RIO, TOKYO PARALYMPIC GAMES AND BEYOND: HOW TO PREPARE ATHLETES WITH MOTOR DISABILITIES FOR PEAKING

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RIO, TOKYO PARALYMPIC GAMES AND BEYOND: HOW TO PREPARE ATHLETES WITH MOTOR DISABILITIES FOR PEAKING

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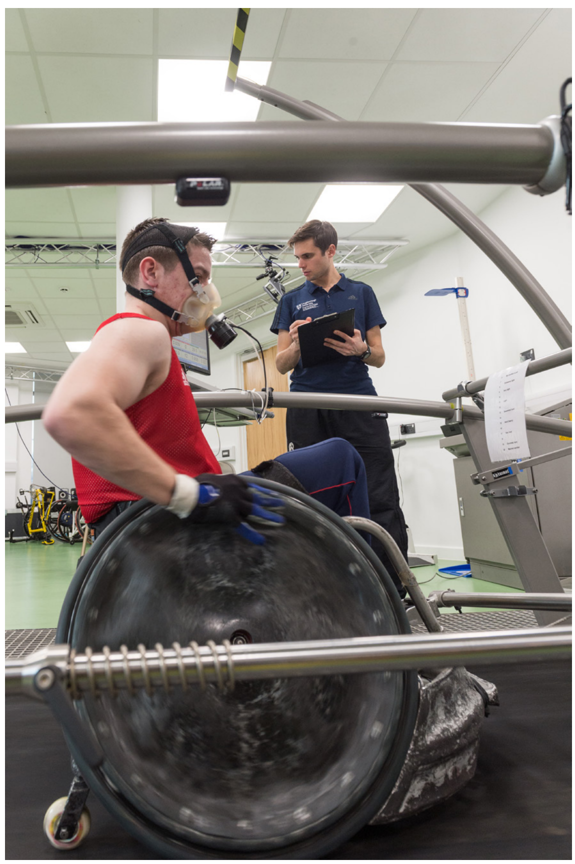

Image by Phil Wilson (Loughborough University)

In 1960, the 9th Annual International Stoke Mandeville Games were supported, for the first time, by the Italian Olympic Committee. Taking place six days after the Closing Ceremony of the XVII Olympic Games, the paralympic games for disabled athletes were born. From Roma in 1960 to London in 2012, the Paralympic Games grew in terms of athletes' number from 400 to 4,237, and now brings together more than 164 nations (Perret, 2015). The word "Paralympic" derives from the Greek preposition "para" (beside or alongside) and the word "Olympic". Paralympics want to be the parallel Games to the Olympics and illustrate how the two movements exist side-by-side (Paralympics – History of the Movement, 2016). Now taking place after the Olympics Games, the Paralympic Games are the pinnacle of the career of athletes with physical impairments and have become the second largest sport event in the world (Perret, 2015; Paralympics – History of the Movement, 2016; Gold and Gold, 2011).

The first statement of the vision of the International Paralympic Committee (IPC), i.e. "to create the conditions for athlete empowerment through self-determination" (Paralympics – History of the Movement, 2016; International Paralympic Committee, 2016), shows the importance of the place of the athlete with an impairment at the heart of the Paralympic Movement. The ultimate aim of the IPC is "to enable Paralympic athletes to achieve sporting excellence and inspire and excite the world." (International Paralympic Committee, 2016). The performance level of athletes with an impairment improved to a point that, in the present days, sport news and world sport movements focus on the potential advantage of artificial limbs among athletes with amputations and their integration in able-bodied competitions (Burkett, 2010). However, they do not represent the totality of athletes with an impairment at the Paralympic Games. Athletes with other physical impairments (visual deficit, spinal cord injury, cerebral palsy or else) are eligible to compete. These impairments induce typical functional and physiological (e.g., cardiovascular, thermoregulatory) responses to exercise. For example, spinal cord injury (athletes with tetraplegia or paraplegia) causes thermoregulatory impairment (Goosey-Tolfrey et al., 2008) and individuals with cerebral palsy have also demonstrated higher thermal and metabolic strain than matched controls during treadmill walking in the heat (Maltais et al., 2004). Thus, hyperthermia among these athletes with an impairment alters their performance compared to their Olympic counterparts (Bhambhani, 2002). Mechanical performance analysis, the description of physiological responses according to the functional impairment or else the response to training and the relationship between laboratory and field testing responses are different parts of a package introduced here to address the aim of the IPC: to enable Paralympic athletes to achieve sporting excellence (Paralympics – History of the Movement, 2016; International Paralympic Committee, 2016).

Paralympic Games, held almost immediately following the respective Olympics in the same site (Gold and Gold, 2011), also have exposed athletes to different environmental conditions. In the present 20-odd years, three of four Summer Paralympic Games have been or will be organized in the heat with or without significant humidity: Beijing 2008 (Average weather in September for Beijing, China., 2016), Rio de Janeiro 2016 (Average weather in September for Rio de Janeiro, Brazil., 2016) and Tokyo 2020 (Average weather in September for Ota, Japan., 2016). It has been established that the environmental conditions not only influences the level of cognitive and exercise performance capacity in trained able-bodied individuals (Veneroso et al., 2015), but their health status may also be affected. Due to the above-mentioned impairment in thermoregulatory capacity athletes with spinal cord injury or cerebral palsy may be more susceptible to hyperthermia during exercise (Goosey-Tolfrey et al., 2008; Maltais et al., 2004; Bhambhani, 2002). During the Paralympic tournament, these athletes of the qualified nations were and will be exposed to heat and/or humid conditions. The hyperthermia induced by exercise among athletes with an impairment plus the effects of heat on core temperature will make their performance in the hot and warm conditions more challenging. Some studies have addressed strategies to prevent the physiologic and psychological impairments in athletic performance induced by exercise performed in the heat (Goosey-Tolfrey et al., 2008). Other proposed that wheelchair athletes should follow recommendations advocated for able-bodied individuals to minimize their risks of heat stress during competition (Bhambhani, 2002). In the present issue, the authors provide a descriptive approach of performance, and especially the preparation of athletes with a physical impairment to optimize their exercise performance.

We argue that the interactions between environmental conditions and typical responses to exercise of athletes with an impairment and the equipment interactions with athlete's body should be taken into account in the preparation of Paralympic athletes in order to witness the most magnificent sporting display: the Paralympic Games. Finally, the motto of Paralympic movement "Spirit in Motion" is also the philosophy of the present compendium: to present new advances and research findings in the field of applied physiology and biomechanics in exercise, within the context of optimize Paralympic preparation and performance of athletes presented an impairment.

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EDITORIAL
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Editorial: Rio, Tokyo Paralympic Games and Beyond: How to Prepare Athletes with Motor Disabilities for Peaking

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The Editorial on the Research Topic

Rio, Tokyo Paralympic Games and Beyond: How to Prepare Athletes with Motor Disabilities for Peaking

The Paralympics are the second largest sport event in the world (Gold and Gold, 2011; Perret, 2015; Paralympics—History of the Movement, 2016). This is evident with the notable 10-fold rise in competitors from Roma in 1960 to London in 2012 (400–4237) and the remarkable growth with 176 nations that competed in Rio 2016. The performance level of athletes with an impairment have improved to a point that, in the present days, sport news and world sport movements focus on the potential advantage of artificial limbs among athletes with amputations and their integration in able-bodied competitions (Burkett, 2010). However, they do not represent the totality of athletes with impairment at the Paralympic Games. Athletes with other physical impairments [visual deficit, spinal cord injury (SCI), cerebral palsy, or others] are eligible to compete. These impairments induce typical functional and physiological (e.g., cardiovascular, thermoregulatory) responses to exercise.

Within this special editorial, the study of Reina et al. offers the reader with an understanding of the functional impairment of soccer players with cerebral palsy on the agility performance. Whereas, SCI becomes the impairment focus of Currie et al. with an emphasis on cardiac function, while Perret et al. explore the respiratory responses to exercise performance. Mechanical performance analysis (Wright; Loturco et al.), the description of physiological responses according to the functional impairment (Weissland et al.) or equipment (Abel et al.), the response to training (Paulson et al.), and the relationship between laboratory and field testing responses (West et al.) are different parts of the issue that address an important aim of the IPC: *to enable Paralympic athletes to achieve sporting excellence* (International Paralympic Committee, 2016; Paralympics—History of the Movement, 2016).

Most notable to the recent Summer Paralympic Games that have been held in Beijing 2008[1], Rio de Janeiro 2016[2], and are to be hosted in Tokyo (in 2020)[3], are the potentially challenging environmental conditions of high temperatures and humidity. It has been established that these environmental conditions not only influences the level of cognitive and exercise performance capacity in trained able-bodied individuals (Veneroso et al., 2015), but their health status may also be affected. Athletes with a SCI (athletes with tetraplegia or paraplegia) are likely to experience a thermoregulatory impairment under these conditions (Goosey-Tolfrey et al., 2008). Furthermore, individuals with cerebral palsy have also demonstrated higher thermal and metabolic strain than matched controls during treadmill walking in the heat (Maltais et al., 2004). Thus, hyperthermia among these athletes with impairment could alter their performance compared to their Olympic counterparts (Bhambhani, 2002). Due to the above-mentioned impairment in thermoregulatory capacity athletes with SCI or cerebral palsy may be more susceptible to hyperthermia during exercise performed in the heat. Some studies have addressed strategies to prevent the physiologic and psychological impairments in athletic performance induced by exercise performed in the heat (Goosey-Tolfrey et al., 2008). Other proposed that wheelchair athletes should follow recommendations advocated for able-bodied individuals to minimize their risks of heat stress during competition (Bhambhani, 2002). In the present issue, the two articles of Price and Girard challenge the reader to critically examine the potential beneficial effects of thermoregulatory management strategies, particularly in athletes with SCI who performed exercise in the heat.

Finally, all contributors of this special topic provide a descriptive approach of performance, and especially the preparation of athletes with a physical impairment to optimize their exercise performance. Attention has been paid to the accuracy of tools to assess physical (Willems et al.) and physiological responses (Weissland et al.) of athletes with impairment. The motto of Paralympic movement "Spirit in Motion," is also the philosophy of the present compendium in order to present new advances and research findings in the field of applied physiology and biomechanics in Paralymipc sport.

[1]Average weather in September for Beijing, China. https://weatherspark.com/averages/34097/9/Beijing-China (Accessed July 8, 2016).

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[3]Average weather in September for Ota, Japan. https://weatherspark.com/averages/33260/9/Ota-Tokyo-Japan (Accessed July 8, 2016).

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Positive Pacing Strategies Are Utilized by Elite Male and Female Para-cyclists in Short Time Trials in the Velodrome

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In para-cycling, competitors are classed based on functional impairment resulting in cyclists with neurological and locomotor impairments competing against each other. In Paralympic competition, classes are combined by using a factoring adjustment to race times to produce the overall medallists. Pacing in short-duration track cycling events is proposed to utilize an "all-out" strategy in able-bodied competition. However, pacing in para-cycling may vary depending on the level of impairment. Analysis of the pacing strategies employed by different classification groups may offer scope for optimal performance; therefore, this study investigated the pacing strategy adopted during the 1-km time trial (TT) and 500-m TT in elite C1 to C3 para-cyclists and able-bodied cyclists. Total times and intermediate split times (125-m intervals; measured to 0.001 s) were obtained from the C1-C3 men's 1-km TT ($n = 28$) and women's 500-m TT ($n = 9$) from the 2012 Paralympic Games and the men's 1-km TT ($n = 19$) and women's 500-m TT ($n = 12$) from the 2013 UCI World Track Championships from publically available video. Split times were expressed as actual time, factored time (for the para-cyclists) and as a percentage of total time. A two-way analysis of variance was used to investigate differences in split times between the different classifications and the able-bodied cyclists in the men's 1-km TT and between the para-cyclists and able-bodied cyclists in the women's 500-m TT. The importance of position at the first split was investigated with Kendall's Tau-b correlation. The first 125-m split time was the slowest for all cyclists, representing the acceleration phase from a standing start. C2 cyclists were slowest at this 125-m split, probably due to a combination of remaining seated in this acceleration phase and a high proportion of cyclists in this group being trans-femoral amputees. Not all cyclists used aero-bars, preferring to use drop, flat or bullhorn handlebars. Split times increased in the later stages of the race, demonstrating a positive pacing strategy. In the shorter women's 500-m TT, rank at the first split was more strongly correlated with final position than in the longer men's 1-km TT. In conclusion, a positive pacing strategy was adopted by the different para-cycling classes.

Keywords: para-cycling, pacing, time trial, performance, Paralympic, velodrome, cycling

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INTRODUCTION

Classification for para-cycling aims to minimize the effect of impairment on competition, so that eligible athletes are grouped based on how their impairments impact the core determinants of performance (Union Cycliste Internationale., 2014). Within a classification, therefore, there may be athletes with neurological impairments (central or peripheral) and athletes with locomotor impairments. In cycling, there are currently five cycling classifications (C1-5), a tandem classification for visually-impaired cyclists (B), two tricycle classifications (T1-2), and five handbike classifications (H1-5). Of these classification types, only the cycle and tandem classes compete on the track in the velodrome. In competitions where athletes from different classifications compete in the same event, e.g., the C1-3 1-km time trial (TT) in the Paralympic Games, a factoring adjustment (usually a percentage change) according to their competing class is applied to the final times to produce the overall medallists.

Within the cycling classes, C1 contains the most affected athletes, with progressively less degree of impairment through the classes up to C5. In the C1 class, this might typically contain athletes with severe hemiplegia (lower and upper limb involvement), diplegia or severe ataxia, multiple amputation, incomplete spinal cord injuries, or muscular impairments (more than 210 points). In the C2 class, this might typically include trans-femoral amputations without the use of prosthesis when cycling, severe hemiplegia (lower limb more involved), or decreases in muscle strength (between 160 and 209 points). In the C3 class, this might typically include athletes with double trans-tibial amputations with use of prostheses, muscular/ multiple impairments (between 110 and 159 points), moderate hemiplegia or moderate ataxia. For further details on classification profiles please see the UCI regulations (Union Cycliste Internationale, 2013).

In cycling time trials, success depends on finishing in the fastest time possible. For optimal performance, all available energy stores should be used before finishing the race, without causing fatigue and a significant deceleration at the end of the race (Atkinson et al., 2007). This process of regulating energy expenditure whilst minimizing the negative consequences of fatigue through variations in momentary power output is referred to as pacing (de Koning et al., 1999; Hulleman et al., 2007). As any energy/ velocity still present after the finish line is effectively wasted kinetic energy (van Ingen Schenau et al., 1992; de Koning et al., 1999), it is suggested that an "all-out" strategy is optimal for the 1-km TT in able-bodied athletes (de Koning et al., 1999; Hulleman et al., 2007; Corbett, 2009). However, a recent laboratory study has suggested that for distances of 500-m and above, a slightly more conservative pacing pattern may be employed (de Jong et al., 2015), and peak power is dampened in trials lasting 30 and 45 s compared to 5 s indicating a central control of initial power output (Wittekind et al., 2011). Therefore, it appears that even in these short-duration trials there is evidence of a positive pacing strategy, where peak speed is achieved early in the event and then declines through the duration of the race (Abbiss and Laursen, 2008).

Events such as the 1-km and 500-m TTs are sensitive to inertial parameters and the time to reach peak speed. As these events are conducted from a stationary start position, the acceleration phase is inevitable and therefore the energy required for this phase is thought to be optimally distributed at the start of the event in a "fast start" strategy (Abbiss and Laursen, 2008). A fast-start is also associated with improved performance in short exercise bouts (3 min) due to faster $\dot{V}O_2$ kinetics (Bailey et al., 2011). Factors such as trunk angle, hand position, and crank position all influence the initial acceleration in track cycling (Padulo et al., 2014). These factors may be constrained in para-cycling based on impairment, e.g., if an athlete is unable to start from a standing position. Therefore, depending on the nature and severity of the impairment may mean a different pacing strategy is used in para-cycling events and this might differ based on cycling class. For example, there may be reduced gross efficiency and therefore reduced exercise tolerance in amputee or neurologically impaired athletes (Hoffman et al., 1997; Sezer et al., 2004; Johnston et al., 2008; de Groot et al., 2012; Lepretre et al., 2012) compared to able-bodied athletes, and this might result in differences in pacing profile in the more affected classes.

The C1-3 classes have been reported to display noticeable inter-class performance differences in response to the 1-km TT (Lepretre et al., 2012). This was particularly apparent for the C1 compared to C2 and C3 classes, where split times increased between the C1 and other classes over the duration of the event; in contrast after a large difference in split time at 250 m, the split times were very similar between the C2 and C3 classes in the final 500 m of the event (Lepretre et al., 2012). This observation may be related to impairment differences between the classes, which may indicate that a combined category is inappropriate, or it may indicate the utilization of different pacing strategies. As the physical characteristics of the environment within the velodrome are very consistent (e.g., temperature, humidity, air resistance) within an event, split times within track racing may be used as a relatively accurate indicator of pacing strategy (Atkinson et al., 2003). Furthermore, analysis of the pacing strategies employed by the different classification groups may offer scope for optimal performance based on the degree of impairment. Therefore, the aim of this paper was to investigate the pacing strategy adopted during the 1-km TT and 500-m TT in elite C1 to C3 male and female para-cyclists. Data from able-bodied cyclists are also presented for comparison. It was hypothesized that differences in pacing profile would be apparent between able-bodied and para-cyclists, and between the different para-cycling classes.

MATERIALS AND METHODS

The data were compiled from High Definition video footage available from youtube.com©. Ethics approval and informed consent were not necessary as all data are publicly available and no athlete interactions were required. Further information on the video footage analyzed is available on request from the author. Observations were made of the para-cyclist and able-bodied cyclist position during the initial acceleration from the stationary start and the position on the bike adopted during the race. Total times and 125 m split times (measured to 0.001 s; Tissot Timing, Switzerland) were obtained from the 2012 London Paralympics in the men's C1-C3 1-km TT and the women's C1-C3 500-m TT. As the 1-km and 500-m TTs were not Olympic events in 2012, data from the 2013 UCI World Track Championships in Minsk were used to provide an able-bodied comparison.

All competitor performances were included in the analysis. Twenty-eight performances were analyzed from the men's 1-km TT. Eight were in the C1 class, 9 were in the C2 class and 11 were in the C3 class. Nine performances were analyzed from the women's 500-m TT ($C1 = 1$, $C2 = 7$, $C3 = 1$). As the women's event had so few competitors, data was not split according to classification for the statistical analysis. Nineteen performances from the finals of the men's 1-km TT and 12 performances from the women's 500-m TT were included in the able-bodied analysis.

Observations on the start and the aerodynamic position adopted by the para-cyclists were fundamentally descriptive, so no conventional statistical analyses were conducted. Split time and total time data are presented as mean $\pm$ SD. Split times are also expressed as a percentage of final time to eliminate the effect that differences in total race time may have on the analysis, and to allow comparison with able-bodied data. Statistical analyses were conducted using SPSS version 21.0 (Chicago, IL), and statistical significance was accepted as $p < 0.05$.

A two-way analysis of variance (classification $\times$ split time), with split time as a repeated measure was used to investigate differences between pacing strategies between the different classifications for actual and factored split times. A two-way analysis of variance (classification $\times$ split time percentages), with split time percentage as a repeated measure was used to investigate differences between pacing strategies between the different classifications and the able-bodied cyclists in the men's 1-km TT and between the para-cyclists and able-bodied cyclists in the women's 500-m TT. The location of any differences were detected using a Bonferonni *post-hoc* analysis.

To gain an understanding of the importance of a relatively fast start to final position in para-cycling, the associations between the ranking at the first split time and final rankings were investigated using Kendall's tau-b test for rank correlation. Positive and negative correlations were perceived as not present/low ($T_B < 0.50$), moderate ($0.50 < T_B < 0.70$) or high ($T_B > 0.70$) (Konings et al., 2015).

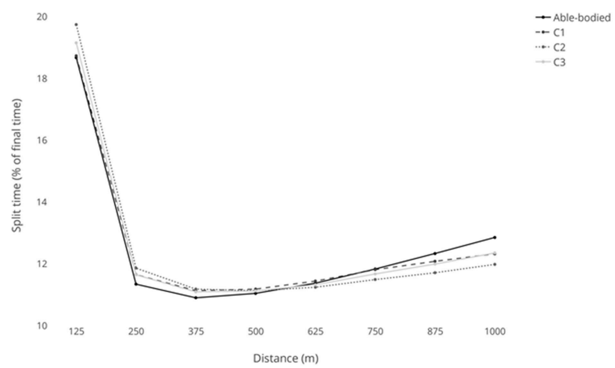
RESULTS

In the men's event, four C1 cyclists, three C2 cyclists, and eight C3 cyclists were able to get out of the saddle at the start of the event. Additionally, five C2 cyclists (all trans-femoral amputees) appeared to be able to raise themselves off the saddle slightly on the initial down pedal stroke on their intact limb. Five C1, six C2, and all eleven C3 cyclists used aero-bars, with the remainder opting for drop, flat or bullhorn handlebars. There was some variation in aero position when using the bars, for example in how tucked the elbows were and whether both hands were transferred to the aero-bars. In contrast to the men, only one of the female cyclists used aero-bars. Five cyclists used drop handlebars, of which four cyclists were trans-femoral amputees. Three cyclists were able to get out the saddle at the start of the event. For the able-bodied cyclists, all competitors were standing for approximately the first 125 m of the TT. All 19 cyclists in the men's 1-km TT and 10 of the 12 cyclists in the women's 500-m TT used aero-bars. The two cyclists who did not use aero-bars opted for drop handlebars.

The first 125 m split time was the slowest due to the acceleration from the stationary start. The third split time (250–375 m) was the fastest for the C1, C3 and able-bodied cyclists, whilst the fourth split time (375–500 m) was the fastest for the C2 cyclists. There was subsequently a progressive increase in split times for the remainder of the event (see **Figure 1**).

For the un-factored time splits, an interaction was found for classification type ($p < 0.001$), with differences observed between the C1 and C3 classifications ($p < 0.001$) and the C2 and C3 classifications ($p < 0.001$). When examining the interclass time differences, at the first 125 m split, the C3 cyclists started the fastest, with the C2 cyclists having the slowest split time (**Table 1**). By the second split (125–250 m), the C2 cyclists were recording faster split times than the C1 cyclists and recorded progressively quicker split times up until the final (875–1000 m) split. The time difference between the C1 and C3 cyclists was greatest at the first 125 m split (C3 cyclists were 1.470 s quicker), and this interclass time difference remained relatively consistent for the remainder of the event. The time difference between the C2 and C3 cyclists was also greatest at the first 125 m split (C3 cyclists were 1.717 s ahead), however this time difference was reduced further at each subsequent split with the C3 cyclists finishing 0.495 s ahead.

When the time splits were subjected to a factoring adjustment, there was no interaction between classification types ($p = 0.229$). When examining the interclass time differences for the factored times, the C1 cyclists recorded the fastest time at the first 125 m



Split	125	250	375	500	625	750	875	1000
125	-	All	All	All	All	All	All	All
250		-	All	AB C3	None	AB	AB	AB C3
375			-	AB	AB	AB C3	AB C3	AB C3
500				-	AB C3	AB C1 C3	AB C1 C3	All
625					-	All	All	All
750						-	AB C1 C3	All
875							-	All
1000								-

FIGURE 1 | Split times (expressed as a percentage of total time) for the men's 1-km Time Trial. Significant differences between splits are expressed in the table below (AB, able-bodied).

