the anterior deltoid and the pectoralis major in posterior settings.[14,36] Therefore, posterior seat positions appear to allow the shoulder to act over a greater range and due to the associated decrease in push frequency, which may also have a bearing on minimising injury risk. This was supported to a certain extent by Mulroy et al.[37] who through the use of a wheel with an instrumented hand-rim and an inverse dynamics algorithm revealed that the resultant forces acting on the shoulder were reduced in their posterior seat positions. Boninger et al.[30] also revealed significant correlations between a reduced rate of force development and posterior settings, further implicating this type of setting for improved user safety/health.

Although the literature would suggest that posterior seat positions may be more favourable from a physiological and safety/health perspective, the lack of standardised settings in the majority of investigations has prevented optimal settings being established. In order to optimise this position for wheelchair athletes, standardisation methods similar to those employed by Hughes et al.[27] and Wei et al.[29] are vital. These settings then need to be examined under more sport specific conditions, as again only Walsh et al.[35] assessed maximal effort mobility performance during a combination of different vertical and horizontal seat positions. Fore-aft position is generally thought to affect manoeuvrability, with a more posterior seat position proposed to allow for improved turning speed. However, no studies have scientifically investigated this area, so determining optimal fore-aft positions has not been possible.

3.2 Rear Wheel Camber

Rear wheel camber has been defined as the angle of the main wheels in relation to the vertical, whereby the distance between the top of the wheels is smaller than the bottom.[43,44] Camber is now a particularly common feature of court sports wheelchairs, with increasing degrees being selected.[17,45,46]. Increasing camber creates a wider wheelbase, which has been associated with a number of proposed advantages such as improvements in lateral stability,[47,48] turning speed [49] and greater hand protection.[17,45,50] In contrast to this, users can also experience greater difficulties when negotiating smaller gaps.[47,51,52] All of these are relevant considerations in the wheelchair court sports.

Camber is a particularly complex area of wheelchair configuration, since manipulations directly influence other areas of configuration unless strictly standardised. If a fixed seat position is used, increasing camber reduces the distance between the users shoulder and top dead centre of the wheel and vice versa. Manipulating camber can also alter the distance between top dead centre of both main wheels, with decreasing distances induced in increased camber. If both these by-products of camber are not controlled for, propulsion kinematics become affected and false interpretations of the effects of camber on mobility performance can be formulated. The final area of configuration that needs to be controlled between camber settings is the alignment of the wheels in the transverse plane, referred to as toe-in toe-out.[44,45] Toe-in toe-out needs to be controlled between camber settings, since as little as 2° misalignment can double the rolling resistance experienced.[53] Table II demonstrates that some authors have attempted to standardise these, although only a few have standardised all areas,[54,55] whereas others failed to report standardisation methods, which brings the validity of certain findings into question. Methods for overcoming these subsidiary effects of camber have been employed. Constant elbow angles have been ensured between camber settings through making minor modifications to the seat height to avoid any unnecessary effects on propulsion kinematics.[50,54,55] The distance between top dead centre of both main wheels has also been standardised through the use of different length camber bars to ensure a constant distance between settings.[51,54-56]

INSERT TABLE II HERE

As a result of differing methodologies and the absence of stringent standardisation methods, the effects of camber on mobility performance specific to the court sports are not well understood. Increasing camber increases the contact area between the tyre and the surface, which when toe-in toe-out has been standardised, associated increases in drag forces have been observed.[51,54] Based on its relationship with P_O and physiological demand,[57] increasing camber would have been anticipated to increase the physiological demand for the user. This was not the case in all studies though, as Veeger et al.[50] and Perdios et al.[52] identified no significant effect of camber on these variables, with Veeger et al.[50] also reporting that ME was unaffected. Yet, there were limitations with each of these studies given the absence of standardisation methods. Although Veeger et al.[50] measured the effects of camber on rolling resistance and reported P_O, it was not clear whether the authors controlled for toe-in toe-out between conditions. Irrespective of this, Veeger et al.[50] also corrected for any changes in rolling resistance to maintain a constant P_O between camber conditions. The ecological validity of this approach is questionable, particularly in a sporting context, whereby P_O cannot be controlled by athletes during on court propulsion. If a certain wheelchair configuration influences the P_O requirement from its user and consequently the ergonomics of propulsion, then this should not be excluded when interpreting the data. Alternatively, P_O should be calculated and reported whenever possible to facilitate interpretations, but not controlled as this prevents reliable findings relating to the effects of wheelchair configuration from being established.

When greater attention to standardisation methods has been taken, increases in physiological demand have been observed in larger camber settings. Buckley and Bhambhani[56] revealed an increase in $\dot{V}O_2$ and HR when increasing camber between 0°, 4° and 8°. However, this range of camber settings were more reflective of daily life wheelchairs and may not have been transferable to the wheelchair court sports, where settings can reach 24°.[11] The most relevant investigation into the effects of camber on the physiological responses of wheelchair court sport athletes has been conducted by Mason et al.[54] investigating a range of standardised settings between 15° and 24°. This confirmed that larger camber settings increased the physiological demand of propulsion at a fixed speed, whereby HR was significantly elevated in 20° compared with 15° and both HR and $\dot{V}O_2$ were elevated in 24° compared with 15° and 18°. These physiological responses appeared to reflect the changes in P_O since a greater workload was evident during the larger 20° and 24° settings compared to the 15° setting.[54]

Investigations into the effects of camber on the biomechanics of wheelchair propulsion has been somewhat limited.[50,51,54] Veeger et al.[50] revealed that adjusting camber between 0° and 9° had a significant impact upon certain technique parameters during the push phase. It was shown that 6° camber significantly increased push angles, push times and shoulder abduction during the push phase in relation to other settings. However, as previously mentioned the failure of this study to standardise additional areas of configuration between camber settings, particularly the distance between top dead centre of the main wheels, severely compromises the validity of the kinematic findings. The standardised camber investigation by Mason et al.[54] revealed that a sports specific range of camber settings did not significantly affect push angles or temporal parameters during propulsion. However, upper body joint kinematics were influenced, with a greater active RoM for shoulder flexion and elbow extension observed in the largest 24° setting compared to the 15° and 18° settings. It was likely that these changes in upper body joint kinematics were linked to the increased P_O and physiological demand observed in the 24° setting. Subsequently, a biomechanical analysis is always advisable alongside a physiological analysis to help explain why any changes in physiological responses are occurring.