TABLE 1 | Split times (in seconds) as actual time and with the factored adjustment for the C1-C3 men's 1-km Time Trial and the interclass time differences (delta, s).

Class	0–125 m	125–250 m	250–375 m	375–500 m	500–625 m	625–750 m	750–875 m	875–1000 m	Total time
C1 ($n = 8$)	15.456 ± 1.646	9.612 ± 1.045	9.166 ± 0.842	9.209 ± 0.704	9.421 ± 0.730	9.720 ± 0.717	9.942 ± 0.720	10.141 ± 0.700	1:22.666 ± 0:06.441
C2 ($n = 9$)	15.703 ± 1.659	9.414 ± 0.569	8.863 ± 0.340	8.821 ± 0.327	8.912 ± 0.394	9.115 ± 0.447	9.283 ± 0.510	9.501 ± 0.516	1:19.612 ± 0:03.361
C3 ($n = 11$)	13.986 ± 0.741	8.494 ± 0.359	8.086 ± 0.342	8.111 ± 0.293	8.253 ± 0.293	8.511 ± 0.270	8.744 ± 0.278	9.005 ± 0.287	1:13.190 ± 0:01.994
C1-C2	−0.247	0.198	0.303	0.388	0.509	0.605	0.658	0.640	3.054
C2-C3	1.717	0.920	0.776	0.710	0.659	0.604	0.540	0.495	6.422
C1-C3	1.470	1.118	1.080	1.098	1.168	1.209	1.198	1.136	9.476
FACTORED TIME									
C1 ($n = 8$)	13.765 ± 1.466	8.560 ± 0.931	8.163 ± 0.750	8.202 ± 0.627	8.390 ± 0.650	8.656 ± 0.639	8.854 ± 0.641	9.031 ± 0.623	1:13.622 ± 0:05.737
C2 ($n = 9$)	14.486 ± 1.530	8.684 ± 0.524	8.176 ± 0.314	8.138 ± 0.302	8.222 ± 0.364	8.408 ± 0.413	8.563 ± 0.470	8.764 ± 0.476	1:13.442 ± 0:03.100
C3 ($n = 11$)	13.986 ± 0.741	8.493 ± 0.359	8.086 ± 0.342	8.111 ± 0.293	8.253 ± 0.293	8.511 ± 0.270	8.744 ± 0.278	9.005 ± 0.287	1:13.190 ± 0:01.994
C1-C2	−0.721	−0.124	−0.012	0.064	0.169	0.248	0.290	0.267	0.180
C2-C3	0.500	0.191	0.090	0.027	−0.032	−0.102	−0.180	−0.241	0.252
C1-C3	−0.221	0.067	0.078	0.091	0.137	0.145	0.110	0.027	0.433
ABLE-BODIED ($n = 19$)									
Time	11.697 ± 0.374	7.097 ± 0.178	6.819 ± 0.177	6.905 ± 0.177	7.112 ± 0.170	7.400 ± 0.176	7.714 ± 0.207	8.042 ± 0.252	1:02.787 ± 0:01.341

Split times (in seconds) for the able-bodied 1-km Time Trial are also presented for comparison.

split, with the C2 cyclists recording the slowest (see **Table 1**). The factoring adjustment blunted the time differences between the classes, although as with the unadjusted times, the C2 cyclists were consistently recording faster split times than either the C1 or C3 cyclists toward the later part of the race.

There was a significant interaction between the able-bodied cyclists and the para-cyclists groups (see **Figure 1**). The first split was significantly slower than all other splits for all groups ($p < 0.001$). The able-bodied cyclists showed the greatest decay in split time from 375 m, whilst the C2 cyclists demonstrated a flatter pacing profile.

For the women's 500-m TT, the first 125 m split was the slowest due to this being the acceleration phase from the stationary start (**Table 2**). The fastest split time was for the third split time (250–375 m). There was a significant interaction between the para- and able-bodied cyclists for the percentage split times (see **Figure 2**). For the able-bodied cyclists, all four split times were significantly different from each other ($p < 0.001$). For the para-cyclists, the first split was significantly slower ($p < 0.001$) and the third split was significantly faster ($p < 0.05$) than all other splits.

For the men's 1-km TT, there was only a low correlation between rank at the first 125 m split and final position ($T_B = 0.413$). Individual data can be observed in **Figure 3**. The gold medallist was ranked second at the first split but was ranked first from 250 m throughout, and also set a World Record for the C1 class. However, the silver medallist was in 12th place at the first split and the bronze medallist was in 19th position and

TABLE 2 | Split times (in seconds) for the para-cyclists and able-bodied cyclists in the women's 500-m Time Trial.

	0–125 m	125–250 m	250–375 m	375–500 m	Total time
PARA-CYCLISTS ($n = 8$)					
Split time	15.181 ± 1.404	9.410 ± 0.596	8.951 ± 0.515	9.167 ± 0.551	42.709 ± 2.724
ABLE-BODIED ($n = 12$)					
Split time	11.961 ± 0.222	7.551 ± 0.146	7.401 ± 0.129	7.693 ± 0.114	34.607 ± 0.552

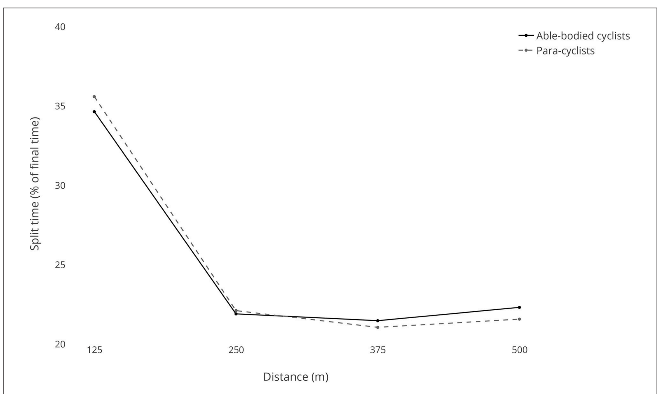


FIGURE 2 | Split times (expressed as a percentage of total time) for the women's 500-m Time Trial.

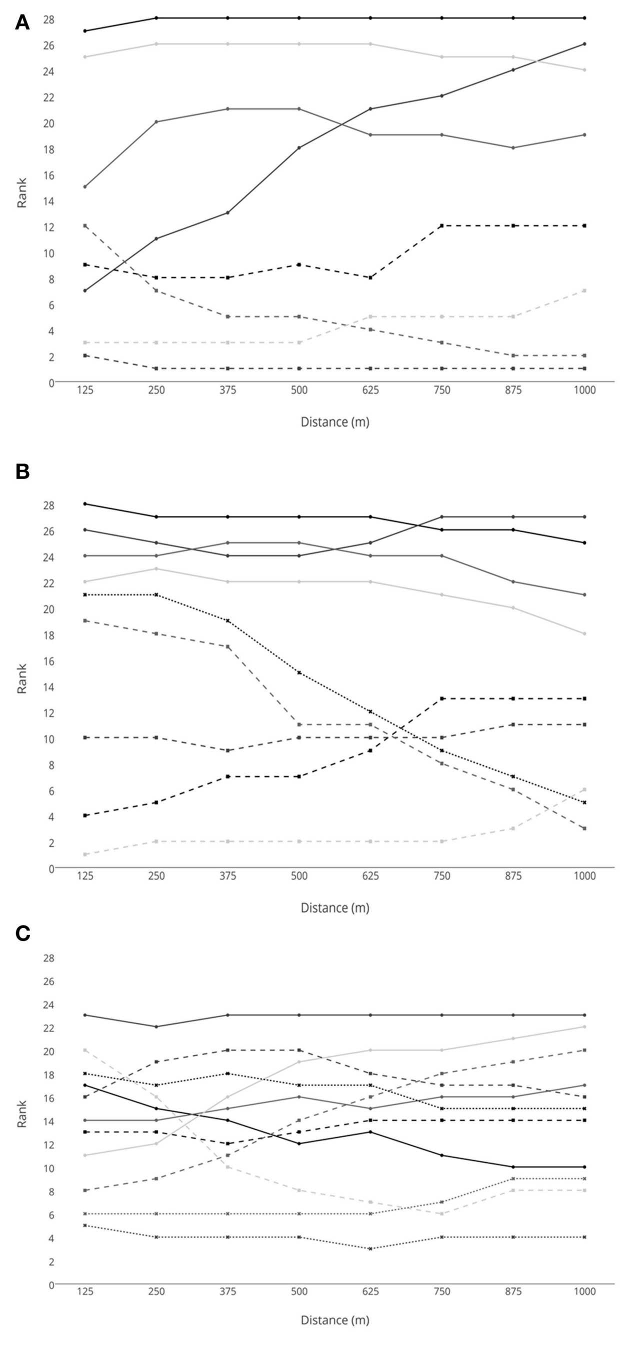


FIGURE 3 | Rank at each split in the men's 1-km Time Trial for (A) C1 cyclists, (B) C2 cyclists and (C) C3 cyclists.

did not enter the top 10 until 750 m into the race. The bronze medallist also set a World Record for the C2 class.

For the women's 500-m TT, the cyclist's rank at the 125 m split ($T_B = 0.611$) was moderately correlated with their final position. Individual position data is visualized in **Figure 4**, where it can be seen that the athletes who finished in the top 4 positions were also in the top 4 positions at each split. The gold medallist set a new World Record for the C2 class, and the bronze medallist set a World Record for the C1 class.

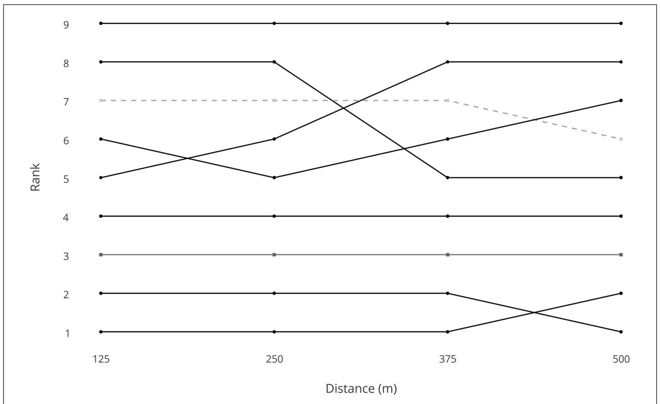


FIGURE 4 | Rank at each split in the women's 500-m Time Trial (C1 ■, C2 ●, C3 -X-).

DISCUSSION

The aim of this study was to investigate pacing strategies adopted by elite C1-C3 para-cyclists in the men's 1-km and women's 500-m TTs, and to compare with pacing strategies employed in elite able-bodied performance. Total time for all para-cycling classes was slower than for able-bodied cyclists at World Championship level, but similar to previously reported times for C1-C3 para-cyclists at World Championship level (Lepretre et al., 2012). In all participants, the first 125 m split time was significantly longer than all other split times. This is unsurprising as both the 1-km and 500-m TT were conducted from a stationary start, so this split time is sensitive to inertial parameters. There was a consistent significant increase in split time from 625 m onwards in the 1-km TT, and a significantly slower final split time compared to the previous split time (250–375 m) in the 500-m TT indicating an inability to maintain work output over the duration of the event. This was consistent with previous modeling (van Ingen Schenau et al., 1992; de Koning et al., 1999), laboratory (Foster et al., 2004), and competition studies (Corbett, 2009) in the 1-km TT and in laboratory studies of the 500-m TT (Foster et al., 2004) in elite able-bodied cyclists. This indicated that able-bodied cyclists and para-cyclists in these C1-3 classes adopted a positive pacing strategy.

Differences between the pacing profiles for the able-bodied and para-cyclist classes were detected in both the 1-km and 500-m TTs. The able-bodied cyclists had the lowest percentage of total time for the first 125 m split, demonstrating the able-bodied cyclists produced a relatively faster start than their para-counterparts. The able-bodied cyclists subsequently have a greater percentage of time spent in later splits in the race, demonstrating greater decay in performance. The relatively slower start for the para-cyclists is likely to be related to the impairments in these athlete populations, for example asymmetrical torque production (Brickley and Gregson, 2010) or reduced gross efficiency (Lepretre et al., 2012). Peak power is lower in cerebral palsy athletes compared to able-bodied athletes (Runciman et al., 2015), and peak power is lower in a seated compared to a standing position (Reiser et al., 2002). Peak power occurs within the first 5 s during maximal intensity cycling from a stationary start (Wright et al., 2007; Wittekind et al., 2011; O'Bryan et al., 2014), and time to peak power does not significantly change with cycling durations up to 45 s (Wittekind et al., 2011). However, as time to peak power is longer in a seated compared to standing position (Bertucci et al., 2005; Padulo et al., 2014), it is likely that for those cyclists unable to use a standing position in the initial acceleration phase at the start of the event that there is an effect on the peak power produced and the time to achieve it. Future research using power measuring cranks in para-cyclists would determine any differences in power profiles between able-bodied and para-cyclists and also between impairment types.

A significant main effect for the C1, C2, and C3 classes was apparent for the split times for the 1-km TT for the actual times. This is unsurprising as times would expect to be reduced in those who are classed as more functional during cycling. When times were factored, these differences between classes were no longer significant. This indicates that although applying a factor to times may be a blunt procedure, it does seem effective in removing the differences between classes. It is beyond the scope of this study to suggest any possible suitable alternatives for these combined-class competitions.

It has previously been suggested that larger differences were present between C1 and either C2 or C3 split times than between C2 and C3 split times in the 1-km TT, particularly as the race progressed (Lepretre et al., 2012). This progressive increase for the C1 athletes and this blunting between C2 and C3 was not present in the un-factored times in the present study. In fact, visual inspection of the split times when expressed as a percentage of total time (**Table 1**; **Figure 1**) indicated that the C1 and C3 classes show similar pacing profiles, whereas the C2 class had a greater initial 125 m split time, followed by a flatter pacing profile for the remainder of the 1-km TT. Six of the nine C2 cyclists in the 1-km TT were trans-femoral amputees. As these cyclists have to engage in single-legged cycling, they have to generate force on the pedal with just one limb throughout the whole pedal cycle. This is going to result in a lower peak power (Bundle et al., 2006), as well as an increased time to peak power through a combination of the use of one limb (Bundle et al., 2006) and being seated as opposed to standing (Bertucci et al., 2005; Padulo et al., 2014). The exercising muscle mass is required to generate more force throughout the pedal cycle in one-legged compared to two-legged cycling resulting in a higher mechanical and metabolic load (Abbiss et al., 2011). However, the differential $\dot{V}O_2$ uptake to one- vs. two-legged exercise suggests that there may be a circulatory inhibitory response to two vs. one-legged exercise (Ogita et al., 2000), and one-legged sprint cycling relying less on anaerobic metabolism than two-legged cycling (Bundle et al., 2006), this may contribute to different fatigue profiles in the C2 class. Additionally, single-legged cycle training can result in significant improvements in the oxidative and metabolic potential of skeletal muscle in trained cyclists (Abbiss et al., 2011). Therefore, it is possible that in the 1-km TT, the slower start due to power having to be produced by a single limb can be compensated later in the event by an increased oxidative capacity for the trans-femoral amputee C2 cyclists compared to the C1 and C3 cyclists. However, previous studies on one- vs. two-legged cycling have used able-bodied cyclists; therefore the findings may not transfer to those with an amputated limb. Further research is warranted on the biomechanics and metabolic response to exercise in this population.

Aero-bars were used by five of the eight C1, six of the nine C2, all eleven C3 cyclists, and all 19 able-bodied cyclists in the men's TT, but only by one para-cyclist and 10 of the 12 able-bodied cyclists in the women's TT. Aero bars are used to reduce aerodynamic drag by reducing the frontal area. Reducing torso angle to reduce frontal area is associated with an increased crank torque but a decreased gross efficiency (Fintelman et al., 2015a). Therefore, for any cyclist the trade-off between reducing aerodynamic drag vs. decreased physiological functioning (Fintelman et al., 2015b) needs to be assessed to optimize performance particularly in a short, track TT. There was some variation in both torso angle and elbow position observed amongst the para-cyclists; whether this was determined for individual optimal performance or was due to balance and strength issues related to the individual's impairment was beyond the scope of this study. Some para-cyclists displayed balance issues when switching to the aero-bars resulting in some loss of momentum, therefore aero-bars are unlikely to be optimal for all cyclists in these categories, which may explain why some competitors have opted not to use them.

Split times from the present study indicated that although total times were slower than in elite able-bodied competition, the pacing profiles showed some similar patterns despite the mixed impairment types within the study population. In studies using elite para-cyclists, no significant differences were observed between amputee and cerebral palsy groups for $\dot{V}O_{2max}$, ventilatory threshold and peak power output (Boer and Terblanche, 2014). In addition, although elite athletes with cerebral palsy displayed lower peak power outputs than able-bodied athletes during Wingate testing, the fatigue index and muscular activation was similar between the two groups (Runciman et al., 2015). Additionally, no significant differences for $\dot{V}O_{2max}$ were found between physically active cerebral palsy and control participants (de Groot et al., 2012). Although these studies did not contain cyclists classed as C1, C2, or C3, the evidence indicates that elite para-athletes who have intensively trained may show a different physiology than that reported in previous studies involving untrained participants. Therefore, caution needs to be expressed extrapolating findings for specific impairments from un-trained participant studies to explain performance in elite para-sport.

In a TT there are no tactical positioning considerations that might be considered in a group race when it comes to pacing strategy (Renfree et al., 2014; Konings et al., 2015). However, by comparing position at the first split with final ranking provides insight into how relatively important it is to be the fastest early in an event in terms of final ranking, and this might provide insight into whether a fast start is optimal. In the men's 1-km TT, the rank at the first split only had a low correlation with the final position. This shows that starting faster than other competitors is not essential for determining the final medal positions at this distance. In fact, the silver medallist was in 12th place at the first split and the bronze medallist was in 19th position at the first split, and the bronze medallist did not enter the top 10 until 750 m into the race (**Figure 3**). Therefore, it is possible that some competitors may have accelerated too fast at the beginning of the race and therefore did not achieve optimal energy expenditure for the distance (Wilberg and Pratt, 1988). In contrast to the men's race, individual position data for the women's 500-m TT indicated that rank does not change much between the first 125 m split and the final position. In fact, the three medallists were ranked in the top 3 places throughout the TT. This indicates that starting faster than the opposition is an important factor in securing a top final position, and is consistent with shorter distances in speed skating (Muehlbauer and Schindler, 2011). As the duration of the event is short (the women's race is half the distance of the men's race), it is unlikely that the disadvantage of a slower start can be overcome before the end of the race. This may prove a disadvantage to C2 cyclists who are trans-femoral amputees if their impairment is impacting on their ability to start as fast as their competitors. Therefore, any improvement that can be gained in training, race position, and bicycle set-up to optimize power production at the start of the event is likely to benefit final position in a 500-m TT.

This study has several limitations. It was not possible to directly measure power output; therefore inferences were made regarding split times and the relationship with power output. It was assumed that peak power occurred during the rapid acceleration phase from the stationary start within the first 125 m of the event. The nature of impairment and the adaptations made to the bike may influence the aerodynamic nature of the adopted position of the cyclist which may influence cycling velocity. Finally, there were only 9 women athletes competing of whom only one was classified as C1 and one as C3. Therefore this small sample size presents a limitation to the generalization of the findings.

Future detailed research is needed on the physiology and biomechanics of para-cycling to gain further insight into the effect of different disabilities on cycling performance in elite athletes. Comparative studies between cyclists with different disabilities will inform the classification structure allowing adjustments to classes if deemed necessary. Future studies investigating responses to training in different pathologies will also inform the optimal preparation for peak performance during competition.

In conclusion, pacing strategies for para-cyclists in both the women's 500-m TT and the men's 1-km TT showed similar patterns to elite able-bodied competitors. This was characterized by a slow first split during the acceleration phase, followed by continued fast splits throughout the race. Split times increased in the later part of the race demonstrating a positive pacing strategy. Cyclists in the C2 category tended to have the slowest first split time in the men's TT, possibly due to an increased time to peak power by the trans-femoral amputee athletes in this class as they tended to remain seated during the initial acceleration phase. Starting comparatively fast and therefore being ranked highly at the first split appeared to be more closely related to final rank in the women's 500-m than the men's 1-km TT. Further research is warranted on the physiology and biomechanics of cycling in these impairment groups to inform on the demands and optimal training for improved performance.

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ORIGINAL RESEARCH
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Locomotor-Respiratory Coupling in Wheelchair Racing Athletes: A Pilot Study

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Purpose: In wheelchair racing, respiratory muscles of the rib cage are concomitantly involved in non-ventilatory functions during wheelchair propulsion. However, the relationship between locomotor-respiratory coupling (LRC: the ratio between push and breathing frequency), respiratory parameters and work efficiency is unknown. Therefore, the aim of the present study was to investigate the LRC in wheelchair racers over different race distances.

Methods: Eight trained and experienced wheelchair racers completed three time-trials over the distances of 400, 800, and 5000 m on a training roller in randomized order. During the time trials, ventilatory and gas exchange variables as well as push frequency were continuously registered to determine possible LRC strategies.

Results: Four different coupling ratios were identified, namely 1:1; 2:1, 3:1 as well as a 1:1/2:1 alternating type, respectively. The 2:1 coupling was the most dominant type. The 1:1/2:1 alternating coupling type was found predominantly during the 400 m time-trial. Longer race distances tended to result in an increased coupling ratio (e.g., from 1:1 toward 2:1), and an increase in coupling ratio toward a more efficient respiration was found over the 5000 m distance. A significant correlation ($r = 0.80$, $p < 0.05$) between respiratory frequency and the respiratory equivalent for oxygen was found for the 400 m and the 800 m time-trials.

Conclusions: These findings suggest that a higher coupling ratio indicates enhanced breathing work efficiency with a concomitant deeper and slower respiration during wheelchair racing. Thus, the selection of an appropriate LRC strategy may help to optimize wheelchair racing performance.

Keywords: spinal cord injury, elite sports, exercise, respiratory muscles, push frequency

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INTRODUCTION

Wheelchair athletes are continually searching to optimize their push frequency strategies (Goosey et al., 2000). In wheelchair racing the movement pattern of the upper extremities follows a repetitive cyclic nature yet the arm movement pattern is not constrained and the athletes are "free" in their technique (Van der Woude et al., 1989). It is evident from wheelchair race disciplines that athletes choose a wide range of push frequencies (Goosey et al., 1997, 1998; Goosey and Campbell, 1998).

TABLE 1 | Physiological time-trial data.

Distance		400 m	800 m	5000 m
Time [s]		61 ± 14	127 ± 36	840 ± 318
$\dot{V}O_2$	Absolute [L·min^{-1}]	2.15 ± 0.34	2.11 ± 0.34	2.03 ± 0.38
	Relative to peak [%]	95.9	94.2	90.3
Heart rate	Absolute [beats min^{-1}]	169 ± 12	171 ± 10	178 ± 17
	Relative to peak [%]	93.4	94.5	98.3
Blood lactate concentration at test end [mmol·L^{-1}]		6.7 ± 3.0	8.1 ± 3.0	7.5 ± 3.9
Visual analog scale				
	Physical fatigue [%]	77 ± 0.1	71 ± 0.2	69 ± 0.1
	Respiratory fatigue [%]	70 ± 0.3	67 ± 0.3	57 ± 0.3

$\dot{V}O_2$: oxygen uptake

TABLE 2 | Predominant coupling types for the different race distances covered.

Participant	400 m	800 m	5000 m
1	2:1	1:1/2:1	2:1
2	1:1/2:1	2:1	2:1
3	1:1	2:1	2:1
4	1:1/2:1	2:1	1:1/2:1
5	3:1	1:1/2:1	2:1
6	2:1	2:1	2:1
7	1:1/2:1	1:1	1:1/2:1
8	1:1/2:1	2:1	drop out

1:1/2:1 indicates a coupling type alternating between 1:1 and 1:2.

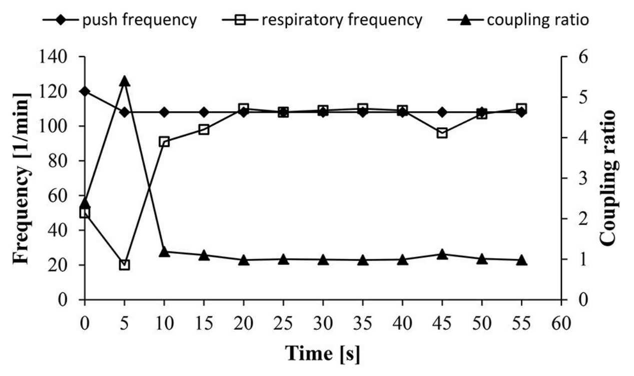

FIGURE 1 | Typical 1:1 coupling ratio between push frequency and respiratory frequency over 400 m after the initial starting phase.

For example, some athletes utilize a slow constant push strategy (Goosey et al., 2000) whilst others select a sequenced type of pushing such as three to four forceful pushes followed by a rest period (Hutzler, 1998). It is not clear what determines these differences in push strategy and how they are affected by race discipline duration. Possibly, the coordination between locomotion and respiration (locomotor-respiratory coupling; LRC) during exercise could help explain these observations.

The existence of LRC has already been described for animals and humans some decades ago by Bramble and Carrier (1983). The advantage of the application of an adequate LRC strategy seems to be a more efficient respiration, leading to a reduction in oxygen consumption as shown for cycling by Bernasconi and Kohl (1993). Thus, an efficient LRC strategy might play an important role in optimizing exercise performance by means of a coupling strategy which reduces the oxygen consumption to a minimum for a given exercise intensity (O'Halloran et al., 2012). For upper body exercise such as rowing a constant coupling ratio seems to be more efficient compared to a ratio change (Mahler et al., 1991a,b). However, only few studies have investigated the LRC ratio during wheelchair propulsion in a wheelchair sporting context; data that can be gleaned from those studies exploring LRC of wheelchair propulsion are limited due to the methodological limitations of slow propulsive speeds and/or use of able-bodied participants (MacDonald et al., 1992; Amazeen et al., 2001). That said, experienced wheelchair users tended to prefer a 2:1 coupling ratio in their daily wheelchair (Amazeen et al., 2001), which remained constant with increasing submaximal speeds from 1.0 to 1.8 m·s^{-1}. Furthermore, whole-number coupling ratios (mostly 4:1, 3:1, and 2:1) were found, which underlines the existence of a LRC strategy during this mode of exercise. The same conclusion can be drawn from findings of Goosey et al. (2000), who were able to show a general coordination of in— and expiration with the time point of hand-wheel contact in wheelchair athletics. It seems that an increasing push frequency results in a significant increase of the coupling ratio toward 3:1 when using a daily wheelchair (Amazeen et al., 2001). On the other hand, both MacDonald et al. (1992) and Fabre et al. (2005) found that the same LRC occurred during hand rim propulsion regardless of push frequency. Nevertheless, it is not clear whether or not this LRC phenomenon occurs during wheelchair racing with speeds up to 8.5 m·s^{-1} and push rates >120 pushes·min^{-1}. If so, coaches may be able to train athletes toward an efficient coupling of respiration and locomotion and in turn optimize wheelchair racing performance. Therefore, the aim of the present study was to investigate the LRC in wheelchair racers over different race distances. We hypothesized to find different LRC types over the different race distances and expected a lower coupling ratio due to a more efficient breathing pattern with increasing race distances and lower speeds.

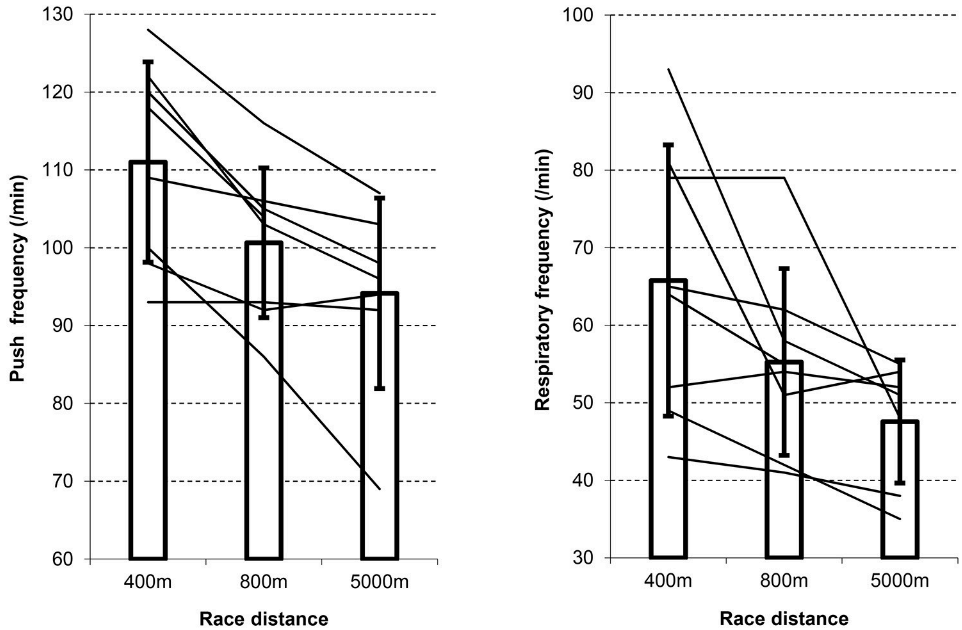

FIGURE 2 | Average and individual push and respiratory frequencies for the different race distances. Note that average push and respiratory frequencies differed significantly ($p < 0.05$) between the different race distances.

MATERIALS AND METHODS

Participants

Eight experienced well trained competitive wheelchair racers from the T53 and T54 racing classification participated in the study. The group comprised of six males and two females, all familiar with the applied testing procedures as such exercise testing interventions were part of their training routine and were performed on a regular basis. All tests were performed in the athletes' own racing wheelchairs with constant tire pressure and self-selected handrim size for each individual and with no abdominal binders worn during the trials.

Study Design

The study was approved by the Local Ethical Committee of the Canton Lucerne and participants gave their written informed consent in accordance with the Declaration of Helsinki before the start of the study. Participants performed a total of four testing sessions at least 48 h apart at the same time of day.

The first session consisted of a ramp exercise test on a treadmill (HP Cosmos, Nussdorf-Traunstein, Germany) to determine peak oxygen consumption (VO_{2peak}). Respiratory parameters were measured breath by breath by means of an ergospirometric device (Oxycon Pro, Jäger, Würzburg, Germany). The test started at a speed of 3.9 $m \cdot s^{-1}$ with a treadmill inclination of 2%. Every minute, treadmill speed was increased by 0.28 $m \cdot s^{-1}$ until subjective exhaustion. VO_{2peak} was determined as the highest 15 s average value during the ramp exercise test.

The following tests were performed on a training roller (Reha-Blitz, Uetendorf, Switzerland) in randomized order. After a 10 min warm-up, participants performed a 400, 800, or 5000 m time-trial at race pace. During these trials ventilatory (breathing frequency, tidal volume) and gas exchange (oxygen uptake and its respiratory equivalent) variables as well as push frequency were continuously recorded with the above mentioned ergospirometric device and a video camera (NV-GS 37, Panasonic, Osaka, Japan), respectively. Subsequently, the different coupling types were determined by calculating the ratio between push frequency and respiratory frequency based on 5 s average values, excluding the first 15 s of the tests. Blood lactate was measured enzymatically (Super GL Ambulance, Ruhrtal Labor Technik, Möhnesee, Germany) from a capillary sample from the earlobe immediately following the tests, and physical (overall) and respiratory fatigue were assessed with a visual analog scale.

Statistical Analysis

For data analysis 5 s average values were used and data are presented as mean ± standard deviation. To compare average respiratory and push frequencies between the different race distances a repeated measures one-way ANOVA was performed. Correlation coefficients comparing respiratory frequency with the respiratory equivalent for oxygen as well as with the tidal volume were calculated for each race distance separately according to Spearman using a statistical software package (SPSS, Version 15.0.1). The level of significance was set at $p < 0.05$.

RESULTS

Athletes with the following characteristics participated in this study: age 34 ± 10 years, height 173 ± 10 cm, body mass

62 ± 7 kg, VO_{2peak} 2.23 ± 0.56 L·min^{-1}, peak heart rate 181 ± 8 beats·min^{-1} and average weekly training volume 11 ± 5 h. Time-trial data with regards to performance, physiology and fatigue are presented in **Table 1**.

Four different coupling types, namely 1:1, 2:1, 3:1, and a 1:1/2:1 alternating type, were identified. For each participant a predominant coupling ratio could be found for every distance covered (**Table 2**). A typical example of a 1:1 coupling ratio of a participant over the 400 m distance is shown in **Figure 1**. Over the 800 and 5000 m distance the most common coupling type was 2:1, whereas over the 400 m a 1:1/2:1 alternating coupling ratio was predominant. Please note that this alternating coupling type was in fact a feature and no artifact due to an unstable coupling one might expect during fast locomotion common for sprint exercise. Respiratory and push frequencies decreased with increasing race distance and were significantly different between the different race distances (**Figure 2**).

Significant correlations between respiratory frequency and the respiratory equivalent for oxygen were found for the 400 ($r = 0.80$, $p < 0.05$) and 800 m ($r = 0.79$, $p < 0.05$) but not for the 5000 m trial ($r = 0.46$, $p > 0.05$; **Figure 3**). Highly significant negative correlations were found between respiratory frequency and tidal volume for the 400 ($r = -0.92$, $p < 0.01$) and 5000 m $r = -0.88$, $p < 0.01$) but not for the 800 m ($r = -0.63$; $p > 0.05$) trial.

DISCUSSION

The main finding of the study was the existence of a LRC strategy with clearly identifiable coupling types in highly trained wheelchair racing athletes over the distances of 400, 800, and 5000 m. We found different coupling types (1:1, 2:1, 3:1, and alternating 1:1/2:1), changing individually depending on race distance. The overall predominant coupling type was a 2:1 ratio between push and respiratory frequency, which was predominantly found with increasing race distances. One likely explanation for this trend toward less frequent breathing per push with increasing race distance is the lower average speed over the longer distances, resulting in lower push frequencies and also a lower burden on the cardiovascular system (Goosey and Kirk, 2003). As a consequence, an economisation of the wheelchair push takes part (Goosey et al., 2000) leading to a reduced respiratory frequency. Our data further showed a lower respiratory frequency at higher tidal volumes, which suggests a more efficient respiration. The significant relationship between respiratory frequency and the respiratory equivalent for oxygen found in our study supports this assumption. Our data are further supported by previous research (Veeger et al., 1989; Vanlandewijck et al., 1994), demonstrating a relationship between speed and push frequency during steady-rate wheelchair propulsion exercise. Studies on daily wheelchair locomotion by MacDonald et al. (1992) refute the appearance of LRC during wheelchair propulsion, whereas Fabre et al. (2005) suggest the occurrence of LRC independent of arm movement frequency with no impact on improved economy of locomotion. This partly contradicts the present findings, however, one has to keep in mind that our study investigated elite wheelchair racing

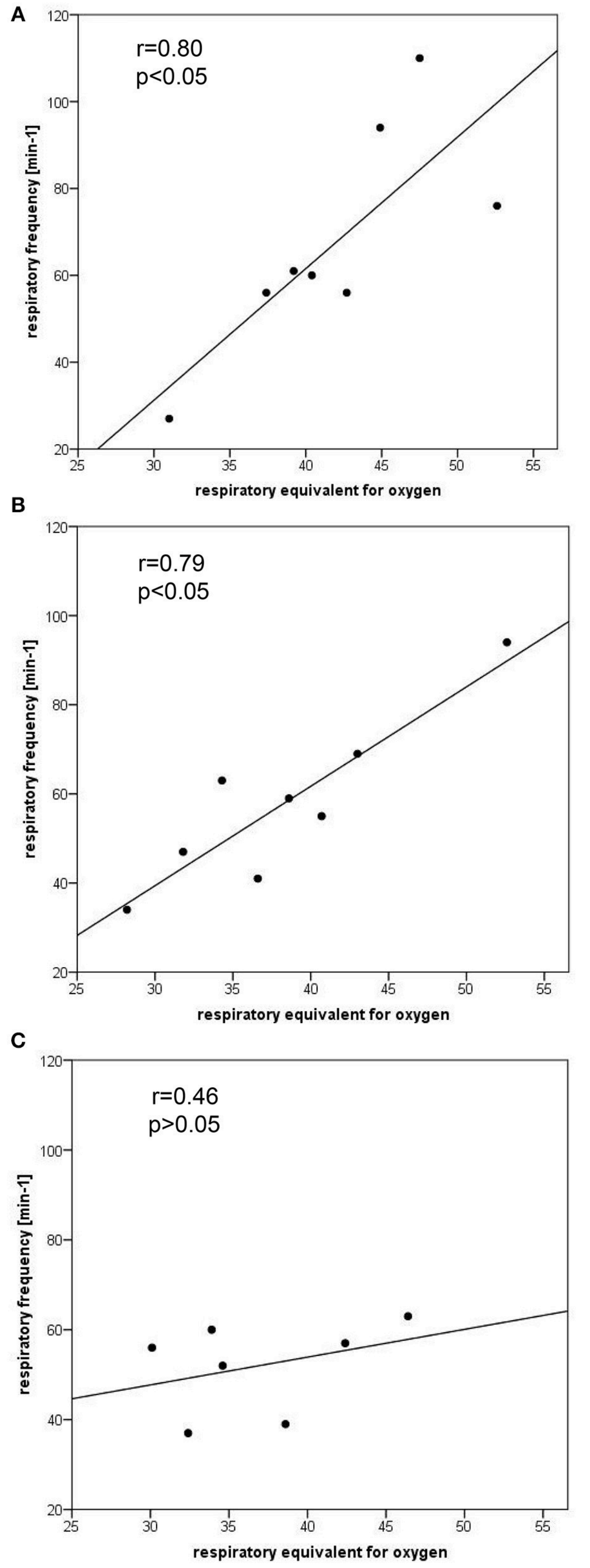

FIGURE 3 | Correlation plots comparing the ventilatory equivalent for oxygen vs. respiratory frequency for the 400 m (A), 800 m (B), and 5000 m (C) time trials.

athletes reaching high race speeds and push rates of over 120 pushes·min^{-1}. Additionally, the sitting position and hand rim size in a race chair markedly differ from the position in a daily wheelchair, which might have an impact on the LRC pattern. These differences make a direct comparison of our data with the above mentioned results from other studies difficult.

In accordance with data from experienced wheelchair users (Amazeen et al., 2001), we also found the 2:1 coupling ratio as the predominant coupling type in trained athletes. However, coupling ratios as high as 4:1 as previously reported (Amazeen et al., 2001), were not found in the present study. This may be due to differences in equipment (daily vs. race wheelchair), propulsion intensity (moderate vs. high intensity exercise) or training status (moderately trained vs. elite athletes). To expand on this issue of differences in wheelchair-user configurations, athletes can change the hand-rim size to suit the wheelchair racing distance, the handrim diameter being the equivalent to gears on a bicycle (Costa et al., 2009). Typically, sprinters would select smaller hand-rims since larger hand rims have a longer lever arm which could be a limiting factor at higher speeds (Costa et al., 2009). That said, the hand rim diameters used by our participants varied between 0.36 and 0.41 m, yet they were the same for individuals between trials. This may explain why the coupling ratios differed for seven of the eight athletes across the race distances—the limitation of a constant handrim size may have been compensated by alterations in the LRC. Further studies may investigate whether athletes settle for a preferred coupling ratio across race distances when given the choice of using a race distance dependent hand-rim. With regards to applicability of the present findings into an elite sport context, a particular strength of this study lies in the fact that the VO_{2peak} (2.23 ± 0.56L.min^{-1}) measured was comparable if not greater to the work of similar athletic trained populations (Tolfrey et al., 2001; Goosey-Tolfrey and Tolfrey, 2004; Bernardi et al., 2010; Perret et al., 2012).

The present findings indicate that an efficient LRC strategy might play an important role in optimizing exercise performance in wheelchair athletics. However, final inferences about implications for efficiency of breathing on performance can't be made based on the present data and further studies are needed to elucidate this issue in more detail. In general, the importance of respiratory muscles is not limited to the respiratory system: respiratory muscles working at higher intensities can directly affect performance by reducing blood flow to working muscles (Harms et al., 1997). Delaying this metaboreflex by respiratory muscle training (Witt et al., 2007) or by reducing the load of respiratory muscles by an appropriate breathing or LRC strategy may therefore directly benefit performance. An efficient coupling strategy may even be more important during upper body exercise (e.g., during wheelchair propulsion) as respiratory muscles of the rib cage are concomitantly involved in ventilatory and non-ventilatory functions (Celli et al., 1988). Therefore, respiratory muscle training might be a future approach to either delay respiratory fatigue directly or indirectly and influence LRC efficiency in wheelchair athletes. Beside this, it is still unclear what determines differences in push strategies and how they are affected by different race durations and speeds or how this might influence individual LRC strategies. Thus, future studies should for example compare the impact on performance of self-chosen LRC vs. prescribed LRC strategies.

CONCLUSIONS

We suggest that the selection of an appropriate LRC strategy might help to optimize wheelchair racing performance. However, final inferences about implications for efficiency of breathing on performance can't be made based on the present data. Additionally, one has to be aware that changing an individual LRC strategy might be challenging and require a considerable amount of coaching and training. Further studies are needed to determine the most efficient coupling types for different racing distances, how they may be influenced by adjustments in the wheel and handrim size and spinal cord injury lesion levels, and what training toward an optimal LRC strategy may entail.

AUTHOR CONTRIBUTIONS

CP substantially contributed to the conception, design, and interpretation of the work, was involved in drafting the work, approved the final version to be published and agrees to be accountable for all aspects of the work. MW highly contributed to the design, acquisition and analysis of data, revised the work critically for important intellectual content, approved the final version to be published and agrees to be accountable for all aspects of the work. CL was substantially involved in the analysis and interpretation of data for the work, critically revised the manuscript for important intellectual content, approved the final version of the manuscript and agrees to be accountable for all aspects of the work. VG highly contributed to the interpretation of data, critically revised the manuscript for important intellectual content, made the final approval of the version to be published and agrees to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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ORIGINAL RESEARCH
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Change of Direction Ability Performance in Cerebral Palsy Football Players According to Functional Profiles

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The aims of the present study were to evaluate the validity and reliability of the two different change of direction ability (CODA) tests in elite football players with cerebral palsy (CP) and to analyse the differences in performance of this ability between current functional classes (FT) and controls. The sample consisted of 96 international cerebral palsy football players (FPCP) and 37 football players. Participants were divided into four different groups according to the International Federation of Cerebral Palsy Football (IFCPF) classes and a control group (CG): FT5 ($n = 8$); FT6 ($n = 12$); FT7 ($n = 62$); FT8 ($n = 14$); and CG ($n = 37$). The reproducibility of Modified Agility Test (MAT) and Illinois Agility Test (IAT) (ICC = 0.82–0.95, SEM = 2.5–5.8%) showed excellent to good values. In two CODA tests, CG performed faster scores compared with FPCP classes ($p < 0.01$, $d = 1.76$–3.26). In IAT, FT8 class comparisons regarding the other classes were: FT5 ($p = 0.047$, $d = 1.05$), FT6 ($p = 0.055$, $d = 1.19$), and FT7 ($p = 0.396$, $d = 0.56$). With regard to MAT, FT8 class was also compared with FT5 ($p = 0.006$, $d = 1.30$), FT6 ($p = 0.061$, $d = 0.93$), and FT7 ($p = 0.033$, $d = 1.01$). No significant differences have been found between FT5, FT6, and FT7 classes. According to these results, IAT and MAT could be useful and reliable and valid tests to analyse CODA in FPCP. Each test (IAT and MAT) could be applied considering the cut point that classifiers need to make a decision about the FT8 class and the other FT classes (FT5, FT6, and FT7).

Keywords: agility, classification, impairment, performance, paralympics

INTRODUCTION

Football for people with cerebral palsy (CP) is a 7-a-side game with two 30 min halves (Kloyiam et al., 2011; Cámara et al., 2013). This is one of the 23 sports included in the programme of the next Paralympic Games in Rio 2016. The Fédération Internationale de Football Association (FIFA) laws of the game apply with some exceptions made by the new (1 January 2015) International Federation of Cerebral Palsy Football (IFCPF). Some of the changes include a smaller pitch and goal posts, no offside rule and players rolling the ball into play instead of a throw in (IFCPF, 2015a). This sport became independent on, under the umbrella of the IFCPF. On the field, teams are made up of seven ambulant CP players.

All players participating in official events must have an IFCPF classification. IFCPF has a classification system which allows all ambulant athletes with CP and related neurological conditions to take part. Paralympic classification systems aim to promote participation in sport by people with disabilities by controlling for the impact of impairment on the outcome of competition (Tweedy et al., 2014). The language and structure of the International Classification of Functioning, Disability, and Health (World Health Organization, 2012) is central to Paralympic classification, and the concepts of impairment and activity limitation are particularly important (Tweedy and Vanlandewijck, 2011). The International Paralympic Committee (IPC) recognizes eight eligible physical impairments in Paralympic sport: five impairments of function (i.e., impaired strength, impaired range of movement, hypertonia, ataxia, and athetosis) and three impairments of structure (i.e., limb deficiency, leg length difference, and short stature). In addition, the activities of focus are the Paralympic sports in which athletes compete. It is not mandatory for Paralympic sports to provide classification systems that cater to all eight physical impairment types (Tweedy et al., 2014). For example, CP Football is for athletes with hypertonia, ataxia, or athetosis of cerebral origin (e.g., cerebral palsy, traumatic brain injury, or stroke). Although this sport is governed by an international federation which includes cerebral palsy in its definition, the classification unit in Paralympic sport is the impairment, and it is related to several health conditions, not only cerebral palsy.