Compared to other areas of configuration, camber has actually received a reasonable amount of evidence-based research from a maximal effort, sports performance perspective.[49,51,55] Faupin et al.[51] investigated the maximal linear sprinting performance of wheelchair basketball players and established that increments in camber were accompanied by increases in push time and decreases in mean velocity during 8-second sprints on a roller wheelchair ergometer (WERG). This suggested that players were less effective when pushing with higher degrees of camber, as sprinting performance was negatively affected, even though the time over which they were applying force to the wheels increased. There are limitations associated with the use of ergometry as a valid representation of over-ground propulsion. Firstly, they fail to account for any shifts in the centre of gravity during propulsion and the inertial forces acting on the wheelchair-user combination, created by the accelerations and decelerations of the trunk, are neglected due to the static attachment of the wheelchair to the device. In addition, a WERG prevents backward tilting in the wheelchair, which can affect propulsion kinematics and force application in comparison to over-ground propulsion.[10] To this extent, field based testing is a favourable environment for the assessment of maximal effort mobility performance specific to the court sports to be investigated under. With this in mind, an earlier field based study by Faupin et al.[49] did not support the latter study's findings with regards to linear mobility performance. Alternatively, using the same three camber settings, no significant effect of camber was evident for the mean or peak velocities reached during a 15 m over-ground sprint. A further benefit of the field based study was that it enabled the effect of camber on manoeuvrability performance to be investigated.[49] During a 'figure of eight' drill it was revealed that increasing camber significantly reduced the times taken to perform turns. Unfortunately standardisation methods were not reported preventing the validity of these findings from being presented, as well as the range of camber settings investigated being inferior to the range commonly used nowadays.

Only Mason et al.[55] have investigated the effects of a sports specific range of camber on maximal effort over-ground propulsion in wheelchair athletes. Using a wheelchair velocometer[58] Mason et al.[55] were able to investigate the effects of camber on mobility performance in far greater detail. Although no statistically significant effect of camber existed, large effect sizes (r = 0.53 to 0.59) were observed for 24° to meaningfully impair initial acceleration performance over the first two and three pushes, which as we know is a key performance indicator in the court sports.[10] The 24° setting was also shown to negatively affect the times taken to complete a 20 m sprint compared with 18° and 20° camber and a linear mobility drill compared with 15° and 18° camber. Mason et al.[55] also observed meaningful improvements in manoeuvrability performance between the 18° (r = 0.68) and 20° (r = 0.71) setting compared with 15°. This suggested that manoeuvrability performance does increase with camber, but only to a certain point within the range investigated, since no further improvements were observed in the 24° setting. Combining these findings with the sub-maximal laboratory based findings,[54] it was clear that 24° was an unfavourable camber setting given its negative effects on aspects of both sub-maximal and maximal effort linear performance, without any benefits in terms of manoeuvrability performance.

3.3 Wheel Size

Wheel size affects the rolling resistance of the wheelchair-user combination, with smaller wheels known to increase resistance at a given speed.[59] This is obviously applicable to the front and rear castor wheels, however from an ergonomics perspective investigations have only focused on the main wheels.[60,61] Adjusting wheel size can also affect the distance between top dead centre of the main wheels and the distance between the shoulder and the top of the wheel, both of which can influence propulsion technique if not controlled for. Investigating a range of wheel sizes from 0.59 m (24 inches) to 0.65 m (26 inches), Mason et al.[60] standardised the distance between shoulder position and the top of the wheel by adjusting seat height accordingly to maintain a fixed elbow angle across conditions. Unfortunately, owing to the use of a fixed length camber bar the distance between top dead centre of both main wheels could not be controlled and was reduced in the larger wheels. Despite this, Mason et al.[60] confirmed the greater resistance associated with smaller wheels by noting significant increases in P_O during sub-maximal, fixed speed propulsion on a motor driven treadmill. The consequence of this was an increase in physiological demand, as demonstrated by higher $\dot{V}O_2$ and HR responses in 0.59 m compared with 0.65 m wheels. The kinematic analysis which accompanied this revealed no significant effect of wheel size on upper body joint kinematics or temporal parameters associated with propulsion. However, the inclusion of a kinetic analysis through the use of different sized SMART[Wheels] revealed that significantly higher mean resultant and tangential forces were applied in the smaller 0.59 m wheels in order to maintain the fixed speed. There were also trends supported by large effect sizes that the rate of force development was greater in 0.59 m wheels compared with 0.65 m wheels ($r = 0.55$), which could have implications for injury risk in a smaller wheel size.[33]

During field based testing, Mason et al.[61] revealed that wheel size also significantly affects maximal effort mobility performance. The times taken to perform a 20 m sprint were shown to be reduced in 0.65 m wheels compared with 0.59 m. The use of a velocometer[58] again enabled linear performance to be investigated in greater detail. Initial acceleration performance was not statistically affected by wheel size, however sprinting performance was since peak speeds reached were meaningfully higher in 0.65 m compared with 0.59 m wheels ($r = 0.63$). Larger negative dips in speed were observed at the beginning of each push near peak speed in 0.59 m wheels, suggesting that difficulties in coupling were experienced in smaller wheels. No significant effect of wheel size was observed for manoeuvrability performance. Therefore based on the results of the laboratory based and field based investigations, 0.65 m wheels appeared to be favourable for highly trained wheelchair athletes. However, these could not be suggested to be optimal given that 0.67 m wheels (27 inches) were not able to be investigated, which are becoming increasingly familiar in the court sports today.

3.4 Hand-rims

The final area of configuration to have received evidence based research into its effects on mobility performance relates to the hand-rims. The hand-rims are vital as they are responsible for driving the main wheels and the wheelchair-user combination and they can be varied in a number of ways.

3.4.1 Hand-rim Diameter / Gear Ratio

Reducing the diameter of a hand-rim in relation to a fixed wheel size effectively reduces the gear ratio available to users during propulsion.[62] The hand-rims of court sport wheelchairs are typically 1” (0.025 m) smaller than the diameter of the main wheel maintaining a fixed gear ratio,[60] however recently variations on the size of the hand-rims in relation to the wheel are being introduced into these sports. Yet, as a possible result of only being a recent innovation in the court sports, no research into the effects of differing hand-rim diameters on the performance of maximal effort tasks, specific to the wheelchair court sports, exists. The effects of this on aspects of mobility performance is something which has received previous research attention from a daily life[63] and wheelchair racing[64-66] perspective.

Investigating a total of five different diameter hand-rims on a fixed wheel size, Woude et al.[64] revealed that the largest two settings significantly increased the physiological demand, through reductions in ME and increases in both $\dot{V}O_2$ and HR responses. Gayle et al.[65] also reported an increase in physiological demand during sub-maximal propulsion in the larger of two hand-rim diameters. More recently, Costa et al.[66] observed a contrasting pattern, whereby elevated HR and blood lactate values were revealed in the smallest hand-rim diameter at the slowest of three test speeds. Although this pattern was shown to be reversed at the highest test speed, it must be noted that this study was only a single participant case study and as such the results may only be applicable to that individual.