Based on these eligible impairments, CP Football has four classes based on the traditional Cerebral Palsy International Sports and Recreation Association (CPISRA) classification system, that is, four classes (C1–C4) for wheelchair athletes and the other four (C5–C8) for ambulant athletes (Reina, 2014). Applied to CP-football, the last four classes (FT) appear in the rules as: "(a) Class FT5: Diplegia, asymmetric diplegia, double hemiplegic, or dystonic. It includes moderate involvement with spasticity grade 2–3; involvement of both legs which may require orthotics/splints for walking; an asymmetric diplegia or double hemiplegic athlete with involvement on both sides with the lower limbs more affected than the upper extremities; or athletes with dystonia where the lower limbs are more affected than the upper extremities. (b) Class FT6: Athetosis, dystonic, ataxic or mixed cerebral palsy or related neurological conditions. It includes moderate involvement in all four limbs; the athlete ambulates without assistive devices but might require orthotics/splints; athetosis, dystonia, or ataxia is typically the most prevalent factor but some athletes can have problems with athetosis or ataxia mixed with spasticity; athletes with dystonic athetosis in all four limbs belong in this classification unless the impairment is minimal. (c) Class FT7. Hemiplegic, including spasticity grade 2–3 in one half of the body (on the frontal plane); athletes walk/run with a clearly noticeable limp due to spasticity in the lower limb; hemi gait pattern 2, 3, or 4 as per grouping described in gait patterns in spastic hemiplegia in children and young adults. They usually have a good functional ability on the other side of the body. (d) Class FT8. Diplegia, asymmetric diplegia, double hemiplegia, and/or dystonia. It includes hemiplegia with spasticity grade 1–2; monoplegia with spasticity grade 1 or 2 in a major joint in the lower limbs; athetosis, dystonia, ataxia or mixed cerebral palsy or other neurological conditions."

In Paralympic sport, an evidence-based system of classification is one in which the system has a clearly stated purpose, and methods used for assigning class will achieve the stated purpose (Tweedy and Vanlandewijck, 2011). Although evidence-based methods for classifying impairments must primarily use valid and reliable measures of impairment, such measures cannot be the sole basis of classification (Beckman and Tweedy, 2009). This is because, although eligible impairments are permanent, many types of impairment are, to varying degrees, responsive to training. In most circumstances, current best practice requires classification panels to assign a class by collectively considering outcomes from the impairment assessment, together with three other forms of assessment [International Paralympic Committee (IPC), 2015]:(a) novel motor tasks, which are tasks that are unlikely to have been practiced by the athlete in the usual course of training for his or her sport; (b) sport-specific activities that are likely to have been frequently practiced by athletes training for the sport; and (c) a detailed training history and other personal and environmental factors likely to affect sports proficiency.

Football players are required to turn, sprint and change pace during matches (Stølen et al., 2005). Indeed, frequent variation in activities has been reported during a competitive match in elite football players (Bloomfield et al., 2007). During a football game, ∼1300 changes in activity are undertaken in off-the-ball conditions (Stølen et al., 2005). Therefore, due to the relevance of change of direction ability (CODA) in this sport, the examination of the nature of this activity and its evaluation is one of the objectives of this study. Evaluating CODA in football has entailed the use of many different tests including *T*-test (Sporis et al., 2010; Chaouachi et al., 2012) *T*-test modifications (Sassi et al., 2009) and Illinois test (Miller et al., 2006). However, despite the fact that CODA has been evaluated in football players (Sporis et al., 2010; Chaouachi et al., 2012) children and adolescents with CP (Verschuren et al., 2009, 2010) and can be a determining performance component in CP Football, to our knowledge, no scientific articles have been published to determine the CODA in elite football players eligible for CP football, and its relationships with current classification profiles.

The aims of the present study were, firstly, to evaluate the reliability of the CODA measured by modified agility test (MAT) and Illinois agility test (IAT) in international football players with cerebral palsy (FPCP); secondly, to evaluate the validity of both CODA tests to check activity limitation of cerebral palsy football players (FPCP) regarding controls; and thirdly, to analyse the differences in this ability between different current IFCPF functional classes. Due to the different CP motor alterations (Unnithan et al., 1998) and that different types of tests used may determine the performance (Chaouachi et al., 2012) our working hypothesis is that there may be differences in the CODA between CPISRA functional classes, and also between FPCP and football players.

MATERIALS AND METHODS

Participants

Ninety-nine international FPCP and 37 football players took part in this study ($n = 136$). Written informed consent was obtained from the participants and their coaches, and data collection was conducted during 2013 CPISRA Intercontinental Cup (ICUP) qualifying tournament for the World Championships in 2015, while the control group was measured 1 month before the end of the regular league. Sixteen teams took part in the CPISRA ICUP, and players from 10 national teams voluntarily participated in the data collection. Reported competition experience indicated that 24.7% of players from FPCP group participated in the last Paralympics Games (London 2012). Football players had national level competition, and this control group (CG) was built up considering the mean age and training activity (**Table 1**). The study was approved by the institutional review committee (DPS.RRV.01.14) of the Miguel Hernández University (Elche, Spain) and conformed to the recommendations of the Declaration of Helsinki.

Procedures

A standardized warm-up was performed, consisting of a 5 min self-paced low-intensity run, skipping exercises, strides and two 15 m sprints with and without changes of direction. Information about the protocols was sent in advance to the teams, and participants practiced test protocols twice before data collection. Each participant performed anthropometric measures and two trials of two agility tests: IAT and MAT. A 3 min rest period was given between each trial (Mayhew et al., 1995). The best score in each test was used for data analysis.

Anthropometric Measurements

The players' heights were measured using a stadiometer with an accuracy of ±1 mm (Harpenden, Holtain® Ltd., Crosswell, UK). Electronic scales (Oregon Scientific®, GR101, Portland, USA) with an accuracy of ± 0.01 kg were used to measure the body mass.

Illinois Agility Test

The IAT is set up with four cones forming the agility area (**Figure 1**). On command, (1) the athlete sprints 10 m, turns and (2) returns to the starting line. After returning to the starting line, (3) he swerves in and out of four cones (4, 5) completing two 10 m sprints to finish the agility course (Miller et al., 2006). Performances were recorded using an electronic timing system (Globus®, Codogne, Italy). The infrared timing gates were positioned at the start and the finish lines at a height of 1 m. No technical advice was given as to the most effective movement technique. Subjects were only instructed to complete the test as quickly as possible. Subjects were instructed not to jump over the markers; they were to run around them, and the trial was not valid if they touched or toppled a marker.

Modified Agility Test

This test was originally described as a measure of four-directional agility and body control that evaluates the ability to change directions rapidly while maintaining balance without loss of speed (Semenick, 1990). The MAT was proposed by Sassi et al. (2009) and Pauole et al. (2000), and recently adapted by Yanci et al. (2013). This is considered a short duration test where linear movement in the antero-posterior and medio-lateral directions is required (Sassi et al., 2009). A previous study conducted with football players showed excellent MAT test reproducibility values (CV = 2.3%) (Yanci et al., 2014). The participants' movements during the MAT were as follows (**Figure 2**): (i) A–B movement (5 m): participants sprinted forward to cone B and touched the top of it with the right hand; (ii) B–C movement (2.5 m): moving laterally without crossing the feet, participants ran to cone C and touched the top of it with the left hand; (iii) C–D movement (5 m): participants ran laterally to cone D and touched the top of it with the right hand; (iv) D–B movement (2.5 m): participants moved back to cone B and touched the top of it with the left hand; (v) B–A movement (5 m): participants ran backward to line A. Start position was standardized, with the preferred foot close to the start line. The test was repeated if the athlete crossed one foot in front of the other, did not touch the cone and failed to face forward throughout. MAT performances test were recorded using an electronic timing system (Globus®, Codogne, Italy) positioned at the start line at a height of 1 m.

Data Analysis

Results are presented as mean ± standard deviation (SD), and coefficient of variation (CV) was also calculated using next formula: $CV = (SD/Mean \cdot 100)$ (Atkinson and Nevill, 1998). Reliability among two trials in each agility test was assessed using intra-class correlations (ICC) and Standard Error Measurement (SEM). ICC > 0.90 were considered excellent, 0.75–0.90 good

TABLE 1 | Descriptive data of elite football players with cerebral palsy (FPCP) and football players (CG).

Class	*n*	Age (yr)	Mass (kg)	Height (cm)	BMI (kg·m^{-2})	Sport experience	Football sessions	Gym sessions
FT5	8	23.2 ± 6.4	67.0 ± 7.5	175.9 ± 6.1	21.7 ± 2.7	11.4 ± 5.2	4.6 ± 1.2	3.0 ± 1.3
FT6	12	27.1 ± 8.9	65.6 ± 6.5	175.3 ± 4.7	21.5 ± 1.5	11.0 ± 3.6	2.6 ± 1.2	2.7 ± 1.1
FT7	64	24.8 ± 6.2	68.3 ± 8.5	175.1 ± 7.6	22.5 ± 2.9	9.8 ± 6.9	3.2 ± 1.3	2.7 ± 1.5
FT8	15	26.5 ± 7.6	73.2 ± 7.9	176.7 ± 8.9	23.5 ± 2.2	13.6 ± 9.6	3.1 ± 0.9	3.5 ± 1.7
CG	37	19.6 ± 3.4	72.6 ± 7.8	178.0 ± 5.9	22.9 ± 1.7	10.2 ± 5.1	3.4 ± 0.5	1.7 ± 0.9
Sample	136	23.7 ± 6.6	69.8 ± 8.2	176.0 ± 7.1	22.6 ± 2.5	10.5 ± 6.5	3.3 ± 1.1	2.5 ± 1.5

BMI, Body Mass Index; Sport experience expressed in years; Football and Gym (strength) sessions expressed by times/week.

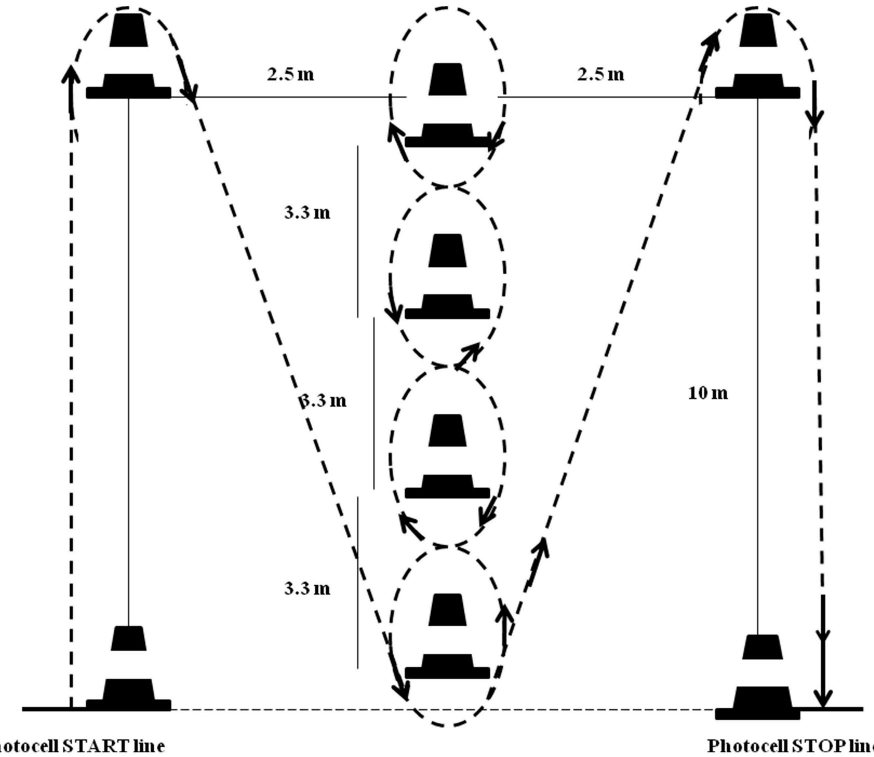

FIGURE 1 | Schematic representations for Illinois Agility Test (IAT).

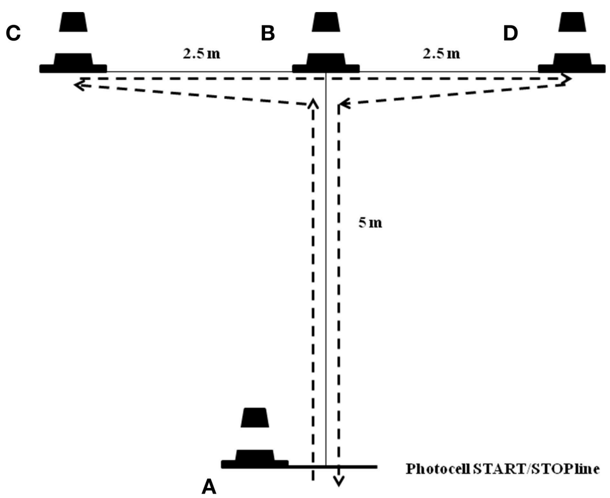

FIGURE 2 | Schematic representations for Modified Agility Test (MAT).

and <0.75 as poor to moderate (Portney and Watkins, 2008). The SEM was calculated by using the following formula: $SEM = SD \cdot \sqrt{1 - ICC}$. Strength of association between two agility tests used in this study was assessed using a Pearson correlation (r). To interpret those results the threshold values for Pearson product-moment used by Salaj and Markovic (2011) were used: low ($r \leq 0.3$), moderate ($0.3 < r \leq 0.7$) to high ($r > 0.7$). A spreadsheet designed by Hopkins (2015) was used to evaluate changes in scores (bias) between testing repetitions.

Kolmogorov test was applied to evaluate the normal data distribution. All analyzed variables had a normal distribution, and parametric statistic was used. Atypical scores were evaluated for those players scoring above 95% interval of confidence, and one player from the class FT6 and two players from the class FT7 have been removed from the data analysis. A One-way analysis of variance (ANOVA) with least significant difference *post-hoc* comparison (Scheffé correction) was used to examine the mean differences between groups and FPCP sub-groups. Cohen's effect sizes (*d*) between groups were also calculated (Cohen, 1988). Interpretation of effect sizes for highly trained athletes was: above 1.0, between 0.5 and 1.0, between 0.25 and 0.5 and lower than 0.25 were considered as large, moderate, small and trivial, respectively (Rhea, 2004). Data analysis was performed using the Statistical Package for Social Sciences (version 21.0 for Windows, SPSS Inc, Chicago, IL, USA). Statistical significance was set at an alpha level of $p < 0.05$.

RESULTS

Due to the different classification profiles about the players who took part in the study, a within-group correlation analysis was conducted between two CODA tests. Within-session reliability for each player was evaluated among two trials performed. IAT reliability was ICC = 0.96 (0.91, 0.98) and SEM = 2.5% (2.23, 2.86) for the FPCP group, and ICC = 0.84 (0.73, 0.91) and SEM = 1.88% (1.57, 2.38) for CG. CV for CG was 4.21%, and higher in the FPCP classes: FT8 = 7.01%, FT7 = 9.48%, FT6 = 6.85%, and FT5 = 10.37%. The change in mean scores (bias) were −0.14 s (−0.26, −0.02) for FPCP group and 0.01 s (−0.12, −0.14) for CG respectively. On the other hand, FPCP group showed a reliability in MAT of ICC = 0.82 (0.75, 0.87) and SEM = 5.84% (5.20, 6.68), while CG was ICC = 0.76 (0.61, 0.86) and SEM = 3.02% (2.53, 3.78). Similar results were obtained regarding CV: CG = 6%, FT8 = 10.01%, FT7 = 11.43%, FT6 = 17.09%, and FT5 = 16.81%. The bias for this test was −0.25 s (−0.37, −0.12) for FPCP group and −0.17 s (−0.24, −0.09) for CG respectively.

Overall correlation analysis between two CODA tests showed a significant and positive relationship ($r = 0.736$, $p < 0.001$); both FPCP ($r = 0.555$, $p < 0.001$) and CG ($r = 0.453$, $p < 0.01$). However, if we analyse this relationship between the different classes in the FPCP group, correlation is not significant for classes FT5 ($r = 0.359$, $p = 0.383$), while it is significant for classes FT6 ($r = 0.838$, $p < 0.01$), FT7 ($r = 0.517$, $p < 0.001$), and FT8 ($r = 0.641$, $p < 0.01$).

Mean, standard deviations, maximum and minimum scores for each group and overall are reported in **Figures 3**, **4**. In IAT, CG performed faster scores (15.91 ± 0.67 s), compared with FT8 (17.75 ± 1.24 s; $d = 1.84$, large), FT7 (18.67 ± 1.77 s; $d = 2.06$, large), FT6 (19.34 ± 1.32 s; $d = 3.27$, large), and FT5 (19.49 ± 2.02 s; $d = 2.38$, large) respectively. Similar results were obtained for MAT: CG (5.99 ± 0.36 s), FT8 (7.09 ± 0.71 s; $d = 1.95$, large), FT7 (7.94 ± 0.91 s; $d = 2.82$, large), FT6 (8.22 ± 1.41 s; $d = 2.17$, large), and FT5 (8.59 ± 1.44 s; $d = 2.48$, large).

One-way ANOVA showed significant differences between groups, both IAT [$F_{(4, 128)} = 36.93$; $p < 0.001$] and MAT [$F_{(4, 129)} = 26.30$; $p < 0.001$]. Pair comparisons also report significant differences between CG and all FPCP classes ($p < 0.001$ regarding FT7, FT6, and FT5; $p < 0.01$ regarding FT8; $d > 1.0$, large).

In IAT, FT8 class comparisons regarding the other classes were: FT5 ($p = 0.128$; $d = 1.03$, large), FT6 ($p = 0.124$; $d = 1.23$, large), and FT7 ($p = 0.325$; $d = 0.60$, moderate). With regard to MAT, FT8 players showed significant differences regarding all the other FPCP groups: FT5 ($p = 0.005$; $d = 1.32$, large), FT6 ($p = 0.034$; $d = 1.01$, large), and FT7 ($p = 0.026$; $d = 1.04$, large). No significant differences have been found between FPCP classes FT5, FT6 and FT7.

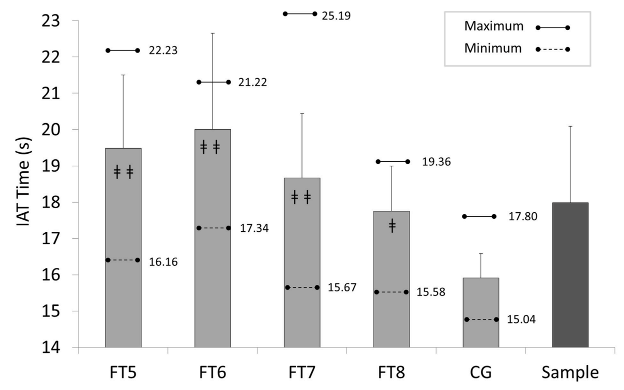

FIGURE 3 | Descriptive scores for each group in Illinois Agility test (IAT): FT5, FT6, FT7, and FT8, Football Players with Cerebral Palsy Classes; CG, control group; ǂǂ, CG vs. FT5, FT6, or FT7, *p* < 0.001; ǂ, CG vs. FT8, *p* < 0.01.

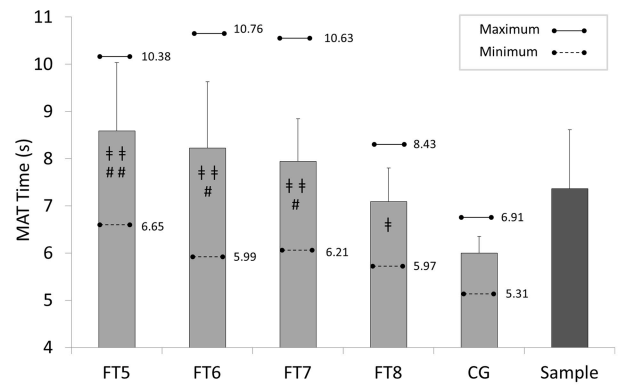

FIGURE 4 | Descriptive scores for each group in Modified Agility test (MAT); FT5, FT6, FT7, and FT8, Football Players with Cerebral Palsy Classes; CG, control group; ǂǂ, CG vs. FT5, FT6, or FT7, *p* < 0.001; ǂ, CG vs. FT8, *p* < 0.01; ##, FT8 vs. FT5, *p* < 0.01; #, FT8 vs. FT6-FT7, *p* < 0.05.

DISCUSSION

The aim of this study was to compare the performance of FPCP and football players in two CODA tests, and analyse its relationship with current functional classification profiles in CP-football. To our knowledge, there is no study in the literature of the CODA in football players with CP and other related neurological conditions eligible for CP-football. According to IPC's Classification Policy, the development of evidence-based classification procedures is necessary, and tis check the activity limitation in sporting skills due to eligible impairment.

The analysis of the reproducibility of MAT and IAT showed excellent to good values, as other studies which used T-design CODA tests (Pauole et al., 2000; Sassi et al., 2009; Yanci et al., 2014) and IAT (Miller et al., 2006; Lockie et al., 2013). Also, high to moderate correlations have been obtained between both tests. However, FPCP groups showed CVs in MAT higher than 10% (FT8 = 10.01%, FT7 = 11.43%, FT6 = 17.09%, and FT5 = 16.81%). Future studies could include three trials of the test to improve CV, although SEM and ICC values were good. On the other hand, this test could be considered a "novel" task for the players (International Paralympic Committee (IPC), 2015).

A test that assesses linear acceleration, in addition to the ability to make several sharp cuts while continuing to sprint forward over specific distances, has value for field sports (Lockie et al., 2013). IAT involves acceleration, as well as directional changes when sprinting in a linear fashion. In the same way, CODA is considered a determinant for successful performance in football (Chaouachi et al., 2012, 2014) and the response to different, short and rapid movements is essential in football players. For this reason, CODA has been tested in order to assess football players' conditioning (Chaouachi et al., 2012; Yanci et al., 2014; Reilly et al., 2000). In spite of the fact difficulty in turning and stopping are characteristics of IFCPF (2015a) to the best of our knowledge, this is the first study of such ability in international FPCP. Both IAT and MAT tests showed that best score in CG is better than the best score in FPCP classes, and both tests could be valid and reliable to evaluate CODA activity limitation due to eligible impairments.

Current CP Football rules state that at least one player from the classes FT5 or FT6 should be on the field of play during the game, and teams cannot play with more than one player of class FT8. This rule is expected to change after the Rio Paralympic Games, and the IFCPF Board have suggested increasing to two FT5 or FT6 players in the lineup. This rule change will have an impact on team management and training, because these two classes are colloquially named "lower classes." Then, the general performance of a team could be influenced by the classification of its players. In other words, a player with "moderate" or "mild" spastic diplegia could be classified as FT5 or FT8, with a major impact on team play or team squad (Reina, 2014). According to Tweedy et al. (2014), to assess the relative strength of association between valid measures of impairment and measures of performance, development of valid measures of impairment must be complemented by the development of standardized, sport-specific measures of performance, and tests applied in this study could be helpful in CP Football classification.

In our study, FT8 ("mild impairment" regarding the other three classes) showed significant differences with FT5, FT6, and FT7 in IAT (large effect sizes); but not in MAT, but with large (FT5 and FT6) and moderate (FT7) effect sizes. Players from class FT5 (e.g., spastic diplegia) presented the worst scores in both tests. Spastic diplegia manifests as high and constant "tightness" or "stiffness" in the muscles of the lower extremities, usually on the legs, hips, and pelvis. The abnormally high muscle tone that results creates lifelong difficulty with all voluntary and passive movement in the legs, such as ankle rotational anomalies, identified as the most frequent cause of lower limb torsional deviations followed by pelvic malalignment (Simon et al., 2015). The consequence of this impairment is shorter strides and difficulties performing rapid changes of direction, which explains the lower scores in both CODA tests.

Class FT6 players showed also significant differences with regard to FT8 players in MAT but not IAT, but both comparisons with large effect sizes ($d = 1.01 - 1.23$). We should consider the eligible impairments for class FT6: ataxia (impaired control of voluntary movement), athetosis (involuntary contractions of the muscles), or dystonia (sustained muscle contractions that cause twisting and repetitive movements or abnormal postures). FT6 players may have good dynamic balance compared with static balance (IFCPF, 2015b). Athletes with dystonia, athetosis and ataxia, in particular, usually have problems with balance and starting, stopping and turning when running. They also have varying degrees of difficulty with balance while hopping and jumping; with many postural body adjustments for static/dynamic balance. If we compare the CV within each class in the two CODA tests, we observe that MAT test has higher scores. Particularly, FT6 class exhibits a CV of 6.85% in IAT and 17.09% in MAT (10.24% difference between tests), higher than the other FPCP classes (FT5 = 6.45%; FT7 = 1.94%; FT8 = 3%). The main activity limitation in these players is the coordination and movement control, and MAT requires displacements in several directions (frontwards, backwards, and lateral). Their CV is lower than other classes as FT5 or FT7 in IAT, because this athlete usually demonstrates better running mechanics or running pace (IFCPF, 2015b). However, because three different impairments are eligible for this class, large variability is also expected among players within this functional profile.

With regard to class FT7, we should consider again the functional profile of this class: spastic hemiplegia. These athletes usually have activity limitations in gait/running both in stance and swing phase on the impaired side. Foot placement is affected by either weakness in dorsiflexion muscles and/or over-activity in plantar flexor muscles. Knee and hip control are also affected by spasticity and possible loss of range of motion due to contracture. The kinematics of walking in youth and adults with CP (e.g., increased limb asymmetry, reduced stride length, and increased stride time) has been linked to their reduced walking economy (Unnithan et al., 1996). Although the athlete usually walks with a noticeable limp, he may appear to have a smoother stride when running but may not have a consistent heel strike. Asymmetry in the angle of touch down during landing probably resides within a compensation for unilateral neurological impairment of the individual (Kloyiam et al., 2011).

Larger angle of touch down (increased plantar flexion) may result from the fact that the affected limb is less able to conserve energy and stabilize the joints during movement. In MAT test, lateral displacements (toward right and left sides) were required, and these athletes exhibited difficulties in pivoting and balancing on the impaired side. In comparison, no differences between FT7 and FT8 classes in IAT could be explained because displacement is forwards, and a higher degree of plantar flexion allows greater energy conservation in the tendon, and the plantar flexed foot acts like a vertical (Fonseca et al., 2004) contributing to greater joint stability. IPC Athletics (2015) classification rulebook states that in T37 athletes, with similar profile to FT7 in CP Football, a limp may disappear almost totally while they run. The reason is that when walking the leg support during stance phase begins with a heel strike, and this is the most difficult action for athletes with a spastic paresis. When running only the forefoot hits the ground, providing support and push off, and a tight calf muscle facilitates the push off. Therefore, MAT appears here as a better CODA test for the cut-point FT7 vs. FT8 than IAT.

CONCLUSIONS

The IPC is continually developing and refining evidence-based classifications for all sports. No research has systematically investigated the relationship between the CP Football players' functional profiles and their ability to perform CODA tests. The present study makes the following suggestions:

a) IAT and MAT could be useful, reliable and valid tests to analyse CODA performance in FPCP, because activity limitation in test performance has been demonstrated compared with controls.
b) Comparing between current FPCP classes (IFCPF, 2015b), each test (IAT and MAT) could be applied considering the cut point that classifiers need to make a decision about the FT8 class and other FT classes (FT5, FT6, and FT7).

According to Tweedy et al. (2014) future research should focus on the assessment of the relative strength of association between valid measures of impairment and measures of performance. It is vital that athletes who have positively influenced their impairment scores through effective training are not competitively disadvantaged by being placed in a class for athletes with less severe impairments (Tweedy and Vanlandewijck, 2011). Since CPISRA classification system is based on a functional approach, more research is necessary to develop a sport-specific and evidence-classification system.

Our results can improve the current classification process in CP Football under the new International Federation (IFCPF), and contribute to the description of the current classification profiles, which will be modified and redefined after Rio 2016 Paralympic Games.

AUTHOR CONTRIBUTIONS

RR: design of the work, data acquisition, analysis, interpretation of data, drafting the work, revising, final approval of the version to be published. JS: design of the work, analysis, interpretation of data, drafting the work, revising. JY: analysis, interpretation of data, drafting the work, revising, final approval of the version to be published. MG: data acquisition, interpretation of data, drafting the work. MC: data acquisition, interpretation of data, drafting the work.

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Dual-Energy X-Ray Absorptiometry, Skinfold Thickness, and Waist Circumference for Assessing Body Composition in Ambulant and Non-Ambulant Wheelchair Games Players

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Field-based assessments provide a cost–effective and accessible alternative to dual-energy X-ray absorptiometry (DXA) for practitioners determining body composition in athletic populations. It remains unclear how the range of physical impairments classifiable in wheelchair sports may affect the utility of field-based body composition techniques. The present study assessed body composition using DXA in 14 wheelchair games players who were either wheelchair dependent (non-walkers; $n = 7$) or relied on a wheelchair for sports participation only (walkers; $n = 7$). Anthropometric measurements were used to predict body fat percentage with existing regression equations established for able-bodied persons by Sloan and Weir, Durnin and Womersley, Lean et al, Gallagher et al, and Pongchaiyakul et al. In addition, linear regression analysis was performed to calculate the association between body fat percentage and BMI, waist circumference, sum of 6 skinfold thickness and sum of 8 skinfold thickness. Results showed that non-walkers had significantly lower total lean tissue mass (46.2 ± 6.6 kg vs. 59.4 ± 8.2 kg, $P = 0.006$) and total body mass (65.8 ± 4.2 kg vs. 79.4 ± 14.9 kg; $P = 0.05$) than walkers. Body fat percentage calculated from most existing regression equations was significantly lower than that from DXA, by 2 to 9% in walkers and 8 to 14% in non-walkers. Of the anthropometric measurements, the sum of 8 skinfold thickness had the lowest standard error of estimation in predicting body fat content. In conclusion, existing anthropometric equations developed in able-bodied populations substantially underestimated body fat content in wheelchair athletes, particularly non-walkers. Impairment specific equations may be needed in wheelchair athletes.

Keywords: spinal cord injury, paralympic, total body mass, basketball, rugby

INTRODUCTION

Body composition measurement is vital in high performance sport because of the association of body fat and lean tissue mass with performance as well as health outcomes. Dual energy x-ray absorptiometry (DXA) is considered a relatively valid and reliable method to determine body composition in both able-bodied (Stewart and Sutton, 2012) and spinal cord injured (SCI) (Jones et al., 1998; Keil et al., 2014) individuals. However, the financial and logistical restrictions of DXA can limit accessibility for many practitioners and field-based body composition assessments are frequently employed as an alternative (e.g., waist circumference, skinfold thickness). Studies have shown body mass index (BMI), waist circumference and skinfold thickness to correlate well with total body fat and trunk fat and prediction equations have been developed to estimate body composition from these measurements (Eston et al., 2005; Weerarathna et al., 2008; Camhi et al., 2011). However, these relationships are population specific, differing according to gender and ethnicity due largely to different tissue distributions between these groups (Schreiner et al., 1996; Hill et al., 1999; Rahman et al., 2009; Camhi et al., 2011). Wheelchair game players present a range of lower and upper limb impairments that may also affect the relationships upon which such prediction equations are based. The accuracy of field-based methods for assessment of body composition in wheelchair game players is not known.

Lower limb paralysis and subsequent atrophy of lean mass following a SCI predisposes individuals to a decreased fat free mass (Maggioni et al., 2003; Stewart and Sutton, 2012), an increased fat mass (Spungen et al., 2003; Emmons et al., 2011) and a reduced resting metabolic rate (Buchholz and Pencharz, 2004). Previously, Spungen et al. (2003) observed comparable total lean and mass between individuals with thoracic and cervical level SCI. In contrast, some wheelchair games players with lower degrees of physical impairment remain ambulant in activities of daily life, only requiring a wheelchair for sports performance. The divergent fat distribution and lean mass profiles of individuals with varying degrees of physical impairments, and therefore modalities of daily ambulation, presents a challenge for cross-sectional and longitudinal body composition assessment. In addition, the standardized position to measure waist circumference and skinfolds in able-bodied persons is with the participant positioned in a standing anatomical reference position (Lohman et al., 1988). However, as this is not possible for most SCI-persons, waist circumference and skinfold thickness must be measured in supine or seated positions. These procedural differences might also affect the relationship between waist circumference, skinfold thickness and body fat and so affect the assessment of body composition by anthropometric techniques.

Two previous studies (Miyahara et al., 2008; Sutton et al., 2008) compared the body composition and fat distribution of male wheelchair athletes with able-bodied athletes and found a significantly lower lean body mass (Miyahara et al., 2008), higher body fat percentage (Miyahara et al., 2008; Sutton et al., 2008) and greater trunk fat mass (Sutton et al., 2008) in wheelchair athletes. In contrast, Sutton et al. (2009) did not find differences between the lean tissue mass and fat mass of the trunk when female SCI athletes and able-bodied non-athletic groups were compared. In addition, several studies (Bulbulian et al., 1987; Maggioni et al., 2003; Sutton et al., 2009) have investigated the applicability of using BMI, waist circumference, and skinfold thickness to estimate body fat percentage in wheelchair athletes using conventional regression-based body composition equations developed for able-bodied populations. These studies found that most regression equations (Sloan and Weir, 1970; Durnin and Womersley, 1974; Lean et al., 1996) underestimated body fat percentage for elite female wheelchair athletes (Sutton et al., 2009) and male paraplegic athletes (Bulbulian et al., 1987; Maggioni et al., 2003), with inaccuracy increasing with higher body fat percentages (Sutton et al., 2009). Interestingly, Sutton et al. (2009) suggested that regression equations that included the waist circumference appear to predict body fat percentage more accurately.

No distinction has yet been made between the body composition of athletes who are wheelchair dependent for daily activities and those that were ambulant yet eligible to compete in wheelchair sports using a sports wheelchair (Goosey-Tolfrey, 2010). The physical and disability characteristics are likely to influence the degree of relationship between field-based body composition assessment and DXA, as well as the accuracy of fat percentage prediction equations. The present study aimed to establish the accuracy of fat percentage prediction equations within wheelchair game players who were ambulant for daily living (walkers) and those who relied on wheelchair propulsion for daily ambulation (non-walkers). A secondary objective was to investigate the association between commonly employed field-based and DXA derived methods of determining body fat percentage in these two groups.

MATERIALS AND METHODS

Participants

Fourteen elite male wheelchair game players were recruited from national wheelchair basketball and national wheelchair rugby squads. All participants visited the laboratory once within the same competitive phase of their training schedule. The participants were divided into two groups; participants who were wheelchair independent during non-sporting activities (7 walkers) and daily wheelchair users (7 non-walkers). The participants' characteristics are shown in **Table 1**. The walkers comprised of five persons with single lower-limb amputations and two with lower limb deficiencies whilst the non-walkers comprised of all SCI-persons (motor complete SCI; C5–C7). All participants provided written informed consent prior to data collection and the study was approved by Loughborough University's Ethics Committee and the National Research Ethics Service.

Anthropometry

The anthropometric measurements performed were: height, body mass, waist circumference, and skinfold thickness. Height was measured in a standing position (walkers) or a supine

TABLE 1 | Participant characteristics, DXA-derived body composition, BMI, waist circumference, and sums of 6 and 8 skinfold thickness.

	Walkers (*n* = 7)	Non–Walkers (*n* = 7)	*P*-value (ES)
Age (years)	26 ± 8	32 ± 7	0.15 (0.8)
Time since injury (years)	19 ± 10	12 ± 7	0.16 (0.8)
Sport	WCB	WCR	n/a
Physical impairment	Amputee (*n* =5); Lower limb deficiency (*n* =2)	SCI (*n* =7)	n/a
Body mass (kg)	79.4 ± 14.9	65.8 ± 4.2	0.05* (1.1)
Fat mass (kg)	16.9 ± 7.6	16.3 ± 5.3	0.88 (0.8)
Fat percentage (%)	21.4 ± 5.9	26.2 ± 8.9	0.25 (0.6)
Lean tissue mass (kg)	59.4 ± 8.2	46.2 ± 6.6	0.01* (1.3)
Lean tissue percentage (%)	75.6 ± 5.5	70.2 ± 9.0	0.21 (0.7)
BMI	23 ± 4	21 ± 2	0.10 (0.9)
Waist circumference (cm)	85.5 ± 8.6	77.9 ± 7.8	0.11 (0.9)
Sum of 6 skinfold thicknesses (mm)	77.2 ± 18.6	85.0 ± 39.9	0.65 (0.3)
Sum of 8 skinfold thicknesses (mm)	102.2 ± 26.6	114.0 ± 47.0	0.57 (0.3)

*All date are mean ± standard deviation. ES, Effect size; WCB, Wheelchair Basketball; WCR, Wheelchair Rugby; SCI, Spinal Cord Injury; BMI, Body Mass Index; Significant differences are indicated with * at a significant level of P < 0.05.*

position (non-walkers), using a Luftkin measuring tape. Body mass was measured using a wheelchair accessible scale (Detecto 6550KGEU Portable, Detecto Scale Company, Webb City, Mo, USA). Participants who were not able to stand on the scale were weighed in their wheelchair, afterwards the wheelchair was weighed and its weight was subtracted from the total weight. Height (m) and body mass (kg) were used to calculate the BMI by the following formula:

$$\text{BMI} = \text{bodymass}/\text{height}^2$$

Waist circumference was measured directly to the skin using an inelastic tape at the narrowest part of the torso after normal expiration (Lohman et al., 1988; Buchholz and Bugaresti, 2005). For walkers, waist circumference was measured in a neutral standing position; for non-walkers, waist circumference was measured in a supine position with their arms at their sides. Waist circumference was measured three times and the average of these three measurements was taken for further analysis.

Skinfold thickness were measured at eight sites and were performed according to the guidelines from the ISAK (Lohman et al., 1988), having the same investigator measuring all skinfolds by using a set of Harpenden Skinfold Calipers (Baty International, West Sussex, UK). Skinfold sites included: biceps, triceps, subscapular, iliac crest, supraspinale, abdominal, anterior thigh, and medial calf. For the non-walkers, skinfolds were measured in a seated position, while the walkers were measured in a standing position. Each skinfold measurement was made in triplicate; true skinfold thickness was taken as the average of those three measures. However, in case of any outliers, the average of two measurements was taken. Afterwards, skinfold thickness were used to calculate the sum of 6 skinfold thicknesses (biceps, triceps, subscapular, iliac crest, supraspinale, and abdominal) and the sum of 8 skinfold thicknesses (biceps, triceps, subscapular, iliac crest, supraspinale, abdominal, thigh, and calf).

Dual Energy X-ray Absorptiometry

Body composition was measured using DXA Lunar Prodigy Advance (GE Medical Systems, Madison, WI, USA) with Encore software version 13.2. The participants were instructed to wear loose fitting clothes without any metal and to remove all metal fixtures such as jewelry. Afterwards, the participants were positioned on the DXA-bed in a supine position as close as possible to standard positioning protocol, with Velcro straps used to help keep the legs still during measurement. Although some participants had muscular spasms during positioning, they were able to remain still once positioned. Scanning time varied between 6 and 10 min depending on the mass and height of the participants. The analyses of all scans were performed by the same operator to avoid any inter-observer variability. The total body scan was used to gain the outcome measures which were: total body fat mass, total body fat percentage, total lean tissue mass (with segmental data of the trunk, arms, and legs), lean tissue percentage and segmental fat mass of the trunk, arms, and legs.

Fat Percentage Predicting Regression Equations

To investigate whether traditional fat percentage predicting regression equations were applicable to elite male wheelchair game players the data acquired from the anthropometry measurements were used to predict body fat. The predicted body fat was than compared to the data resulting from the DXA scan. The regression equations to which the data were applied are from Sloan and Weir (1970), Durnin and Womersley (1974), Lean et al. (1996), Gallagher et al. (2000), and Pongchaiyakul et al. (2005).

Statistical Analyses

All statistical tests were performed using IBM SPSS Statics 22.0 and statistical significance was set *a priori* at $p < 0.05$. Firstly, the assumption of normal distribution was checked for all data by visual inspection of the box plot and q-q plot and also the Shapiro-Wilk test within the groups. Equality of variance was checked using the Levene's test. As all data were normally distributed, independent t-tests were used to compare body mass, DXA derived fat mass, body fat percentage, lean tissue mass, lean tissue percentage, and waist circumference, BMI and sum of 6 skinfold thickness and sum of 8 skinfold thickness between the walking and non-walking group. Further, segmental lean and fat mass for the trunk, arms, and legs were compared between groups. For all variables the 95% CI for the mean difference was determined and effect sizes were calculated for all variables using the method of Cohen (1992), where an effect size of 0.2 represents a small effect, 0.5 a moderate effect, and 0.8 a large effect. To test the agreement between the results of the fat percentage predicting regression equations and DXA outcomes, the statistical method of Bland and Altman (2012) was used.

Paired t-tests were performed for all five equations between the results of the DXA and equations to check for significant systematic errors. Also, Pearson's correlations were performed to check for proportional biases and heteroscedasticity. For the walkers and non-walkers, the association between body fat percentage and BMI, waist circumference, sum of 6 skinfold thicknesses and sum of 8 skinfold thicknesses was calculated by performing linear regression analysis and interpretation of slope and intercept.

RESULTS

Body Composition

There were no significant differences for age and time since injury between the two groups (**Table 1**). **Table 1** shows the physical characteristics of the two groups, where non-walkers were lighter than walkers ($P = 0.05$) with significantly lower lean tissue mass than the walking group ($P < 0.01$). Lean tissue mass was significantly lower ($P < 0.04$; effect size > 1.0) across the trunk, arms, and legs for non-walkers (**Figure 1**). For the other variables (fat mass, fat percentage, lean tissue percentage, segmental fat mass, BMI, waist circumference, sum of 6 skinfold thicknesses, and sum of 8 skinfold thicknesses) no significant differences between the two groups were found. However, the effect sizes of BMI and waist circumference were 0.9, indicating substantially, but not significantly, lower BMI and waist circumference in the non-walkers.

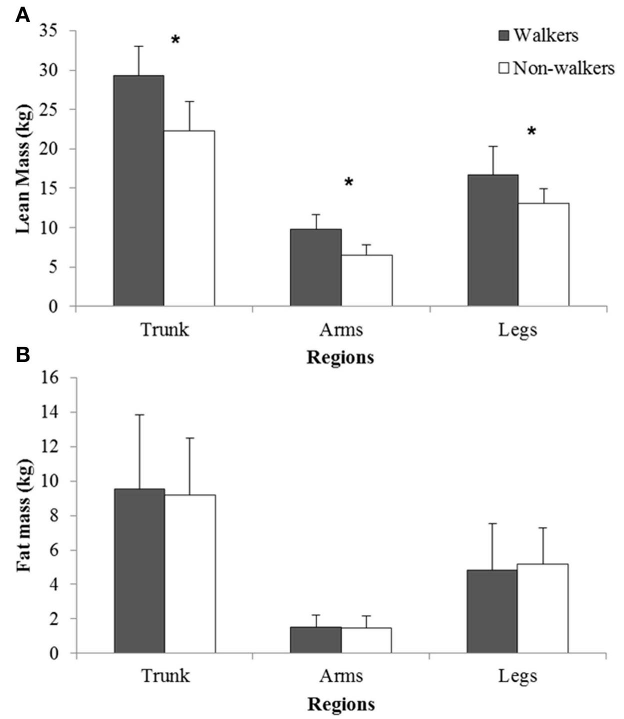

FIGURE 1 | Comparison of (A) segmental (trunks, arms, legs) lean tissue mass and (B) fat mass for walkers and non-walkers. * Significant difference between groups ($P < 0.04$).

Fat Percentage Prediction Equations

The results of body fat percentage derived by DXA scan and the fat percentages calculated by the anthropometric prediction equations for walkers and non-walkers can be found in **Figure 2**. The agreement between the percent fat estimated from DXA and anthropometric predictions equations, displayed as mean percentage systematic error and 95% limits of agreement, are shown in **Table 2**. Pearson's correlations revealed that there were no proportional biases or heteroscedasticity within the walking group ($P \geq 0.93$) and non-walking group ($P \geq 0.142$). In the walking group, the equation of Lean et al. (1996) did not show a significant difference between the predicted body fat percentage and percent body fat measured by DXA. Also, this equation showed the lowest systematic error which was an underestimation of 2.1% of body fat percentage. The limits of agreements showed that the equation of Lean et al. (1996) will, 95% of the time, produce body fat percentage estimates between 9.7% less and 5.5% more than the DXA value. All other formulae showed significant differences between the equation outcomes and DXA measured body fat percentage ($P \leq 0.04$). For the non-walking group (see **Table 2**), all formulae showed significant differences between the equation outcomes and DXA measured body fat percentage, with underestimated body fat percentage and a large systematic errors (ranging from 8.3 to 13.7%).

Regression Analysis

Waist circumference was associated with percentage fat in walkers only (**Table 3**). However, the relationship appeared different between the groups, particularly for waist circumference (**Table 3**). This is highlighted by the lower percentage fat, but higher waist circumference, in walkers than non-walkers (**Table 1**). BMI was not significantly associated with percentage fat in either group (**Table 3**) and the standard error of estimate of percentage fat from BMI was large, particularly in the non-walkers. The sums of 6 or 8 skinfold thickness were significantly associated with % fat in both groups, with standard errors of estimate within 5% in both groups. Also, the relationship between the sum of skinfold thicknesses and % fat did not seem to differ so substantially between groups (**Table 3**).

DISCUSSION

The estimation of body fat percentage in wheelchair game players is a difficult task due to the variety of disabilities and the consequent differences in distribution of body tissues from able-bodied persons. This may explain the paucity of studies that have evaluated the use of predictive equation techniques from anthropometric measurements in this population. The primary finding of our study is that fat percentage predicting regression equations, based on skinfold thickness, waist circumference, age, and sex, used in the able-bodied populations are not applicable to ambulant and non-ambulant wheelchair sportspersons. Due the strong correlations and positive association found for sum of 6 skinfold thicknesses and sum of 8 skinfold thicknesses in non-walkers and walkers with body fat percentage, respectively, these

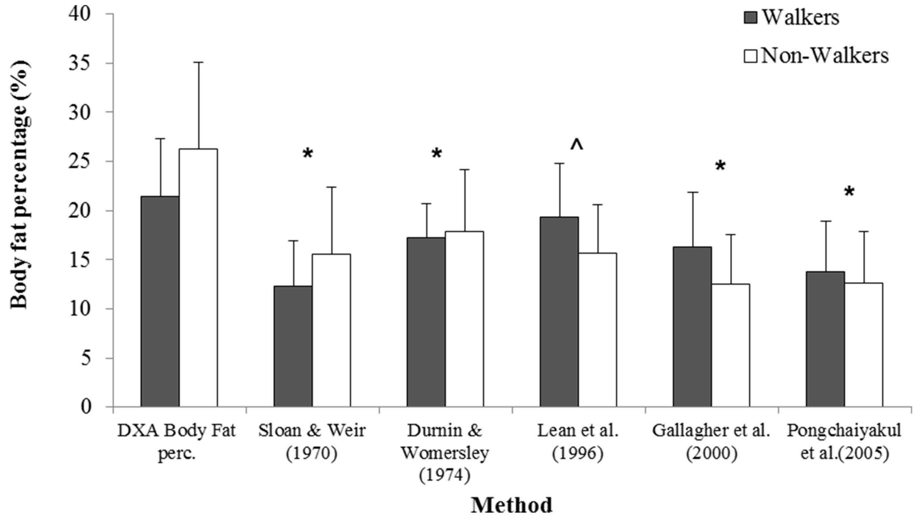

FIGURE 2 | Body fat percentage derived by DXA scan and the fat percentages calculated by the anthropometric prediction equations for walkers and non-walkers. * Both groups significantly lower than DXA ($P < 0.05$), ^ Non-walkers significantly lower than DXA ($P < 0.05$).