Given the fixed wheel sizes, vehicle mechanics such as rolling resistance won’t be affected by adjustments in hand-rim diameter, meaning that any changes observed in physiological demand are the likely result of biomechanical adaptations to changes in gear ratio. Changes in propulsion technique would be anticipated given that un-standardised, fixed seat heights were used across investigations, causing an increased distance between the shoulder and top dead centre of the hand-rim when the diameter is reduced, which is likely to affect muscle mechanics. This lack of standardisation obviously makes it difficult to establish whether any changes in physiology are the result of the hand-rim adjustments, the different seating position in relation to the hand-rims or a combination of both. To this extent Woude et al.[64] attributed the differences in physiological demand observed with hand-rim diameter to the greater shoulder flexion/extension RoM, maximum abduction and elbow flexion values resulted from increasing hand-rim diameters.[64] Guo et al.[63] supported the physiological findings of Woude et al.[64] and Gayle et al.[65] when it was observed that larger diameter hand-rims increased the linear velocities of the hand, forearm and upper arm during propulsion at fixed speeds. Woude et al.[64] revealed that manipulating hand-rim diameter/gear ratio did not affect the temporal parameters during sub-maximal wheelchair propulsion, whereas Costa et al.[66] observed an increase in push frequencies and a reduction in push times in the larger diameter hand-rim. However, it must be reiterated that the latter was a single participant case study, whose results are unlikely to be representative of the population of wheelchair athletes. Differences in work per cycle have also been observed, whereby Woude et al.[64] identified no changes between hand-rim diameters, whilst Guo et al.[63] revealed an increase in work with larger hand-rim diameters. These differences may stem from the disparities in ability and experience of the participants investigated, given that the range of hand-rim diameters were similar (table III).

Although this research has focused heavily on racing wheelchairs, both Woude et al.[64] and Costa et al.[66] noted that the majority of participants could not maintain the highest test velocity in the largest hand-rim condition. Therefore, there are potential implications applicable to the wheelchair court sports that would merit investigation, as these results suggest that a larger gear ratio may be ineffective for maximal sprinting performance.

INSERT TABLE III HERE

3.4.2 Hand-rim Configuration

Areas of hand-rim configuration, including the diameter, shape, material and flexibility of the tube have also been investigated from an ergonomic perspective (table IV). All of these are vital considerations when configuring a new wheelchair since the hand-rim is the immediate interface between the wheelchair and the user and the site of force transmission between the two.[67] Each of these areas are also relevant to the court sports where dependent on factors such as players role on court and even just personal preference, the diameter of the tube, material and proximity of the rim to the wheel are especially important considerations.

However, each of the investigations into hand-rim configurations has focused on aspects of daily life propulsion, which as we know does not necessarily translate into the wheelchair court sports.

INSERT TABLE IV HERE

Linden et al.[68] investigated the effects of two different hand-rim tube diameters on various physiological and biomechanical parameters and revealed that the hand-rim with a larger tube diameter reduced $\dot{V}O_2$ and improved ME. However, the changes in physiological demand observed with different tube diameters could not be explained by any biomechanical adaptations, as temporal parameters and force application remained consistent between conditions. Woude et al.[69] also examined various hand-rim configurations, which differed in material, shape, and tube diameter. No significant differences were observed for any of the physiological or biomechanical parameters investigated between the hand-rim configurations, yet the subjective analyses revealed that cylindrical, rubber coated hand-rims were most favourable in terms of user acceptance/comfort. Although, user acceptance was the only measure to be affected by the manipulations, it was unclear whether the material, shape, tube diameter or a combination of each were what led to the favourable performance of the cylindrical, rubber coated hand-rim due to multiple changes in configuration at once.

More recently, innovative hand-rim designs have been developed in an attempt to improve wheelchair performance. A variable compliance [70,71] and a 'natural-fit' hand-rim,[72,73] which differ in terms of material, shape and flexibility in comparison to standard hand-rims have been investigated. A reduction in finger and wrist flexor activity has been established in a flexible, high friction hand-rim[71] This may have implications on efficiency, as Linden et al.[68] proposed that the improvements they observed in ME may have been the result of a reduced amount of muscular activity being required to grip the hand-rim. User safety/health has also been considered between hand-rim configurations, with increases in compliance having been shown to increase the rate of rise of force development, thus potentially exacerbating the risk of injury.[70] Subjectively, comparisons between the performances of these hand-rims in relation to standard hand-rims have also been sought, with reductions in hand and wrist pain and improvements in the ease of propulsion reported in the ‘natural-fit’ hand-rims.[72,73] Unfortunately, all the aforementioned investigations have focused on improving the ergonomics of propulsion for the daily life user and the application of such findings to sporting populations is once again prevented.

4. Future Research

Having reviewed the previous literature investigating the ergonomics of wheelchair configuration, it was clear that wheelchair configuration can have a significant impact on aspects of mobility performance. However numerous procedures must be considered to further improve understanding and to make findings applicable to the wheelchair court sports, since previous investigations into wheelchair configuration have adopted an extremely biased focus on aspects of daily life propulsion. This has obviously limited translations that can be applied to a sporting context. Yet, there are still a number of procedures that can be implemented and precautions that must be taken that have been derived from these studies to benefit future research.

4.1 Type of Wheelchair

To investigate the effects of manipulating sports wheelchair configuration, testing must take place in a sports wheelchair in settings that are common to the court sports. Examining the effects of configuration in daily life or racing wheelchairs does not generate results that are transferable to the court sports given the differences in design and the variations in the settings that are common to each type of wheelchair.

4.2 Standardisation

To assist with the identification of reliable cause and effect relationships, stricter standardisation methods need to be applied to other areas of configuration. This is due to the fact that manipulating one area of configuration can have knock on effects on other area/s of configuration if not controlled for. In association with this only one area of configuration should be manipulated at a time to start with. Adjustments also need to be standardised to the anthropometrics of the user, as we have seen in a handful of previous investigations.[14,19,20,22,27,29,36,37,54,55,60,61] This enables research findings to be more applicable to the general population who have not participated in the investigation and will facilitate the identification of optimal settings. For example, numerous studies making un-standardised adjustments have made reference to the ‘most posterior setting’ or the ‘highest setting’, which can only be used in the context of that specific study and the findings are not transferable to others.