TABLE 2 | Agreement between DXA-determined percent body fat and values given by anthropometric equations for walkers ($n = 7$) and non-walkers ($n = 7$).

		Mean bias in % fat (anthropometry- DXA; mean ± SD)	*p*-value for bias	95% limits of agreement (Bland and Altman)		
				Lower	Upper	Range
Walkers	Sloan and Weir, 1970	−9.0 ± 2.6%	<0.01*	−14.0	−4.0	10.0
	Durnin and Womersley, 1974	−4.2 ± 3.8%	0.03*	−11.6	+3.3	14.9
	Lean et al., 1996	−2.1 ± 3.9%	0.21	−9.7	+5.5	15.3
	Gallagher et al., 2000	−5.1 ± 5.3%	0.04*	−15.5	+5.3	20.8
	Pongchaiyakul et al., 2005	−7.7 ± 5.0%	<0.01*	−17.5	+2.1	19.6
Non-walkers	Sloan and Weir, 1970	−10.6 ± 4.5%	<0.01*	−19.4	−1.78	17.6
	Durnin and Womersley, 1974	−8.3 ± 4.8%	<0.01*	−17.7	+1.1	18.8
	Lean et al., 1996	−10.6 ± 7.4%	<0.01*	−25.1	+3.9	29.0
	Gallagher et al., 2000	−13.7 ± 7.5%	<0.01*	−28.4	+1.0	29.4
	Pongchaiyakul et al., 2005	−13.6 ± 6.5%	<0.01*	−26.3	−0.9	25.5

*Eq., Equations; SD, Standard Deviation. Significant differences are indicated with * at a significant level of $P < 0.05$.*

variables could be useful to establish regression equations in the future for non-walking and walking wheelchair game players.

The results showed a difference in body mass between the groups, caused by a significantly lower lean tissue mass in the non-walkers as the fat mass was not significantly different between the groups. Segmental data for the trunk, arms, and legs showed lower lean tissue across all regions, representing the muscular atrophy associated with paralysis and impaired muscle innervation. These findings are in is line with findings of other studies who found significantly lower lean tissue mass in SCI-individuals (Maggioni et al., 2003; Miyahara et al., 2008; Stewart and Sutton, 2012). Previous studies showed a significantly higher body fat percentage for wheelchair athletes compared to able-bodied controls (Miyahara et al., 2008; Sutton et al., 2008). It could have been expected that this increased fat percentage in wheelchair athletes is caused by the increased fat mass of the SCI-athletes, as people with SCI are previously reported to have a higher fat mass (Spungen et al., 2003; Emmons et al., 2011). However, our results showed that DXA derived body fat mass in the walkers is not significantly different form the non-walkers. The main difference in body composition between non-walkers and walkers is thus lean tissue mass and not a difference in fat mass. BMI and waist circumference showed no significant differences between the groups but the effect sizes were very high.

The equations that were applied in this study were all established for the able-bodied population. The results showed that they are not transferrable to the non-walking or the walking athletic wheelchair population. For the walkers, the equation of Lean et al. (1996) predicted a fat percentage that was not significantly different from DXA-measured fat percentage.

TABLE 3 | Linear regression analysis of anthropometric measures and DXA-derived percentage body fat.

	Correlation co-efficient (*r*)		SEE		Intercept		Slope (95% CI)	
	Walkers	Non-Walkers	Walkers	Non-Walkers	Walkers	Non-Walkers	Walkers	Non-Walkers
WC	0.79*	0.62	4.00	7.61	−24.7	−29.37	0.54 (0.05 to 1.21)	0.71 (−0.32 to 1.74)
BMI	0.49	0.59	5.65	7.83	2.5	−21.35	0.81 (−0.84 to 2.46)	2.32 (−1.2 to 5.93)
Sum of 6	0.84*	0.87*	3.54	4.78	0.81	9.75	0.27 (0.07 to 0.47)	0.19 (0.07 to 0.32)
Sum of 8	0.98*	0.88*	1.16	4.65	−0.95	7.32	0.22 (0.17 to 0.26)	0.17 (0.06 to 0.27)

*WC, waist circumference; BMI, body mass index; SEE, standard error of the estimate. Significant correlations are indicated with * at a significant level of $P < 0.05$.*

However, the limits of agreement were wide, making the prediction very inaccurate. Therefore, it is not advisable to use the equation for ambulant disabled wheelchair game players. All other equation based predictions for the non-walkers and walkers were significantly different from DXA-measured fat percentage, and are thus not usable to estimate body fat percentage in these populations. Our results are in agreement with the findings from Sutton et al. (2009), Maggioni et al. (2003), and Mojtahedi et al. (2009) who also concluded that the equations underestimate body fat percentage and are not accurate enough to use in daily practice.

No significant correlations between BMI and body fat percentage were found for either the walkers or non-walkers, in contrast to the results of Sutton et al. (2009) who found a strong correlation in female wheelchair athletes. The large standard error of estimation of percentage fat from BMI demonstrates that BMI is a particularly poor indicator of obesity in wheelchair athletes. Waist circumference correlated with body fat percentage in the walkers which is in agreement with the work of Sutton et al. (2009), however, no significant correlation was not found for the non-walkers. Despite the more centrally located fat mass in SCI (Spungen et al., 2003), non-walkers tended to have lower waist circumference at any given fat percentage than walkers, although the sample size was not sufficient to detect a significantly different relationship between the two groups. In contrast to Sutton et al. (2009) suggestion, the high SEE of fat percentage estimated from waist circumference suggests that waist circumference does not provide a better indicator of body fat content than skinfolds in this population.

The sums of 6 and 8 skinfold thickness showed the highest correlation with body fat content in this sample. A closer look at those correlations shows that for non-walkers, the correlation of sum of 6 skinfold thickness and sum of 8 skinfold thickness are similar, although the lower standard error of estimate with 8 skinfold thickness suggests this measure may provide most accuracy. Although existing skinfold thickness equations developed in able-bodied populations substantially underestimated body fat content, in this sample, the relatively low SEE for the regression of fat percentage and skinfold thickness suggests that it may be possible to derive population specific equations for wheelchair athletes based on skinfold thickness. Theoretically, it may be desirable to also include a variable that may reflect the atrophy of lean tissue, e.g., thigh circumference. Furthermore, given that height may be substantially affected in double amputees and also some SCI, an alternative index of body size such as arm-span may be more appropriate in this population. However, one difficulty in developing such equations is the limited sample of wheelchair athletes, and a further difficulty is the heterogeneity of the population. Pending any future developments in body composition assessment in these groups, we suggest that body composition be assessed by DXA, and any estimates from anthropometric equations be adjusted accordingly.

In the present study DXA was used to assess body composition and not a four component model, which is standard better criterion measure for assessing body composition. Although some studies found very high precision of DXA in able-bodied persons (Stewart and Sutton, 2012) and in SCI individuals (Jones et al., 1998), the accuracy of DXA for assessing body composition is still debated (Van Loan and Mayclin, 1992; Glickman et al., 2004). Therefore, inaccuracies in body composition measurements might have occurred in this study. However, considering the reported accuracy of DXA (Jones et al., 1998; Stewart and Sutton, 2012), possible inaccuracies in assessing body composition should be relatively small. Another limitation of this study might be the small sample size. As the study deals with a highly specific population (Paralympic wheelchair athletes) it is hard to increase the sample size number. Despite the low participant number we were still able to uncover interesting results about the body composition of athletes classified as non-walkers and walkers. This study is the first study trying to assess body composition in wheelchair athletes with anthropometric measurements, differentiating between non-walkers and walkers. Given the interesting results of this study, further research into body composition assessment of non-walking and walking athletes should be able to establishing separate field-methods for body composition assessment within these populations.

CONCLUSION

In conclusion, there were notable differences for the total lean tissue mass between the non-walkers and walkers. Non-walkers displayed significantly lower segmental lean mass of the trunk, arms, and legs, resulting in significant differences in total body mass between groups. The regression equations developed from able-bodied populations using BMI, waist circumference, age, and skinfold thickness measurements substantially underestimated body fat content, particularly in non-walkers. All formulae, apart from that of Lean et al.'s (1996) in the walkers, showed significant differences between the equation outcomes and DXA-derived body fat percentage, with an underestimation in body fat percentage and large systematic errors across present in all equations (ranging from 8 to 14%). Due the strong correlation between sum of 8 skinfold thickness and body fat percentage, and the low SEE for walkers and non-walkers, this variable could be suitable to establish future impairment specific regression equations for wheelchair game players.

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Differences in Left Ventricular Global Function and Mechanics in Paralympic Athletes with Cervical and Thoracic Spinal Cord Injuries

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Following a spinal cord injury, there are changes in resting stroke volume (SV) and its response to exercise. The purpose of the following study was to characterize resting left ventricular structure, function, and mechanics in Paralympic athletes with tetraplegia (TETRA) and paraplegia (PARA) in an attempt to understand whether the alterations in SV are attributable to inherent dysfunction in the left ventricle. This retrospective study compared Paralympic athletes with a traumatic, chronic (>1 year post-injury), motor-complete spinal cord injury (American Spinal Injury Association Impairment Scale A-B). Eight male TETRA wheelchair rugby players (34 ± 5 years, C5-C7) and eight male PARA alpine skiers (35 ± 5 years, T4-L3) were included in the study. Echocardiography was performed in the left lateral decubitus position and indices of left ventricular structure, global diastolic and systolic function, and mechanics were derived from the average across three cardiac cycles. Blood pressure was measured in the supine and seated positions. All results are presented as TETRA vs. PARA. There was no difference in left ventricular dimensions between TETRA and PARA. Additionally, indices of global diastolic function were similar between groups including isovolumetric relaxation time, early (E) and late (A) transmitral filling velocities and their ratio (E/A). While ejection fraction was similar between TETRA and PARA (59 ± 4 % vs. 61 ± 7 %, $p = 0.394$), there was evidence of reduced global systolic function in TETRA including lower SV (62 ± 9 ml vs. 71 ± 6 ml, $p = 0.016$) and cardiac output (3.5 ± 0.6 L/min vs. 5.0 ± 0.9 L/min, $p = 0.002$). Despite this observation, several indices of systolic and diastolic mechanics were maintained in TETRA but attenuted in PARA including circumferential strain at the level of the papillary muscle (−23 ± 4% vs. −15 ± 6%, $p = 0.010$) and apex (−36 ± 10% vs. −23 ± 5%, $p = 0.010$) and their corresponding diastolic strain rates (papillary: 1.90 ± 0.63 s^{-1} vs. 1.20 ± 0.51 s^{-1}, $p = 0.028$; apex: 3.03 ± 0.71 s^{-1} vs. 1.99 ± 0.69 s^{-1}, $p = 0.009$). All blood pressures were lower in TETRA. The absence of an association between reduced global systolic function and mechanical dysfunction in either TETRA or PARA suggests any reductions in SV are likely attributed to impaired loading rather than inherent left ventricular dysfunction.

Keywords: athletes, echocardiography, paraplegia, strain, stroke volume, tetraplegia

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INTRODUCTION

The classification of Paralympic athletes is sports specific and considers physical, visual and/or intellectual impairments. Typically athletes with a spinal cord injury (SCI) are competing against individuals with a similar lesion level (i.e., cervical or thoracic SCI). However, there are sporting competitions where individuals with cervical and thoracic SCI are competing against each other, in addition to other non-SCI athletes. The consideration of how the lesion level may influence exercise performance is therefore necessary to ensuring fair competition between the diverse population of Paralympic athletes.

One contributing factor to exercise performance is the capacity of the cardiovascular system to adequately respond to the body's demands. This includes the responses of the heart, vasculature, and adrenal medulla. Following SCI, there are lesion level dependent alterations in how the cardiovascular system responds to an exercise stimulus. While sympathetic preganglionic neurons originate in the thoracic and upper lumbar segments of the spinal cord (T1-L2), sympathetic innervation of target organs is segmental. Innervation of the heart and vascular smooth muscle of the upper body arise from the high thoracic segments (T1-T5), while innervation of the vascular smooth muscle of the lower body and adrenal medulla arise from the lower thoracic and lumbar segments (T6-L2). Cervical SCI results in the most dramatic alterations in cardiovascular outcomes at rest and in response to exercise, due to the disruption of descending sympathetic input to target organs below the level of injury (Krassioukov, 2009). We recently confirmed this by demonstrating individuals with tetraplegia who had an autonomic complete SCI also reached attenuated peak heart rates of 102 ± 34 bpm while individuals with tetraplegia and autonomic incomplete SCI reached higher peak heart rates (161 ± 20 bpm) (Currie et al., 2015). Additional cardiovascular responses that are attenuated during exercise in individuals with tetraplegia include the changes in blood pressure (Thijssen et al., 2009), catecholamine levels (Schmid et al., 1998a,b), and stroke volume (SV) (Kessler et al., 1986; Hostettler et al., 2012). Contrary to tetraplegia, individuals with high and low paraplegia have either partial or full preservation of descending sympathetic pathways to the heart, vascular smooth muscle and adrenal medulla, and therefore are capable of mounting an appropriate cardiovascular response during exercise. Previous research has demonstrated individuals with paraplegia are capable of reaching peak heart rates in range of their age-predicted heart rate maximum (Hopman et al., 1992, 1993; Jacobs et al., 2002) and display exercise-induced increases in circulating catecholamines (Schmid et al., 1998a,b) and blood pressure (Dela et al., 2003; Claydon et al., 2006). SV responses to aerobic exercise in individuals with paraplegia, however, are inconclusive with previous research either demonstrating no change (Davis and Shephard, 1988; Hopman et al., 1993; Raymond et al., 2001; Theisen et al., 2001) or small increases (Davis et al., 1987; Hopman et al., 1992; Raymond et al., 1999). Overall, exercise-induced increases in cardiac output ($\dot{Q}$) in individuals with SCI are primarily driven by changes in heart rate, with individuals with paraplegia exhibiting a greater capacity to increase $\dot{Q}$ during exercise.

Altered SV responses in SCI have primarily been attributed to a reduction in loading (i.e., decreased venous return) (Theisen, 2012). However, no studies have examined whether factors inherent to the left ventricle (LV) *per se* are also a contributing factor. Echocardiographic assessments of LV mechanics are a non-invasive tool that may help to determine if changes in LV performance following SCI are associated with SV reductions. Indices of LV mechanics include strain (ε) and strain rates (SR) which assess the degree and rate of myocardial deformation in longitudinal, radial and circumferential axes; rotation (Rot) and rotation rates (RotR) of the base and apex of the LV; and overall LV twist and twisting/untwisting rates (Voigt et al., 2015). In clinical conditions, such as chronic heart failure, there is a concomitant reduction in global LV systolic function [SV; LV ejection fraction (EF)] and LV systolic mechanics (Leung and Ng, 2010; Ma et al., 2014), and recent evidence suggests lower ε in these patients is associated with a reduced exercise capacity (Hasselberg et al., 2015). Additionally, indices of LV mechanics are sensitive to increases and decreases in sympathetic activity (Weidemann et al., 2002; Akagawa et al., 2007), which may provide insight into the influence of lesion level on LV performance. Few studies have performed echocardiographic assessments in athletes with SCI (Huonker et al., 1998; Gates et al., 2002; Schumacher et al., 2009; Maggioni et al., 2012; West et al., 2012a; De Rossi et al., 2014), with none of these investigations examining LV mechanics. Given evidence that global LV systolic dysfunction is associated with impairments in LV mechanics, and that these functional changes may limit exercise performance, the examination of LV structure, function and mechanics in athletes with SCI may help to elucidate potential factors limiting cardiac responses to exercise. Therefore, the purpose of this study was to compare resting LV structure, function and mechanics in high-performance athletes with SCI.

MATERIALS AND METHODS

Participants

This was a retrospective comparison of echocardiography data collected at both summer and winter Paralympic events. Inclusion criteria included males between 18-60 years of age who had sustained a chronic (>1 year post-injury), motor-complete [American Spinal Injury Association Impairment Scale (AIS) A-B], traumatic SCI, and who have been competing at the international level for at least 3 years. Eight Paralympic wheelchair rugby players with a cervical SCI (TETRA) and eight Paralympic alpine skiers with a thoracic SCI (PARA) met the criteria and were included in the study. The neurological level of injury and AIS was confirmed using the International Standards for Neurological Classification of SCI (Kirshblum et al., 2011). Exclusion criteria for the study included any history of cardiovascular disease or acute illness/infection, which was confirmed with a verbal medical history, and any language or cognitive barrier that prevented the participant from following English instructions. The International Paralympics Committee, University of British Columbia Clinical Research Ethics Board, and Brunel University Research Ethics Board approved all protocols, which conformed to the Declaration of Helsinki, and all individuals provided written informed consent prior to participation. Prior to testing, participants were instructed to abstain from food and drink for 4 h, alcohol and caffeine for 12 h, and exercise for 24 h. On the day of testing, all participants were instructed to void their bladder to reduce the potential influence of sympathetic reflex activation on blood pressure.

Blood Pressure Assessments

Blood pressures were measured from the left brachial artery using an automated machine (Dinamap Pro 300 V2; GE Healthcare, Milwaukee, USA). Seated and supine measurements were collected in duplicate following 5 and 10 min of quiet rest, respectively.

LV Assessments

Cardiac images were collected with the participants in the left lateral decubitus position using two-dimensional echocardiography (Vivid 7; GE Healthcare, Horton, Norway) according to the recommendations of the American Society for Echocardiography (Quiñones et al., 2002; Lang et al., 2005; Voigt et al., 2015). Heart rate was measured continuously using a single-lead electrocardiogram. Images were analyzed offline using dedicated software (EchoPAC; GE Healthcare, Horten, Norway) by a single blinded investigator, and the average of three cardiac cycles is presented.

Indices of LV structure were measured at end-diastole (d) and end-systole (s) from the parasternal long axis view, including LV internal diameter (LVID), and interventricular septal wall (SWT), and posterior wall (PWT) thickness. Relative wall thickness (RWT) was calculated as [(2 × PWTd)/LVIDd]. LV mass (LVMI) was calculated according to an established formula (Devereux et al., 1986), and indexed to body surface area (Du Bois and Du Bois, 1989). Modified single-plane Simpson's method was used to analyze apical four-chamber views to determine end-diastolic (EDV) and end-systolic (ESV) volumes, and the global systolic function outcomes of SV, EF, and $\dot{Q}$ which was calculated as the product of SV and heart rate. Global diastolic function outcomes were determined from pulsed-wave Doppler at the tips of the mitral valve leaflet. Outcomes included early (E) and late (A) transmitral filling velocities and their ratio (E/A), and isovolumetric relaxation time (IVRT).

Indices of LV mechanics were derived from 2D speckle-tracking analysis of apical four-chamber and parasternal short axis images at the level of the mitral valve (basal), papillary muscle (mid), and apex (apical) using established guidelines (Mor-Avi et al., 2011). Using a cubic spline algorithm, raw speckle-tracking traces were interpolated by customized post-processing software (2D Strain Analysis Tool, Stuttgart, Germany) into 600 points in systole and 600 points in diastole to control for heart rate differences. Peak ε and SR in systole and diastole were determined from short-axis (radial, circumferential) and four-chamber (longitudinal) images. Peak Rot and RotR in systole and diastole were determine at the basal and apical levels, and twist was determined as the maximum value from subtracting frame-by-frame basal and apical Rot data. Peak systolic twisting velocity and early diastolic untwisting velocity were determined the same way using frame-by-frame basal and apical RotR data.

Statistical Analyses

Statistical analyses were performed using Statistical Package for Social Science software (IBM Corporation, Armonk, NY, USA). Data were assessed for normality using Shapiro-Wilk tests and Q-Q plot analyses. Between group differences were determined using independent t-tests and Mann-Whitney U-tests for normally and non-normally distributed data, respectively. Effect sizes were calculated using Cohen's d. Data are presented as mean ± SD unless otherwise noted, with $P < 0.05$ considered statistically significant.

RESULTS

Individual and group values for participant characteristics are presented in **Table 1**. Body surface area was similar in TETRA ($1.84 \pm 0.13\,m^2$) and PARA ($1.93 \pm 0.15\,m^2$, $p = 0.232$). Self-reported training history was available in 5 of 8 TETRA and all 8 PARA athletes. There was no significant difference in the number of years competing at an international level (TETRA: 11 ± 4 years; PARA: 8 ± 5 years, $p = 0.275$) or weekly training volume (TETRA: 10 ± 3 hours/week; PARA: 16 ± 13 hours/week, $p = 0.192$). For seated and supine hemodynamics, heart rates were

TABLE 1 | Participant characteristics.

	Lesion Level	AIS	TPI (yr)	Age (yr)	Height (m)	Mass (kg)
TETRA						
1	C5	A	14	38	1.68	61
2	C6	A	11	38	1.76	62
3	C6	A	12	37	1.76	63
4	C6	B	12	25	1.76	55
5	C6	B	20	36	1.80	72
6	C7	B	6	29	1.86	80
7	C7	A	15	32	1.83	70
8	C7	B	19	33	1.85	71
Mean ± SD	–	–	14 ± 5	34 ± 5	1.79 ± 0.06	67 ± 8
PARA						
1	T4	A	8	39	1.96	83
2	T4	A	24	41	1.76	72
3	T5	A	20	38	1.77	70
4	T8	A	7	24	1.85	64
5	T10	A	14	35	1.85	85
6	T10	A	19	32	1.68	58
7	T11	A	11	35	1.86	72
8	L3	A	18	34	1.86	72
Mean ± SD	–	–	15 ± 6	35 ± 5	1.82 ± 0.08	72 ± 9

A, motor- and sensory-complete; AIS, American Spinal Injury Association Impairment Scale; B, motor-complete and sensory-incomplete; C, cervical; L, lumbar; T, thoracic; TPI, time post-injury.

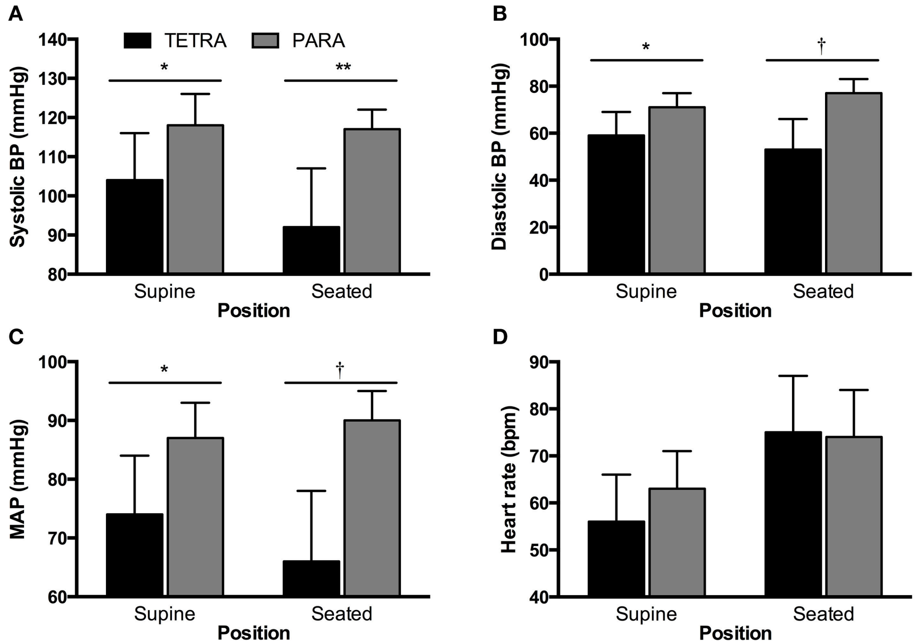

FIGURE 1 | Supine and seated systolic (A) and diastolic (B) blood pressure (BP), mean arterial pressure (C, MAP) and heart rate (D) for TETRA (black bars) and PARA (gray bars) groups. Between-group differences: $^{*}p < 0.05$; $^{**}p < 0.01$; $^{\dagger}p \leq 0.001$.

similar between groups while all blood pressure values were lower in TETRA compared to PARA (**Figure 1**).

Indices of LV structure and global function are presented in **Table 2**. Structure and global diastolic function was similar between groups, while global systolic function was reduced in TETRA compared to PARA including slower heart rates and smaller SV and $\dot{Q}$. Indices of LV mechanics are presented in **Table 3**. Basal Rot and RotR in both systole and diastole were higher in TETRA. The TETRA group also presented with higher circumferential ε (**Figure 2**) and diastolic SR at the mid and apical levels compared to PARA.

DISCUSSION

This is the first study to examine the influence of lesion level on resting LV structure, function and mechanics in Paralympic athletes with SCI. We observed no difference in LV dimensions or global diastolic function, while global systolic function was reduced in TETRA compared with PARA. Despite these observations, there were no indicators of LV mechanical dysfunction in the TETRA group, while PARA presented with attenuated systolic and diastolic mechanics. This observation may suggest a training induced improvement in mechanical efficiency in PARA that would increase their capacity to respond during an exercise bout.

The athletes included in this retrospective study were from two distinct sporting events. While we would consider any Paralympic athlete as highly trained, the nature of the training regiments for wheelchair rugby and alpine skiing are unique and incorporate different amounts of endurance and resistance exercise. While there is evidence in the able-bodied literature that endurance and resistance exercise training elicit differential cardiac adaptations (Spence et al., 2011), evidence from a cross-sectional examination of athletes with paraplegia found no differences in LV dimensions or global LV function between power-trained and endurance-trained athletes (Gates et al., 2002). Furthermore, endurance and resistance training in individuals with paraplegia has been shown to elicit similar improvements in peak oxygen uptake (Jacobs, 2009). Thus, it is unlikely that the differences observed between the TETRA and PARA groups are attributed to the differences in training modality. Both groups had similar weekly volumes of exercise training, and had been engaging in international competition for a similar duration. Additionally, the global LV indices observed in PARA athletes are comparable to values recently reported by De Rossi et al. (2014) in their examination of endurance trained athletes with paraplegia (i.e., wheelchair basketball, handball and tennis). While the training regiments for wheelchair rugby and alpine skiing are different, they do incorporate both aerobic and resistance exercises, which based on the literature to date, do not appear to elicit specific cardiac adaptations in individuals with SCI.

Exercise training may exert differential effects on global LV function depending on lesion level. De Rossi et al. (2014) demonstrated increased global diastolic function in athletes with tetraplegia and paraplegia relative to their sedentary peers with tetraplegia and paraplegia. However, SV was reduced in both sedentary and athletic groups with tetraplegia and only improved in athletes with paraplegia relative to sedentary individuals with paraplegia. Findings from the present study are in support of lesion level dependent differences in global function. We observed no difference in global diastolic function

TABLE 2 | Indices of LV structure and global systolic and diastolic function.

Variable	TETRA	PARA	*P*-value	Cohen's *d*
STRUCTURE				
Aortic annulus diameter (cm)	2.26 ± 0.13	2.38 ± 0.15	0.118	0.85
LVID d (cm)	4.86 ± 0.40	4.92 ± 0.21	0.341	0.19
SWT d (cm)	0.91 ± 0.06	0.90 ± 0.10	0.869	0.12
PWT d (cm)	0.84 ± 0.05	0.83 ± 0.12	0.956	0.11
LVID s (cm)	3.24 ± 0.22	3.32 ± 0.43	0.635	0.23
SWT s (cm)	1.27 ± 0.05	1.18 ± 0.16	0.177	0.76
PWT s (cm)	1.20 ± 0.10	1.26 ± 0.10	0.215	0.60
RWT	0.34 ± 0.04	0.34 ± 0.05	0.789	0.00
LVM Index ($g \cdot m^{-2}$)	79.3 ± 10.1	75.8 ± 9.4	0.491	0.36
EDV (ml)	106 ± 9	117 ± 10	**0.036**	1.16
ESV (ml)	44 ± 3	46 ± 11	0.551	0.25
GLOBAL SYSTOLIC FUNCTION				
SV (ml)	62 ± 9	71 ± 6	**0.016**	1.18
Heart rate (bpm)	57 ± 11	71 ± 6	**0.008**	1.58
$\dot{Q}$ (L/min)	3.5 ± 0.6	5.0 ± 0.9	**0.002**	1.96
EF (%)	59 ± 4	61 ± 7	0.394	0.35
GLOBAL DIASTOLIC FUNCTION				
E (cm/s)	86 ± 12	84 ± 7	0.733	0.20
A (cm/s)	43 ± 6	47 ± 12	0.373	0.42
E/A	2.02 ± 0.18	1.90 ± 0.50	0.544	0.32
IVRT (ms)	81 ± 6	75 ± 14	0.326	0.56

Data are mean ± SD. A, late transmitral filling velocity; d, end-diastolic; E, early transmitral filling velocity; EDV, end-diastolic volume; EF, ejection fraction; ESV, end-systolic volume; IVRT, isovolumetric relaxation time; LVID, left ventricular internal diameter; LVM, left ventricular mass; PWT, posterior wall thickness $\dot{Q}$, cardiac output; RWT, relative wall thickness; s, end-systolic; SV, stroke volume; SWT, septal wall thickness. Bolded values in P-value column indicate significant between-group differences.

TABLE 3 | Peak systolic and diastolic LV mechanics.

Variable	TETRA	PARA	*P*-value	Cohen's *d*
PEAK (SYSTOLE)				
Basal Rot (degrees)	−7.3 ± 2.2	−4.4 ± 1.1	**0.005**	1.67
Apical Rot (degrees)	13.4 ± 3.3	14.4 ± 9.2	0.791	0.14
Twist (degrees)	19.5 ± 3.4	16.7 ± 10.3	0.527	0.37
ε_l (%)	−18 ± 3	−17 ± 2	0.344	0.39
ε_r (%)				
Basal Level	34 ± 11	30 ± 19	0.568	0.26
Mid Level	34 ± 16	32 ± 11	0.774	0.15
Apical Level	33 ± 17	13 ± 7	0.060	1.54
ε_C (%)				
Basal Level	−19 ± 7	−14 ± 5	0.147	0.82
Mid Level	−23 ± 4	−15 ± 6	**0.010**	1.57
Apical Level	−36 ± 10	−23 ± 5	**0.010**	1.64
Basal RotR ($degrees \cdot s^{-1}$)	−84 ± 26	−59 ± 21	**0.047**	1.06
Apical RotR ($degrees \cdot s^{-1}$)	91 ± 30	89 ± 28	0.874	0.07
Twist velocity ($degrees \cdot s^{-1}$)	129 ± 26	110 ± 31	0.218	0.66
SR (s^{-1})				
SR_l	−0.92 ± 0.20	−0.91 ± 0.18	0.904	0.05
SR_r basal	1.90 ± 0.35	1.87 ± 1.0	0.946	0.04
SR_r mid	1.40 ± 0.61	1.69 ± 0.34	0.268	0.59
SR_r apical	1.71 ± 0.76	1.06 ± 0.51	0.173	1.00
SR_C basal	−1.25 ± 0.34	−0.93 ± 0.35	0.083	0.93
SR_C mid	−1.27 ± 0.17	−1.04 ± 0.38	0.137	0.78
SR_C apical	−2.40 ± 1.13	−1.85 ± 0.25	0.487	0.67
PEAK (DIASTOLE)				
Basal RotR ($degrees \cdot s^{-1}$)	55 ± 18	33 ± 12	**0.013**	1.44
Apical RotR ($degrees \cdot s^{-1}$)	−78 ± 34	−85 ± 42	0.751	0.18
Untwisting velocity ($degrees \cdot s^{-1}$)	−107 ± 22	−84 ± 30	0.110	0.87
SR (s^{-1})				
SR_l	1.32 ± 0.32	1.15 ± 0.16	0.246	0.67
SR_r basal	−1.64 ± 0.56	−2.26 ± 1.38	0.273	0.59
SR_r mid	−2.00 ± 0.80	−2.44 ± 1.38	0.455	0.39
SR_r apical	−1.97 ± 1.19	−2.16 ± 1.61	0.840	0.13
SR_C basal	1.29 ± 0.32	1.31 ± 0.51	0.931	0.05
SR_C mid	1.90 ± 0.63	1.20 ± 0.51	**0.028**	1.22
SR_C apical	3.03 ± 0.71	1.99 ± 0.69	**0.009**	1.49

Data are mean ± SD. c, circumferential; ε, strain; l, longitudinal; r, radial; Rot, rotation; RotR, rotation rate; SR, strain rate. Bolded values in P-value column indicate significant between-group differences.

between TETRA and PARA, while SV and $\dot{Q}$ were lower in TETRA compared to PARA. The reduction in SV and subsequently $\dot{Q}$ are likely attributed to a smaller EDV given ESV was similar between groups, which implies reduced cardiac filling was likely responsible for the attenuated SV. LV dimensions were similar between groups; therefore the observed reduction in EDV is unlikely attributed to a smaller ventricle. While no investigations have directly compared LV dimensions between TETRA and PARA athletes, Kessler et al. (1986) observed smaller dimensions in sedentary individuals with tetraplegia compared to sedentary individuals with paraplegia. A more recent investigation using a pooled sample of athletes with tetraplegia and paraplegia observed no difference in LV dimensions when compared to able-bodied individuals and larger dimensions when compared to sedentary individuals with tetraplegia and paraplegia (De Rossi et al., 2014). Therefore, our observation of similar dimensions between the two groups is not unusual, and is likely attributed to the training status of our sample.

Contrary to the global systolic indices, systolic mechanics appear to be higher in TETRA relative to PARA. This includes higher basal Rot and circumferential ε at the level of the papillary muscle and apex, and a faster basal RotR. The ε-values reported in our TETRA sample are similar to values reported in the able-bodied literature (Yingchoncharoen et al., 2013). It is, therefore, unlikely that systolic mechanics are enhanced in the TETRA group, but rather the values in PARA group are lower. Head-down bed rest, which typically mirrors the

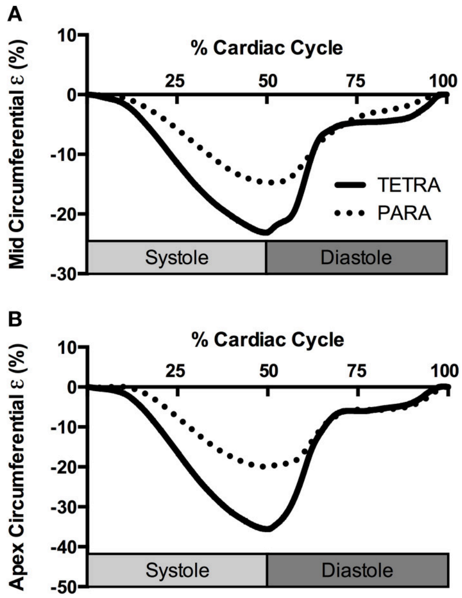

FIGURE 2 | Group averaged circumferential strain (ε) traces at the level of the papillary muscle (A) and apex (B) for TETRA (solid line) and PARA (dotted line), normalized to percentage of the cardiac cycle.

cardiac adaptations following SCI, has been shown to elicit a reduction in SV, ε and systolic SR in able-bodied individuals (Kozakova et al., 2011; Scott et al., 2014). The observation of preserved systolic mechanics and reduced SV in TETRA was therefore unanticipated, and may be attributed to their hemodynamic state. In particular, reductions in afterload have been shown to increase systolic mechanics (Burns et al., 2010); therefore the lower blood pressure in our TETRA group may have created an environment where systolic mechanics can be maintained despite reductions in loading. Hypotension has consistently been demonstrated in sedentary (West et al., 2012b) and athletic (West et al., 2014) individuals with tetraplegia, and is attributed to the disruption of descending sympathetic input to the vasculature.

The observation of lower systolic and diastolic mechanics in our PARA group may be indicative of two scenarios: LV dysfunction/disease or a "resetting" of resting mechanics. Lower resting LV mechanics have been documented in clinical populations (Leung and Ng, 2010); however, we believe our finding is not pathological since global LV diastolic and systolic function (E/A and EF) were in a normal range (Lang et al., 2005; Dalen et al., 2010). The "resetting" of LV mechanics to lower resting values have been observed in high performance able-bodied athletes (Richand et al., 2007; Nottin et al., 2008), and while the mechanisms behind this adaptation are presently unknown, it is believed to create a large range for cardiovascular adjustments during exercise (Nottin et al., 2008). Both systolic and diastolic mechanics are increased during exercise in able-bodied individuals (Notomi et al., 2008; Stohr et al., 2011; Lee et al., 2012; Hensel et al., 2014). In addition to the obvious association between elevations in SV and ε, the augmentation of diastolic mechanics during exercise is key to promoting efficient diastolic filling, which in turn supports the elevations in SV (Notomi et al., 2008). It is presently unknown if exercise training in individuals with SCI elicits similar changes in LV mechanics as high-performance able-bodied athletes. Given cross-sectional evidence that athletes with paraplegia experience more favorable LV adaptations than athletes with tetraplegia (De Rossi et al., 2014), we postulate that involvement in high-performance sports and its associated large volume of exercise training may be capable of modifying LV mechanics to a lower resting value in PARA. Whether this modification has any impact on LV performance during exercise remains to be determined since LV performance *per se* has never been investigated during exercise post-SCI. Indeed, the few studies that have investigated the cardiac response to exercise in SCI have focused on measures of SV and report conflicting results, with some studies reporting increases in SV during arm-exercise (Davis et al., 1987; Hopman et al., 1992; Raymond et al., 1999), and others reporting no change (Davis and Shephard, 1988; Hopman et al., 1993, 1998; Raymond et al., 1999, 2001; Theisen et al., 2001). The discrepancy in these observations may be attributed to differences in the method used to estimate SV (ex. CO_2 rebreathing, echocardiography, or impedance cardiography) and the acute exercise protocol (sub-maximal vs. maximal arm exercise). Nevertheless, the absence of apparent LV mechanical dysfunction at rest in high-performance athletes with SCI in the present study suggests any abnormal SV responses during exercise are likely attributable to reduced loading.

LIMITATIONS

The absence of an able-bodied control group makes it difficult to draw conclusions regarding the direction of the LV mechanics. While global LV outcomes suggest the PARA group is free from LV dysfunction, it is possible that the attenuated LV mechanics values are indicative of impending cardiac dysfunction. Conversely, the TETRA group may have experienced an "enhancement" of LV mechanics to accommodate the cardiovascular requirements of their endurance sport. In order to fully understand the influence of lesion level of LV mechanics in Paralympic athletes, future research should attempt to evaluate athletes in similar sporting events, especially sports in which TETRA and PARA athletes are in competition against each other (ex. wheelchair basketball or Para-cycling team relays).

CONCLUSION

In conclusion, high-performance athletes with TETRA and PARA experience differential changes in LV indices. While we would speculate these changes are attributed to lesion level, they may also be influenced by their training modality. TETRA athletes can be characterized as having normal diastolic function but reduced systolic function, an observation likely attributed to impaired venous return. On the other hand, PARA athletes demonstrated lower values for LV mechanics yet had no evidence of global systolic or diastolic dysfunction. We speculate this observation may be attributed to training induced improvements in LV efficiency rather than indicative of inherent LV dysfunction.

AUTHOR CONTRIBUTIONS

KC—Conception of the work; data acquisition, analysis and interpretation; drafting and revising manuscript; approved final copy; and agrees to be accountable. CW—Conception of the work; data acquisition and interpretation; critically revised manuscript; approved final copy; and agrees to be accountable. AK—Conception of the work; data acquisition and interpretation; revising manuscript; approved final copy; and agrees to be accountable.

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PERSPECTIVE
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Perspective: Does Laboratory-Based Maximal Incremental Exercise Testing Elicit Maximum Physiological Responses in Highly-Trained Athletes with Cervical Spinal Cord Injury?

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The physiological assessment of highly-trained athletes is a cornerstone of many scientific support programs. In the present article, we provide original data followed by our perspective on the topic of laboratory-based incremental exercise testing in elite athletes with cervical spinal cord injury. We retrospectively reviewed our data on Great Britain Wheelchair Rugby athletes collected during the last two Paralympic cycles. We extracted and compared peak cardiometabolic (heart rate and blood lactate) responses between a standard laboratory-based incremental exercise test on a treadmill and two different maximal field tests (4 min and 40 min maximal push). In the nine athletes studied, both field tests elicited higher peak responses than the laboratory-based test. The present data imply that laboratory-based incremental protocols preclude the attainment of true peak cardiometabolic responses. This may be due to the different locomotor patterns required to sustain wheelchair propulsion during treadmill exercise or that maximal incremental treadmill protocols only require individuals to exercise at or near maximal exhaustion for a relatively short period of time. We acknowledge that both field- and laboratory-based testing have respective merits and pitfalls and suggest that the choice of test be dictated by the question at hand: if true peak responses are required then field-based testing is warranted, whereas laboratory-based testing may be more appropriate for obtaining cardiometabolic responses across a range of standardized exercise intensities.

Keywords: field tests, aerobic exercise, tetraplegia, cardiovascular system

INTRODUCTION

With the advancement of the Paralympic movement over the last 10–20 years the physiological monitoring of Paralympic athletes, including maximal aerobic and anaerobic exercise testing in both the field and laboratory, is now common practice (Goosey-Tolfrey, 2010). Technological advances in treadmill and wheelchair roller design permit externally valid assessments of physiological parameters during wheelchair propulsion under carefully controlled laboratory conditions. The majority of studies that have assessed maximal exercise responses of elite athletes with cervical spinal cord injury (SCI) during wheelchair propulsion on a treadmill, including our own, have reported peak oxygen uptake values in the range of 0.8–1.6 L/min and maximal heart rate (HR) values in the range of 100–140 bpm, although the mean is typically around 120 bpm (Coutts et al., 1983; Wicks et al., 1983; Lasko-McCarthey and Davis, 1991; Schmid et al., 1998; Leicht et al., 2013; Paulson et al., 2013; West et al., 2014a). The dogmatic pathophysiological explanation for these relatively low values is purported to be loss of descending sympathetic cardiac control along with an attenuated catecholamine response and a decreased active muscle mass (Figoni, 1993; Hopman et al., 1998).

Recently, we reported that field-based exercise testing in elite wheelchair rugby athletes with cervical SCI elicits HR values of 140–180 bpm (West et al., 2014b). These values far exceed those collected in the same athletes during arm-crank ergometry and wheelchair propulsion on a treadmill (West et al., 2013). Further investigation revealed that a large number of these elite tetraplegic athletes (both rugby and hand-cycling) exhibit sparing of descending sympathetic fibers in the face of a motor and sensory compete injury (i.e., autonomic incomplete injury; Currie et al., 2015). Thus, it appears that factors other than disrupted descending sympathetic control may preclude the attainment of true peak physiological responses in the laboratory. To date, no study has specifically compared peak cardiometabolic responses between maximal field- and laboratory-based wheelchair exercise tests in highly-trained athletes with cervical SCI.

We have been collecting physiological data leading into the Beijing and London Paralympic cycles on the Great Britain wheelchair rugby squad. During this time, we have conducted a variety of field- and laboratory-based exercise tests on the same group of athletes, but have never directly compared peak physiological variables between laboratory- and field-based maximal wheelchair exercise tests. In the present study, we retrospectively reviewed our data and compared peak physiological responses between a standard incremental laboratory-based wheelchair treadmill test and two different field testing protocols.

MATERIALS AND METHODS

Data Included

Nine male wheelchair rugby athletes with motor complete traumatic cervical SCI (C6-C7; 28.6 ± 2.6 year, 71 ± 16 kg, 1.80 ± 0.10 m, 7.1 ± 3.7 year post injury) were included into the study. The data were part of other research studies, some of which have been published elsewhere (8 of the present participants' 4 min push data, West et al., 2014b, and 8 of the present participants' maximal incremental test data Leicht et al., 2013; West et al., 2014a). All of the studies were approved by the University research ethics committee. In addition to peak physiological values, we extracted participant demographics and their International Wheelchair Rugby Federation (IWRF) classifications at the time of testing.

Study Design

Data were extracted for three different maximal exercise trials. Trial 1 consisted of a maximal 4 min field-based exercise test on a 110 m long indoor athletics track with a wide turnaround area at each end. Trial 2 ($n = 7$) consisted of a maximal 40 min field-based exercise test in a sports hall. Trial 3 consisted of an incremental wheelchair propulsion test on a treadmill. Athletes were thoroughly familiar with the testing protocols. Each trial was completed with athletes exercising in their own rugby wheelchair with regular strapping and gloves. Prior to each trial, athletes received the same standardized pre-test instructions, namely to void their bladder to minimize the chance of autonomic dysreflexia, and to avoid strenuous exercise for 24 h, caffeine for 4 h and food for 2 h prior to assessment. Trials 1 and 3 were performed between 1 and 8 months apart. Trial 3 was performed approximately 1 month after trial 2.

Experimental Trials

Trial 1

Athletes completed a maximal 4 min push on a 110 m synthetic indoor running track with minimal rolling resistance. Athletes pushed maximally in a straight line and were only required to turn at each end of the track where a wide area was provided to facilitate the maintenance of high speeds. Athletes were encouraged to cover as much distance as they could during 4 min. Environmental temperature ranged from 18.2 to 19.4°C, humidity from 40 to 42%, and barometric pressure from 737 to 739 mmHg.

Trial 2

Athletes completed a maximal 40 min push around a large sports hall. The push consisted of: a straight 40 m push along the first side, a 30 m zigzag push along the second side, a straight 40 m push along the third side and a 30 m backwards zigzag push along the final side. The athletes were encouraged to cover as much distance as possible during 40 min.