4.3 Participants

Previous investigations have frequently sampled AB participants, as they are thought to be more of a homogeneous group, due to the larger inter-individual differences that exist within impaired individuals resulting from differences in the severity of impairment.[17] Although AB individuals may be useful for formulating theoretical concepts about the learning process of manual wheelchair propulsion and for observing generic responses to certain propulsion conditions, we know that these individuals differ to wheelchair dependent individuals in various physiological and biomechanical traits during wheelchair propulsion.[23-26] Therefore, when attempting to optimise the mobility performance of wheelchair athletes through wheelchair configuration, individuals competing in these sports need to be studied in order to test under the most ecologically valid conditions.[10]

4.4 Simulation of Wheelchair Propulsion

To create the most ecologically valid testing conditions for wheelchair athletes, an assessment of over-ground propulsion is ideal since this is the most specific to the environment in which they compete in, hence why a far greater emphasis on field based testing is required in future. Yet, laboratory based investigations are still important as a starting point due to the controlled conditions they create. However, it is recommended that these investigations may be more suitable on motor driven treadmills than on a WERG as these may give a more realistic simulation of over-ground propulsion.[17]

4.5 Exercise Protocols

As previously mentioned, field based testing is important so that the effects of configuration can be investigated without any constraints on speed, performing the type of movements specific to those required during competition. Outcome measures such as times taken to perform drills should be assessed along with the speeds and accelerations achieved. In the laboratory it is advisable that fixed speeds are employed. This enables a measure of the drag forces experienced in each configuration to be obtained, which is important information as it enables P_O to be calculated. Studies should then report P_O whenever possible to highlight the effects of configuration on this measure, yet it should not be controlled for as has previously been seen,[50] as this is something that cannot be controlled by athletes on court. During laboratory based protocols, measures of physiological demand should be combined wherever possible with a kinematic and kinetic analysis to give the most valid ergonomic assessment of certain wheelchair configurations.

INSERT TABLE V HERE

5. Conclusions

All of the methodological considerations demonstrate the complexity of the task and may partly explain why the effects of sports wheelchair configuration have received so little evidence based research in the past, as it is undoubtedly an important area. However future multidisciplinary research combining a number of physiological, biomechanical and performance measures in both a laboratory and field based environment adopting the methodological considerations outlined, can better inform athletes, coaches and manufacturers about the consequences of wheelchair configuration on mobility performance. However, far greater consideration needs to be given to its effects on injury risk as this has never been objectively investigated. The information from standardised research investigations can be used to benefit the younger, less experienced and novice wheelchair athlete who often have no previous information to base selections about their wheelchair configuration on. Table V summarises some of the general effects that have been shown to occur when making standardised changes to certain areas of wheelchair configuration, which may be of use to these individuals. However, this type of information will not be specific enough to influence elite, highly trained wheelchair athletes, who differ in a number physical factors (anthropometrics, severity of impairment etc.) and game related factors (role on court and which aspect of mobility performance is most important to that role). Therefore an individual and longitudinal case study approach is recommended with this population group using scientific equipment sensitive enough to detect minimal changes in performance. It is important to monitor the effects of wheelchair configuration over time in order to account for an adaptation period that can exist with a new wheelchair.[11]

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References

1. Murrell KF. Ergonomics: man and his working environment. New York: Chapman & Hall, 1965

2. Reilly T, Lees A. Exercise and sports equipment: some ergonomic aspects. Appl Ergon 1984; 15: 259-79

3. Reilly T, Ussher M. Sport, leisure and ergonomics. Ergon 1988; 31: 1497-500

4. Woude van der LHV, Groot de S, Hollander AP, et al. Wheelchair ergonomics and physiological testing of prototypes. Ergon 1986; 29: 1561-73

5. Coutts KD. Dynamics of wheelchair basketball. Med Sci Sports Exerc 1992; 24: 231-34

6. Bloxham LA, Bell GJ, Bhambhani Y, et al. Time motion analysis and physiological profile of Canadian world cup wheelchair basketball players. Sports Med Train Rehabil 2001; 10: 183-98

7. Roy JL, Menear KS, Schmid MM, et al. Physiological responses of skilled players during a competitive wheelchair tennis match. J Strength Cond Res 2006; 20: 665-71

8. Goosey-Tolfrey VL, Castle P, Webborn N, et al. Aerobic capacity and peak power output of elite quadriplegic games players. Brit J Sports Med 2006; 40: 684-87

9. Sarro KJ, Misuta MS, Burkett B, et al. Tracking of wheelchair rugby players in the 2008 demolition derby final. J Sports Sci 2010; 28: 193-200

10. Vanlandewijck YC, Theisen D, Daly D. Wheelchair propulsion biomechanics: implications for wheelchair sports. Sports Med 2001; 31: 339-67

11. Mason BS, Porcellato L, Woude van der LHV, et al. A qualitative examination of wheelchair configuration for optimal mobility performance in wheelchair sports: a pilot study. J Rehabil Med 2010; 42: 141-49

12. Yilla AB, La Bar RH, Dangelmaier BS. Setting up a wheelchair for basketball. Sports 'n Spokes 1998; 24: 63-65

13. Tweedy S, Diaper N. Introduction to wheelchair sport. In: Goosey-Tolfrey V, editor. Wheelchair sport: a complete guide for athletes, coaches and teachers. Champaign (IL): Human Kinetics, 2010:3-28

14. Masse LC, Lamontagne M, O'Riain MD. Biomechanical analysis of wheelchair propulsion for various seating positions. J Rehabil Res Dev 1992; 29: 12-28

15. Majaess GG, Kirby RL, Ackroyd-Stolarz, et al. Influence of seat position on the static and dynamic forward and rear stability of occupied wheelchairs. Arch Phys Med Rehabil 1993; 74: 977-82

16. Vanlandewijck YC, Daly D, Spaepen A, et al. Biomechanics in handrim wheelchair propulsion: wheelchair-user interface adjustment for basketball. Educ Phys Train Sport 1999; 4: 50-53

17. Woude van der LHV, Veeger HEJ, Dallmeijer AJ, et al. Biomechanics and physiology in active manual wheelchair propulsion. Med Eng Phys 2001; 23: 713-33

18. Brubaker CE, McLaurin CA, Gibson JD. Effect of seat position on wheelchair performance. In: Proceedings of the International Conference on Rehabilitation Engineering; 1980: Toronto: 134-36

19. Woude van der LHV, Veeger HEJ, Rozendal RH, et al. Seat height in handrim wheelchair propulsion. J Rehabil Res Dev 1989; 26: 31-50

20. Woude van der LHV, Veeger HEJ, Rozendal RH, et al. Seat height in hand rim wheelchair propulsion: a follow-up study. J Rehabil Sci 1990; 3: 79-83

21. Samuelsson KAM, Tropp H, Nylander E, et al. The effect of rear-wheel position on seating ergonomics and mobility efficiency in wheelchair users with spinal cord injuries: a pilot study. J Rehabil Res Dev 2004; 41: 65-74

22. Woude van der LHV, Bouw A, Wegen van J, et al. Seat height: effects on submaximal hand rim wheelchair performance during spinal cord injury rehabilitation. J Rehabil Med 2009; 41: 143-49

23. Brown DD, Knowlton RG, Hamill J, et al. Physiological and biomechanical differences between wheelchair-dependent and able-bodied subjects during wheelchair ergometry. Eur J Appl Physiol 1990; 60: 179-82

24. Patterson P, Draper S. Selected comparisons between experienced and non-experienced individuals during manual wheelchair propulsion. Biomed Sci Instrum 1997; 33: 477-81

25. Veeger HEJ, Lute EMC, Roeleveld K, et al. Differences in performance between trained and untrained subjects during a 30-s sprint test in a wheelchair ergometer. Eur J Appl Physiol 1992; 64: 158-64

26. Robertson RN, Boninger ML, Cooper RA, et al. Pushrim forces and joint kinetics during wheelchair propulsion. Arch Phys Med Rehabil 1996; 77: 856-64

27. Hughes CJ, Weimar WH, Sheth PN, et al. Biomechanics of wheelchair propulsion as a function of seat position and user-to-chair interface. Arch Phys Med Rehabil 1992; 73: 263-69

28. Richter MW. The effect of seat position on manual wheelchair propulsion biomechanics: a quasi-static model-based approach. Med Eng Phys 2001; 23: 707-12

29. Wei S, Huang S, Jiang C, et al. Wrist kinematic characterization of wheelchair propulsion in various seating positions: implication to wrist pain. Clin Biomech 2003; 18: S46-52

30. Boninger ML, Baldwin M, Cooper RA, et al. Manual pushrim biomechanics and axle position. Arch Phys Med Rehabil 2000; 81: 608-13

31. Kotajarvi BR, Sabick MB, An KN, et al. The effect of seat position on wheelchair propulsion biomechanics. J Rehabil Res Dev 2004; 41: 403-13

32. Boninger ML, Cooper RA, Baldwin MA, et al. Wheelchair pushrim kinetics: body weight and median nerve function. Arch Phys Med Rehabil 1999; 80: 910-15

33. Boninger ML, Souza AL, Cooper RA, et al. Propulsion patterns and pushrim biomechanics in manual wheelchair propulsion. Arch Phys Med Rehabil 2002; 83: 718-23

34. Boninger ML, Impink BG, Cooper RA et al. Relation between median and ulnar nerve function and wrist kinematics during wheelchair propulsion. Arch Phys Med Rehabil 2004; 85: 1141-45

35. Walsh CM, Marchiori GE, Steadward RD. Effect of seat position on maximal linear velocity in wheelchair sprinting. Can J Appl Sports Sci 1986; 11: 186-90

36. Gutierrez DD, Mulroy SJ, Newsam CJ, et al. Effect of fore-aft seat position on shoulder demands during wheelchair propulsion: part 2 – an electromyographic analysis. J Spinal Cord Med 2005; 28: 222-29

37. Mulroy SJ, Newsam CJ, Gutierrez DD, et al. Effect of fore-aft seat position on shoulder demands during wheelchair propulsion: part 1 – a kinetic analysis. J Spinal Cord Med 2005; 28: 214-21

38. Brubaker CE, McClay IS, McLaurin CA. Effect of seat position on wheelchair propulsion efficiency. In: Proceedings of the 2nd International Conference on Rehabilitation Engineering; 1984: Ottawa: 12-14

39. Jones D, Baldini F, Cooper R, et al. Economical aspects of wheelchair propulsion. Med Sci Sports Exerc 1992; 24: S32

40. Goosey VL, Campbell IG. Pushing economy and propulsion technique of wheelchair racers at three speeds. Adapt Phys Activ Q 1999; 15: 36-50

41. Goosey VL, Campbell IG, Fowler NE. Effect of push frequency on the economy of wheelchair racers. Med Sci Sports Exerc 2000; 32: 174-81

42. Goosey-Tolfrey VL, Kirk JH. Effect of push frequency and strategy variations on economy and perceived exertion during wheelchair propulsion. Eur J Appl Physiol 2003; 90: 154-58

43. Higgs C. An analysis of racing wheelchairs used at the 1980 Olympic Games for the disabled. Res Q Exerc Sport 1983; 54: 229-33

44. Frank TG, Abel EW. Drag forces in wheelchairs. In: Woude van der LHV, Meijs PJM, Grinten van der, et al. editors. Ergonomics of manual wheelchair propulsion: state of the art. Amsterdam: IOS Press, 1993: 255-67

45. Cooper RA. Wheelchair selection and configuration. New York: Demos Medical Publishing Inc, 1998

46. Ardigo LP, Goosey-Tolfrey VL, Minetti AE. Biomechanics and energetics of basketball wheelchairs evolution. Int J Sports Med 2005; 26: 388-96

47. Trudel G, Kirby RL, Bell AC. Mechanical effects of rear-wheel camber on wheelchairs. Assist Technol 1995; 7: 79-86

48. Trudel G, Kirby RL, Ackroyd-Stolarz SA, et al. Effects of rear-wheel camber on wheelchair stability. Arch Phys Med Rehabil 1997; 78: 78-81

49. Faupin A, Campillo P, Weissland T, et al. Effect of the wheel camber of a wheelchair on the linear speed and on the speed of turning of the basketball player. Cinesiologie 2002; 201: 4-6

50. Veeger HEJ, Woude van der LHV, Rozendal RH. The effect of rear wheel camber in manual wheelchair propulsion. J Rehabil Res Dev 1989; 26: 37-46

51. Faupin A, Campillo P, Weissland T, et al. The effects of rear-wheel camber on the mechanical parameters produced during the wheelchair sprinting of handibasketball athletes. J Rehabil Res Dev 2004; 41: 421-28

52. Perdios A, Sawatzky BJ, Sheel AW. Effects of camber on wheeling efficiency in the experienced and inexperienced wheelchair user. J Rehabil Res Dev 2007; 44: 459-66

53. O'Reagan J, Thacker J, Kauzlarich J, et al. Wheelchair dynamics. In: Wheelchair mobility 1976-1981. Rehabilitation Engineering Center, University of Virginia, 1981: 33-41

54. Mason BS, Woude van der LHV, Groot de S, et al. The effects of camber on the ergonomics of propulsion in wheelchair athletes. Med Sci Sports Exerc 2011; 43: 319-26

55. Mason BS, Woude van der LHV, Tolfrey K, et al. The effects of rear wheel camber on maximal effort mobility performance in wheelchair athletes. Int J Sports Med 2012; 33: 199-204

56. Buckley SM, Bhambhani YN. The effects of wheelchair camber on physiological and perceptual responses in younger and older men. Adapt Phys Activ Q 1998; 15: 15-24

57. Woude van der LHV, Hendrich KMM, Veeger HEJ, et al. Manual wheelchair propulsion: effects of power output on physiology and technique. Med Sci Sports Exerc 1988; 20: 70-78

58. Moss AD, Fowler NE Tolfrey VL. A telemetry-based velocometer to measure wheelchair velocity. J Biomech 2003; 36: 253-57

59. Kauzlarich JJ, Thacker JG. Wheelchair tire rolling resistance and fatigue. J Rehabil Res Dev 1985; 22: 25-41

60. Mason BS, Woude van der LHV, Tolfrey K, et al. Effects of wheel and hand-rim size on sub-maximal propulsion in wheelchair athletes. Med Sci Sports Exerc 2012; 44: 126-134

61. Mason BS, Woude van der LHV, Goosey-Tolfrey VL. The effect of wheel size on mobility performance in wheelchair athletes. Int J Sports Med; In Press

62. Veeger HEJ, Woude van der LHV, Rozendal RH. Effect of handrim velocity on mechanical efficiency in wheelchair propulsion. Med Sci Sports Exerc 1992; 24: 100-07

63. Guo L, Su F, An K. Effect of handrim diameter on manual wheelchair propulsion: mechanical energy and power flow analysis. Clin Biomech 2006; 21: 107-15

64. Woude van der LHV, Veeger HEJ, Rozendal RH, et al. Wheelchair racing: effects of rim diameter and speed on physiology and technique. Med Sci Sports Exerc 1988; 20: 492-500

65. Gayle GW, Pohlman RL, Glaser RM. Cardiorespiratory and perceptual responses to arm crank and wheelchair exercise using various handrims in male paraplegics. Res Q Exerc Sport 1990; 61: 224-32

66. Costa GB, Rubio MP, Belloch SL, et al. Case study: effect of handrim diameter on performance in a Paralympic wheelchair athlete. Adapt Phys Activ Q 2009; 26: 352-63

67. Gaines RF, La WH. Users' responses to contoured wheelchair handrims. J Rehabil Res Dev 1986; 23: 57-62

68. Linden van der ML, Valent L, Veeger HEJ, et al. The effect of wheelchair handrim tube diameter on propulsion efficiency and force application. IEEE Trans Rehabil Eng 1996; 4: 123-32

69. Woude van der LHV, Formanoy M, Groot de S. Hand rim configuration: effects on physical strain and technique in unimpaired subjects? Med Eng Phys 2003; 25: 765-74

70. Richter MW, Axelson PW. Low-impact wheelchair propulsion: achievable and acceptable. J Rehabil Res Dev 2005; 42: 21-34

71. Richter MW, Rodriguez R, Woods KR, et al. Reduced finger and wrist flexor activity during propulsion with a new flexible handrim. Arch Phys Med Rehabil 2006; 87: 1643-47

72. Koontz AM, Yang Y, Boninger DS, et al. Investigation of the performance of an ergonomic handrim as a pain-relieving intervention for manual wheelchair users. Assist Technol 2006; 18: 123-43

73. Dieruf K, Ewer L, Boninger D. The natural-fit handrim: factors related to improvement in symptoms and function in wheelchair users. J Spinal Cord Med 2008; 31: 571-85

List of Figures:

Table I. Testing procedures of previous investigations into the effects of seat positioning on aspects of mobility performance

Reference	Height / Fore-aft	Wheelchair	Participants	Mode	Speeds ($m \cdot s^{-1}$)	Power Output	Standardisation	Measures
Woude et al.[19]	H	WCS	AB – 9	MDT	0.55 – 1.39	0.17 – 0.44 W/kg	S - elbow angle (°)	Physiology, temporal, kinematics
Woude et al.[20]	H	simulator	AB – 3 WA – 2	WERG	1.11 – 1.39	Reported, not controlled	S - elbow angle (°)	Physiology, temporal
Woude et al.[22]	H	simulator	WU – 12	WERG	0.42 – 0.83	5.4-13.9 W	S - elbow angle (°)	Physiology, temporal, kinetics
Brubaker et al.[18]	H & F	ADL	AB – 4	WERG	Not reported	0.25 W/kg	U	Physiology, temporal
Brubaker et al.[38]	H & F	ADL	WU – 9	WERG	1.10	20 W	U	Physiology
Walsh et al.[35]	H & F	RAC	WU – 9	WERG	3.45 – 6.18	Not controlled or measured	U	Performance
Hughes et al.[27]	H & F	simulator	AB – 9 WU – 6	WERG	0.83	15 W	S - elbow angle (°) & arm length (%)	Temporal, kinematics
Masse et al.[14]	H & F	RAC	WU – 5	WERG	3.22 – 3.81	Not controlled or measured	S - elbow angle (°) & U (fore-aft)	Temporal, kinetics
Boninger et al.[30]	H & F	ADL	WU – 40	WERG	0.90 & 1.80	Not controlled or measured	U	Temporal, kinetics
Wei et al.[29]	H & F	ADL	WU – 11	WERG	Self selected (not reported)	Not controlled or measured	S - elbow angle (°) & arm length (%)	Temporal, kinematics
Kotajarvi et al.[31]	H & F	WCS	AB – 20 WU – 13	OG	Self selected (1.48 ± 0.16)	Not controlled or measured	U	Temporal, kinetics
Samuelsson et al.[21]	H & F	ADL	WU – 12	MDT	1.00	Reported, not controlled	U	Physiology, temporal
Gutierrez et al.[36]	F	ADL	WU – 13	WERG	Self selected (1.07 – 2.22)	Not controlled or measured	S - elbow angle (°) U (fore-aft)	Kinetics
Mulroy et al.[37]	F	ADL	WU – 13	WERG	Self selected (1.07 – 2.22)	Not controlled or measured	As Gutierrez et al.[36]	Kinetics

H = height; **F** = fore-aft; **ADL** = daily life wheelchair; **RAC** = racing wheelchair; **WCS** = sports wheelchair; **AB** = able-bodied; **WU** = wheelchair user; **WA** = wheelchair athlete; **MDT** = motor driven treadmill; **WERG** = wheelchair ergometer; **OG** = over-ground; **S** = standardised; **U** = un-standardised.

Table II. Summary of methodologies used by previous investigations into the effects of camber on mobility performance

Reference	Wheelchair	Camber (°)	Standardisation			Participants	Mode	Speeds ($m \cdot s^{-1}$)	Power Output	Measures
			Seat Height	'Toe'	TDC to TDC					
Buckley & Bhambhani [56]	ADL	0, 4 & 8	U	S	S	AB – 19	WERG	0.56	Not controlled or measured	Physiology
Perdios et al.[52]	ADL	0, 3 & 6	U	U	U	AB – 21 WU – 13	OG & Q	Self selected (not reported)	Not controlled or measured	Physiology, subjective
Veeger et al.[50]	WCS	0, 3, 6 & 9	S	U	U	AB – 8	MDT	0.56 – 1.39	0.17 – 0.44 W/kg	Physiology, temporal, kinematics
Faupin et al.[49]	WCS	9, 12 & 15	?	?	?	WA – 9	OG	Maximal effort	Not controlled or measured	Performance
Faupin et al.[51]	WCS	9, 12 & 15	U	S	S	WA – 8	WERG	Maximal effort	Reported, not controlled	Temporal, performance
Mason et al.[54]	WCS	15, 18, 20 & 24°	S	S	S	WA – 14	MDT	2.20	Reported, not controlled	Physiology, temporal, kinematics
Mason et al.[55]	WCS	15, 18, 20 & 24°	S	S	S	WA – 14	MDT	Maximal effort	Not controlled or measured	Performance

ADL = daily life wheelchair; **WCS** = sports wheelchair; **S** = standardised; **U** = un-standardised; **TDC** = distance between top dead centre of main wheels; **AB** = able-bodied; **WU** = wheelchair user; **WA** = wheelchair athlete; **MDT** = motor driven treadmill; **WERG** = wheelchair ergometer; **OG** = over-ground; **Q** = questionnaire

***?** = unclear from the methodology as to whether standardisation methods were imposed

Table III. Testing procedures adopted by previous investigations into the effects of hand-rim diameter on mobility performance

Reference	Wheelchair	Participants	Mode	Speeds ($m \cdot s^{-1}$)	Power Output	Hand-rim Diameters (m)	Seat Position	Measures
Woude et al.[64]	RAC	WA – 8	MDT	0.83 - 4.17	Measured, not reported	0.30, 0.35, 0.38, 0.47 & 0.56	U	Physiology, temporal, kinematics
Gayle et al.[65]	RAC	WU – 15	WERG & OG	1.10, 2.20 & maximal effort	Not controlled or measured	0.25 & 0.41	U	Physiology, performance
Guo et al.[63]	ADL	AB – 12	?	Self selected	Reported, not controlled	0.32, 0.43 & 0.54	U	Kinetics, kinematics
Costa et al.[66]	RAC	WA – 1	OG	3.33 – 6.67	Not controlled or measured	0.34, 0.36 & 0.37	U	Physiology, temporal

ADL = daily life wheelchair; **RAC** = racing wheelchair; **AB** = able-bodied; **WU** = wheelchair user; **WA** = wheelchair athlete; **MDT** = motor driven treadmill; **WERG** = wheelchair ergometer; **OG** = over-ground; **U** = un-standardised.
***? =** mode unclear from methodology

Table IV. Summary of protocols adopted by previous ergonomic investigations into the role of hand-rim configuration on aspects of mobility performance

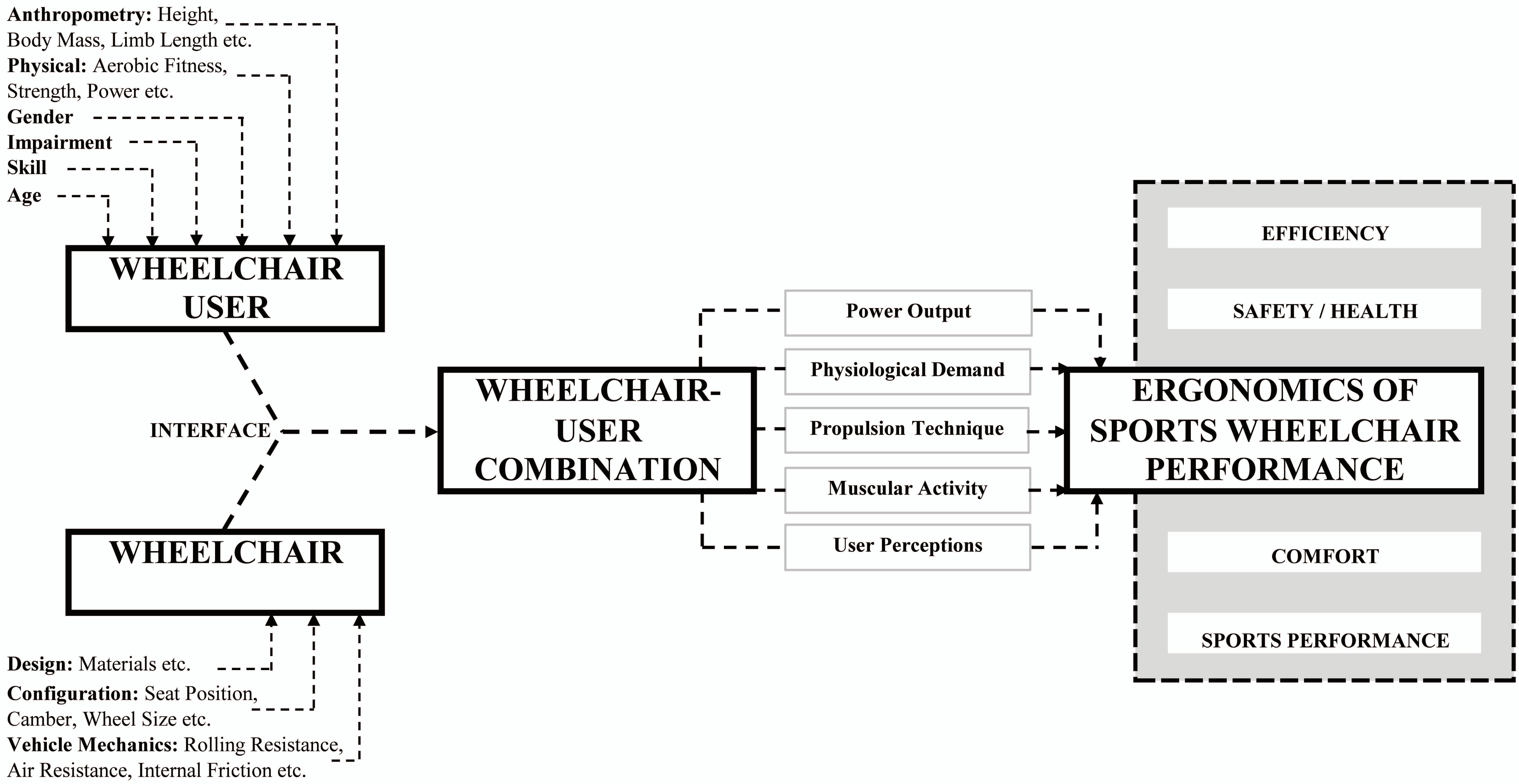
Reference	Wheelchair	Participants	Mode	Speeds ($m \cdot s^{-1}$)	Power Output	Manipulation	Measures
Gaines & La[67]	ADL	WU – 29	Q	n/a	n/a	Shape	Subjective
Linden et al.[68]	simulator	AB – 6	WERG	1.11 – 1.67	18 – 25 W	Tube diameter, shape	Physiology, kinetics, temporal
Woude et al.[69]	simulator	AB – 10	WERG Q	1.11	0.15 – 0.40 W/kg	Material, tube diameter, shape	Physiology, kinetics, temporal subjective
Richter & Axelson[70]	ADL	WU – 24	OG & MDT	0.22 – 0.94	Reported, not controlled	Flexibility	Physiology, kinetics, temporal, subjective
Koontz et al.[72]	ADL	i) WU – 10 ii) WU – 46 iii) WU – 82	WERG Q Q	0.90 & 1.80	Not controlled or measured	Material, shape	Kinetics, temporal, subjective
Richter et al.[71]	ADL	WU – 24	MDT	Self selected	Not controlled or measured	Material, flexibility	Kinetics
Dieruf et al.[73]	n/a	WU – 87	Q	n/a	n/a	Material, shape	Subjective

ADL = daily life wheelchair; **AB** = able-bodied; **WU** = wheelchair user; **MDT** = motor driven treadmill; **WERG** = wheelchair ergometer; **OG** = over-ground; **Q** = questionnaire; **n/a** = not measured or used.

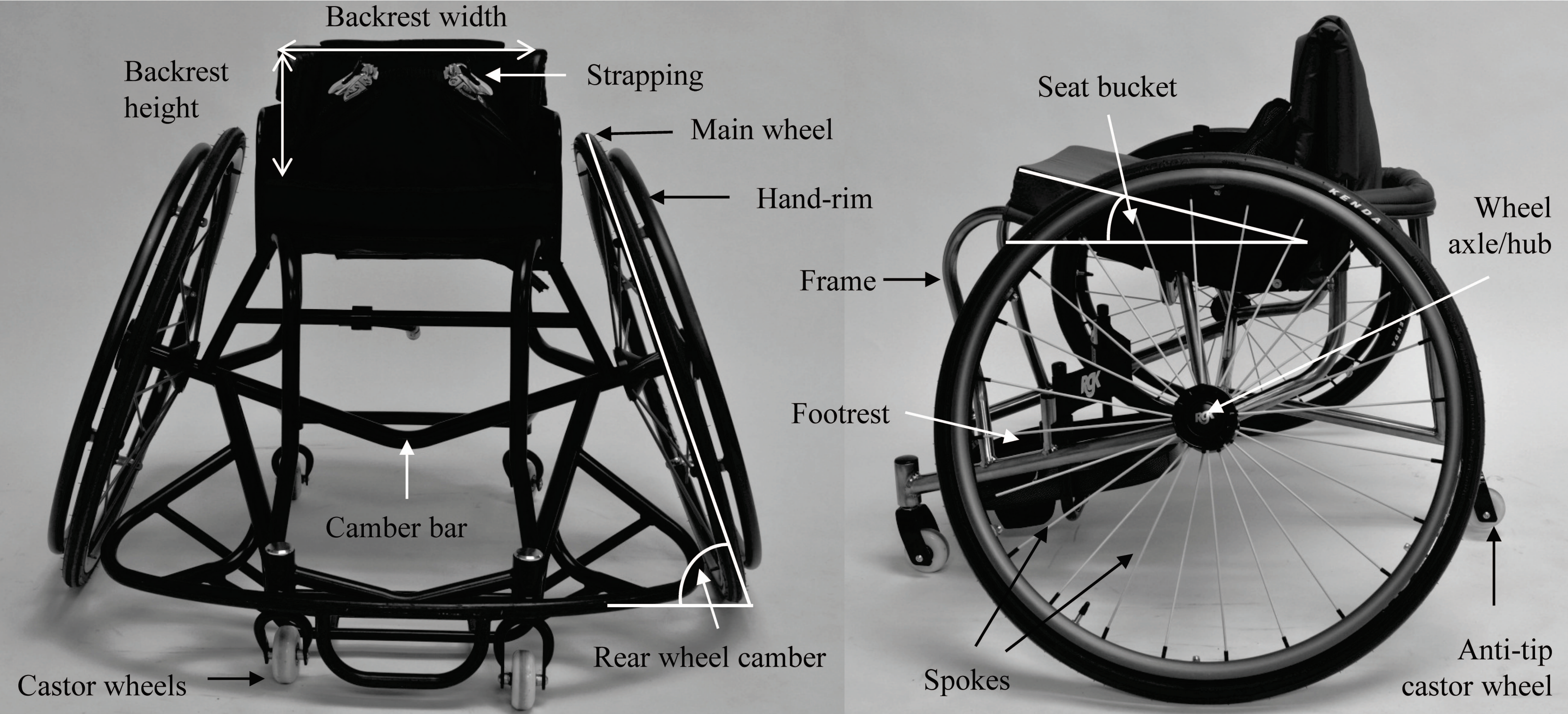
Table V. A summary of the general changes in the ergonomics of sports wheelchair performance that have been documented between the extreme settings of standardised investigations into the effects of wheelchair configuration

			Increased Seat Height [22]	Posterior Seat Position [27,29]	Greater Camber [54,55]	Larger Main Wheels [60,61]	Lower Gear Ratio [63-65]
Sub-maximal - Laboratory		Power output	=	?	↑	↓	=
	Physiology	Mechanical efficiency	↑	?	↑	↓	↑
		Oxygen uptake	↓	?	↑	↓	↓
		Pushing economy	↑	?	↓	↑	↓
		Heart rate	↓	?	↑	↓	↓
		RPE	?	?	=	=	?
	Kinematics	Push times	↓	↑	=	=	=
		Stroke frequencies	↑	=	=	=	=
		Push angles	↓	↑	=	↓	=
	Kinetics	Resultant force	↑	?	?	↓	?
		Tangential force	?	?	?	↓	?
		Force development rate	?	?	?	= (↓ trends)	?
		Torque	↓	?	?	↓	?
		Work per cycle	?	?	?	↓	↓
Maximal - Field	Performance	Sprinting - linear times	?	?	↑	↓	?
		Initial acceleration	?	?	= (↓ trends)	=	?
		Peak velocity	?	?	=	↑	↑
		Braking	?	?	=	?	?
		Manoeuvrability	?	?	↑	=	?

Key: ↑ increase; ↓ decrease; = no change; ? unknown / not measured *all changes reported are statistically significant



Anthropometry: Height, Body Mass, Limb Length etc.
Physical: Aerobic Fitness, Strength, Power etc.
Gender
Impairment
Skill
Age
WHEELCHAIR USER
INTERFACE
WHEELCHAIR
Design: Materials etc.
Configuration: Seat Position, Camber, Wheel Size etc.
Vehicle Mechanics: Rolling Resistance, Air Resistance, Internal Friction etc.
WHEELCHAIR-USER COMBINATION
Power Output
Physiological Demand
Propulsion Technique
Muscular Activity
User Perceptions
ERGONOMICS OF SPORTS WHEELCHAIR PERFORMANCE
EFFICIENCY
SAFETY / HEALTH
COMFORT
SPORTS PERFORMANCE


Backrest width
Backrest height
Strapping
Main wheel
Hand-rim
Camber bar
Rear wheel camber
Castor wheels
Seat bucket
Wheel axle/hub
Frame
Footrest
Spokes
Anti-tip castor wheel