Trial 3

Athletes completed a maximal incremental wheelchair test to volitional exhaustion on a motorized treadmill with a moving rail to prevent falls (Saturn 300/125r, HP Cosmos, Nussdorf-Traunstein, Germany). Treadmill speed was kept constant and ranged from 2.0 to 2.8 m·s^{-1}, depending on IWRF classification and previous performance during incremental treadmill exercise. The gradient was set at 1% and was increased gradually by 0.1–0.2% every 40 s. The maximal test was terminated when athletes were unable to maintain the treadmill speed, i.e., when they touched the spring of the safety rail for a third time. Standardized verbal encouragement was given throughout the test and push rate was freely chosen. All athletes underwent a standardized warm up as described elsewhere (Leicht et al., 2013). Environmental temperature ranged from 20.2 to 23.7°C, humidity from 27 to 61%, and barometric pressure from 741 to 758 mmHg.

Methods of Measurement

Heart Rate

For trials 1 and 2, HR was measured beat-by-beat using a team system (Suunto team POD, Suunto Oy, Vantaa, Finland). For trial 3, HR was measured beat-by-beat using an individual HR transmitter coupled to a receiver (Polar Vantage NV, Polar Electro Oy, Kempele, Finland). HR_{peak} was defined for all trials as the highest HR averaged over a 5 s rolling window.

Metabolic

In trials 1 and 3, lactate concentration in haemolysed whole blood ($[L_a^-]_B$) was assessed at rest and immediately post-exercise using an automated analyser [Biosen C-line Sport, EKF Diagnostics, Barleben, Germany (Trial 1) or YSI 1500 SPORT, YSI Incorporated, Yellow Springs, OH, USA (Trial 2)]. In trial 3, oxygen uptake ($\dot{V}o_2$) was assessed using an online system (MetaLyzer 3B, Cortex Biophysik GmbH, Leipzig, Germany). $\dot{V}o_{2peak}$ was defined as the highest $\dot{V}o_2$ over a 30 s rolling window.

Statistics

Between-trial differences in physiological outcomes were assessed using either a one-way repeated-measures ANOVA (HR) or paired sample *t*-test ($[L_a^-]_B$). Relationships between peak physiological indices from field- and laboratory-based testing were assessed using Pearson's product moment correlation. Statistical analyses were carried out using STATA v12.0, with significance set at $p < 0.05$.

RESULTS

Individual athlete data for all trials are reported in **Table 1**. HR_{peak} was different between trials ($p = 0.0035$) and *post-hoc* testing revealed HR_{peak} was higher in trial 1 and trial 2 vs. trial 3 ($p = 0.008$ and $p = 0.048$, respectively). There was no difference in HR_{peak} between trial 1 and trial 2 ($p = 0.29$), and the values during both field-based exercise tests were strongly correlated ($r = 0.88$, $p = 0.002$; **Figure 1B**). There were no significant correlations between HR_{peak} achieved during the field-based tests and HR_{peak} achieved in the laboratory ($r = 0.56$–0.61, $p > 0.08$). During field-based testing, HR increased rapidly at the onset of exercise in all athletes and remained elevated throughout (**Figure 1C**). Blood lactate concentration was higher during trial 1 vs. trial 3 ($p = 0.010$; **Figure 1D**).

PERSPECTIVE

For the first time we report that peak heart rate and blood lactate concentration during maximal field-based exercise testing exceed values attained during maximal incremental laboratory-based wheelchair exercise on a treadmill. This suggests that incremental exercise testing in the laboratory, at least using the protocol described herein, does not elicit true peak cardiometabolic responses in highly-trained wheelchair rugby athletes with cervical SCI.

The HR values elicited during our laboratory-based treadmill test typify those reported in previous studies that have used wheelchair ergometry or treadmill exercise to investigate peak exercise responses in tetraplegic athletes (Coutts et al., 1983; Wicks et al., 1983; Lasko-McCarthey and Davis, 1991; Schmid et al., 1998; Paulson et al., 2013; Leicht et al., 2014; West et al., 2014a). An interesting observation from the two field-based trials compared to the laboratory trial was the push technique utilized. In the field-based trial, the athletes favored three small pushes followed by a short break for deep inhalation. During the push-phase many athletes also tended to "lean" into the abdominal strapping used to secure them into their sports chair. Anecdotally, athletes report that this push technique allows them to produce more force (power) with each push stroke. Leaning into the chest strapping likely compresses the abdomen and impairs diaphragmatic descent. In turn, this would be expected to reduce the force generating capacity of the diaphragm and may explain why athletes had to pause every three strokes for

TABLE 1 | Individual peak physiological responses.

			Trial 1		Trial 2	Trial 3				
	Level	IWRF	HR (bpm)	$[L_a^-]_B$ (mmol/L)	HR(bpm)	Duration (min)	HR (bpm)	$[L_a^-]_B$ (mmol/L)	$\dot{V}o_2$ (L/min)	$\dot{V}o_2$ (ml/kg/min)
1	C6	0.5	126	5.6	129	5.83	122	4.2	1.03	18.2
2	C7	1	146	5.5	Not collected	6.66	115	5.8	0.85	17.9
3	C6	1.5	142	6.9	Not collected	16.66	125	4.4	1.45	21.0
4	C7	2	169	5.3	157	13.33	137	5.2	1.47	23.6
5	C7	2.5	172	6.4	171	15.00	178	4.6	2.30	33.7
6	C7	2.5	135	7.2	139	9.41	130	5.9	1.42	21.8
7	C7	2.5	165	8.8	169	9.25	127	5.6	1.87	27.3
8	C7	2.5	148	5.5	150	7.86	119	5.3	1.98	27.3
9	C6	2.5	147	7.5	154	4.83	119	4.1	1.82	18.9
MEAN			150*	6.5*	153*	9.87	130	5.1	1.57	23.3
SD			16	1.2	15	4.19	19	0.7	0.46	5.3

*Trial 1: 4 min field-based maximal exercise test; trial 2: 40 min field-based maximal exercise test; trial 3: maximal laboratory-based incremental wheelchair propulsion test on a treadmill; IWRF, International Wheelchair Rugby Federation; HR, heart rate; $[L_a^-]_B$, blood lactate concentration; $\dot{V}o_2$, oxygen uptake. *Significantly different from trial 3 ($p < 0.05$).*

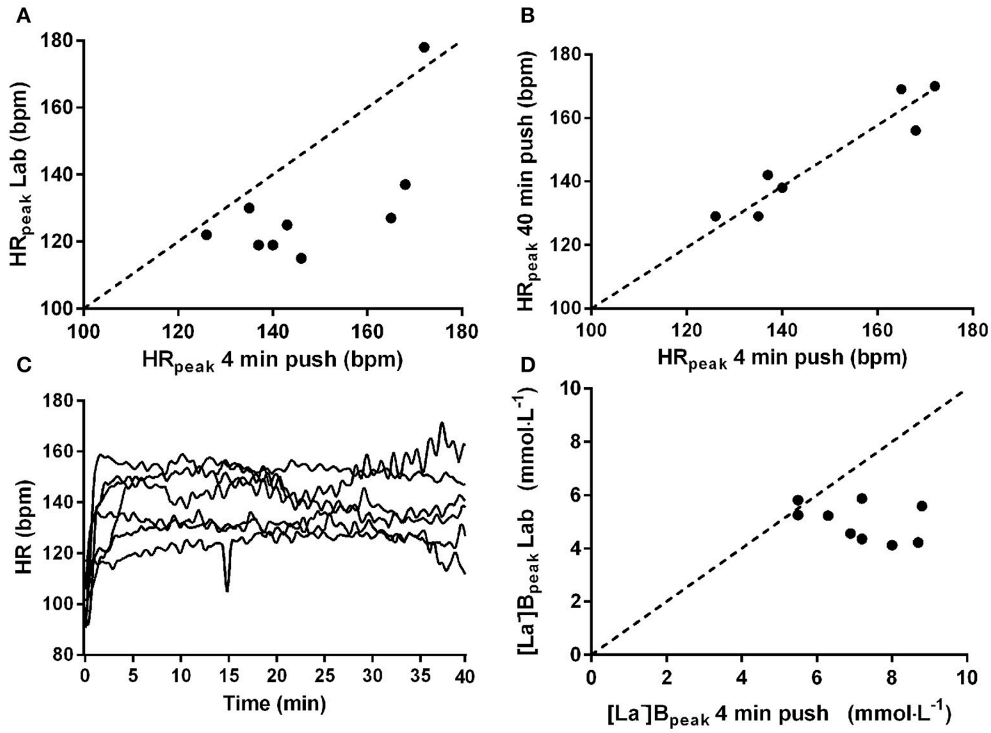

FIGURE 1 | Association between field- and laboratory-based peak heart rate (HR_{peak}; A). Association between HR_{peak} during two different field-based assessments **(B)**. Individual HR responses to prolonged field-based exercise **(C)**. Associations between field- and laboratory based peak blood lactate concentration ($[L_a^-]_B$peak; **D**).

deep inhalation. On a treadmill, this technique is impossible to replicate as the wheelchair would roll to the back of the treadmill if pushing were to cease, thereby terminating the test. Thus, different push patterns may have been responsible for the lower cardiometabolic responses during treadmill exercise. To our knowledge, no study has directly compared maximal push mechanics between laboratory- and field-based testing in tetraplegic athletes. In able-bodied individuals, recent research suggests that current treadmill wheelchair propulsion protocols are unable to accurately reproduce the forces applied during field-based (i.e., over ground) propulsion (Mason et al., 2014). It is not yet clear whether these findings translate to highly-trained athletes with cervical SCI. An interesting observation was that the heart rate in three athletes (#1, 5, and 6) was similar between field- and laboratory-based testing. It is unclear why this was the case for these three athletes only. One explanation could be that these three athletes utilize a push technique that can easily be replicated in both the laboratory and field conditions. The idea of "transferability" of different propulsion techniques between laboratory and field settings has to our knowledge never been investigated in elite tetraplegic athletes but may provide important insight as to why some athletes can achieve similar maximal exercise responses in both the laboratory and field settings whilst others cannot.

Lower laboratory-based HR responses may also be a consequence of the inferior metabolic demand of incremental laboratory exercise compared to high-intensity constant load exercise. Increased acidosis associated with a higher blood lactate concentration in the field would be expected to drive greater peripheral and central chemoreceptor activation and augment central sympathetic outflow (Somers et al., 1989). In cervical SCI athletes with autonomic incomplete injuries, central sympathetic stimulation would elicit a direct and indirect (catecholaminergic) inotropic response. In autonomic complete athletes, it is possible that the sub-lesional sympathetic circuitry can still be activated from chemoreflexes via the pulmonary stretch receptors. Unfortunately, no studies have examined the interactions between chemoreceptor activation and vasomotor outflow after SCI. Moreover, while circulating catecholamines increase marginally during wheelchair ergometry in untrained cervical SCI (Schmid et al., 1998), no study has investigated the catecholaminergic response to field-based exercise. In our opinion, such studies are critical to advance our understanding of the physiological responses to exercise in athletes with cervical SCI.

The field-based measures of physiological performance reported herein are relatively crude, but are typical of those collected by researchers and/or sports physiologists during sports-specific field-based testing. We are yet to conduct field-based assessments of peak oxygen uptake using a portable metabolic cart. Such measures are the next step to confirm that peak cardiometabolic responses during laboratory-based exercise testing are indeed inferior to those obtained in response to field-based exercise testing. Nevertheless, we measured HR values that were considerably higher during both short- and long-duration field-based exercise compared to laboratory testing. Thus, future research should investigate why field-based exercise testing provides superior cardiometabolic responses (at least for most athletes) and seek to optimize maximal treadmill testing protocols. Until such studies are carried out we suggest that sports physiologists working in applied settings continue to use both laboratory and field-based testing and that the choice of test should be dictated by the question at hand as well as the availability of resources. Field-based maximal exercise testing provides superior external validity, the ability to accommodate large groups, and the free choice of push mechanics. Conversely, a laboratory-based exercise test allows for a more detailed physiological assessment under carefully controlled conditions with respect to protocol, temperature, and humidity.

CONSIDERATIONS

We chose to use laboratory-based wheelchair propulsion to investigate peak responses because it is the most externally valid laboratory modality and because peak responses are slightly higher during wheelchair propulsion than during other laboratory modalities such as arm-crank exercise (Gass and Camp, 1984). Our decision to increment grade only was based on previous research that reported no significant differences in peak responses between treadmill protocols which increment speed, gradient, or a combination of both (Hartung et al., 1993). Finally, our participants were highly motivated wheelchair rugby athletes who were well versed in maximal incremental exercise testing. We are confident therefore that the laboratory testing environment was conducive to eliciting peak responses in the laboratory. That we measured similar HR_{peak} values during both field tests suggests that higher values in the field are indeed a real phenomenon and not an anomaly. Moreover, the mean values reported in the present study are almost identical to our previous field-based assessments of Paralympic hand-cyclists with cervical SCI (West et al., 2015). Finally, environmental conditions were similar between Trial 1 and 3 (not noted for Trial 2), suggesting differences in environmental conditions do not explain between-test differences in physiological responses. Thus, we are confident that the data presented herein represent true differences in physiological responses between laboratory- and field-based exercise testing.

CONCLUDING REMARKS

The present data imply that peak physiological indices measured in response to maximal incremental exercise testing in the laboratory using current protocols may not represent true maximal responses for athletes with tetraplegia. We suggest that future studies should investigate why field-based exercise testing provides superior cardiometabolic responses and seek to optimize maximal treadmill testing protocols to probe true peak responses in elite athletes with cervical SCI.

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ORIGINAL RESEARCH
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Effect of Three Different Grip Angles on Physiological Parameters During Laboratory Handcycling Test in Able-Bodied Participants

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Introduction: Handcycling is a relatively new wheelchair sport that has gained increased popularity for people with lower limb disabilities. The aim of this study was to examine the effect of three different grip positions on physical parameters during handcycling in a laboratory setting.

Methods: Twenty one able-bodied participants performed three maximum incremental handcycling tests until exhaustion, each with a different grip angle. The angle between the grip and the crank was randomly set at 90° (horizontal), 0° (vertical), or 10° (diagonal). The initial load was 20 W and increased by 20 W each 5 min. In addition, participants performed a 20 s maximum effort.

Results: The relative peak functional performance (W/kg), peak heart rate (bpm), associated lactate concentrations (mmol/l) and peak oxygen uptake per kilogram body weight (ml.min^{-1}.kg^{-1}) for the different grip positions during the stage test were: (a) Horizontal: 1.43 ± 0.21 W/kg, 170.14 ± 12.81 bpm, 9.54 ± 1.93 mmol/l, 30.86 ± 4.57 ml/kg; (b) Vertical: 1.38 ± 0.20 W/kg, 171.81 ± 13.87 bpm, 9.91 ± 2.29 mmol/l, 29.75 ± 5.13 ml/kg; (c) Diagonal: 1.40 ± 0.22 W/kg, 169.19 ± 13.31 bpm, 9.34 ± 2.36 mmol/l, 29.39 ± 4.70 ml/kg. Statistically significant ($p < 0.05$) differences could only be found for lactate concentration between the vertical grip position and the other grips during submaximal handcycling.

Conclusion: The orientation of three different grip angles made no difference to the peak load achieved during an incremental handcycling test and a 20 s maximum effort. At submaximal load, higher lactate concentrations were found when the vertical grip position was used, suggesting that this position may be less efficient than the alternative diagonal or horizontal grip positions.

Keywords: adapted physical activity, biomechanics, spinal cord injury

INTRODUCTION

Handcycling has opened a new world of mobilization for people who are restricted to a wheelchair, from both a health perspective (Abel et al., 2003a; Arnet et al., 2016) and for sports performance (Abel et al., 2006; Goosey-Tolfrey et al., 2006; de Groot et al., 2014). During the last 5 years, race performance has increased significantly with the adoption of elite athlete training approaches and technical developments concerning the handcycle itself. In comparison to wheelchair propulsion, handcycling has a higher mechanical efficiency (Abel et al., 2003a; Dallmeijer et al., 2004; Simmelink et al., 2015; Arnet et al., 2016), which gives the person restricted to a wheelchair the benefit of increased mobility. It has been postulated that regular engagement with handcycling will likely lead to fewer painful and debilitating overuse injuries (van der Woude et al., 2006; Arnet et al., 2014). Energy expenditure in handcycling is sufficient to offer protection against the development of secondary conditions such as cardiovascular disease (Abel et al., 2003a; van der Woude et al., 2013). As a relatively new device there have been a range of areas investigated to improve handcycle performance, such as the influence of back rest position, gear ratios (Faupin et al., 2008; Arnet et al., 2014). Whilst the efficiency of the athlete and handcycle as a complete system has been assessed, the influence of some key components within this system have not yet been quantified, such as the type or orientation of the hand grip.

As a mechanical device, the transmission of force from the athlete to the cycle plays a major role in handcycling performance. To better understand this interface between the athlete and the cycle, the influence of crank length (Goosey-Tolfrey et al., 2008; Krämer et al., 2009) and crank patterns (Verellen et al., 2004, 2008) on the transmission of forces has been investigated. In fine tuning this connection further, the configuration of cranking, either synchronous or asynchronous, has also been investigated (Hopman et al., 1995; Mossberg et al., 1999; Abel et al., 2003b; Dallmeijer et al., 2004; Goosey-Tolfrey and Sindall, 2007; van der Woude et al., 2008). To date the research on crank configurations has failed to address the critical question of hand-crank grip position. From a purely anatomical perspective, the musculoskeletal structure of the human forearm is a significant determinant of the ergonomics of the wrist, with the maximum generation of force found when the wrist is orientated near maximum flexion (Morse et al., 2006; Khan et al., 2009). Due to their disability, the users of a handcycle often have some degree of movement limitation in their forearm, therefore the optimisation of grip position for these athletes is of great importance (Bressel et al., 2001). In practice, disabled athletes commonly self-experiment with different grip angels and different grip forms. To investigate the optimal grip-crank interface, the aim of this study was to examine the effect of three different grip angles on the physiological responses to incremental and maximal handcycling in a laboratory setting. The hypothesis herby is that altering the grip orientation, and therefore altering the muscle length and specific load applied to the forearm and upper muscles, will result in changes change in power generated as well as changes in physiological reactions at submaximal and maximal load.

METHODS

Participants

Twenty-one participants (15 male and six female; age 27 ± 5 years, height 178.0 ± 11.9 cm, weight 74.7 ± 13.3 kg) performed three stage tests until exhaustion with different grip angles. The participants were able-bodied and with a good training status of the upper extremity (active athletes in swimming and triathlon).

This study was carried out in accordance with the recommendations of guidelines of the International Committee of Medical Journal Editors. All subjects gave written informed consent in accordance with the Declaration of Helsinki. All investigations were approved by the German Sports University ethical advisory committee.

Experimental Overview

For all tests, participants sat in an arm-power race handcycle (Sopur Shark, Sunrisemedical Germany) connected to an ergometer (Cyclus II, Richter; Germany). The crank length was 175 mm, backrest angle approximately 45° adapted to the participants to avoid full elbow extension during crank revolutions. Crank housing position was set on a horizontal line to shoulder angle, crank configuration synchronous. The Cyclus II ergometer has been validated as an accurate measure of handcycling work load (Reiser et al., 2000). The angle between the grip and the crank was set in one of three configurations (see **Figure 1**), (a) 90° (horizontal = H), (b) 0° (vertical = V) and (c) 10°with respect to the vertical (i.e., diagonal, common way of cranking = D). Participants conducted an incremental test and a 20-s peak force test. The 20-s peak test was carried out after the incremental test und separated by 2 h. Tests were repeated three times using each of the grip configurations, in a random order, and each testing session was separated by a 3-day recovery period.

Incremental Test Protocol

After a standardized warm up period, the participants commenced hand cycling using one of the defined grip positions. Cycling cadence was freely chosen above 50 rpm. The initial load during test was 20 W and increased by 20 W every 5 min until the load where the 50 rpm cadence was not able to be maintained.

Expired air was collected continuously (ZAN 600, ZAN, Germany) during exercise for the assessment of oxygen consumption. Immediately before every test session, gas analyzers were calibrated with known reference gas mixtures (room air and a standard certified commercial gas preparation). The expiratory airflow volume was calibrated using a 1.0-l syringe. Blood samples to determine lactate concentrations were taken from the earlobe during the last 30 s of each stage (Biosen C, Eppendorf, Germany). Heart rate was monitored continuously (Polar X-Trainer, Polar, Finland).

Data Analysis

The descriptive mean and standard deviations for each of the measures of work, heart rate, blood lactate, and oxygen consumption were calculated using STATISTICA for Windows Version 7.1 F (StatSoft Inc, Tulsa, USA). An analysis of variance

FIGURE 1 | Angle between the grip and the crank (A) 90° (horizontal) (B) 0° (vertical) (C) 10° (diagonal).

TABLE 1 | Physiological values at peak load during the stage test.

	Horizontal	Vertical	Diagonal
Relative work load (W/kg)	1.43 ± 0.21	1.38 ± 0.20	1.40 ± 0.22
Heart rate (bpm)	170.14 ± 12.81	171.81 ± 13.87	169.19 ± 13.31
Lactate (mmol/l)	9.54 ± 1.93	9.91 ± 2.29	9.34 ± 2.36
Relative oxygen uptake (ml/kg)	30.86 ± 4.57	29.75 ± 5.13	29.39 ± 4.70

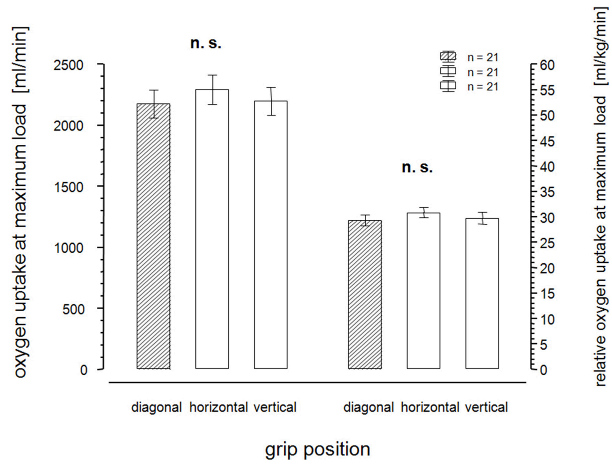

FIGURE 2 | Absolute and relative oxygen uptake at maximum load.

with repeated measurements for submaximal and peak values was used to determine the presence of TIME and GRIP effects for heart rate, lactate and VO_{2peak}. *Post-hoc* (least significant difference Test LSD) analysis was performed where there were significant main effects and interactions to determine the precise location of differences or changes. A *P*-value less than 0.05 was considered significant.

RESULTS

The peak functional performance (W/kg), peak heart rate (bpm), the associated lactate concentrations (mmol/l), and peak oxygen uptake per kilogram body weight (ml/kg) for the three different grip positions during handcyling are shown in **Table 1**.

As shown in **Figure 2**, there were no significant differences for peak oxygen uptake between the three grip positions during the incremental test. There were also no differences between the three grip positions for the other peak variables during handcycling, including functional performance, heart rate and blood lactate. **Figure 3** shows the lactate concentrations at defined submaximal work loads of 20, 60, and 100 W during the incremental test watts. There was a statistically significant difference between the vertical grip position and the other grips at 60 and 100 W.

Peak and average data for each of the variables during the 20 s all out test are shown in **Table 2**. No significant differences were found between the three gips positions.

DISCUSSION

The aim of this study was to examine the effect of three different grip angles on functional performance and associated physiological variables during handcycling. To the authors' knowledge, this aspect of handcycling has not been previously investigated.

While absolute an relative oxygen uptake tended to be lower at submaximal and peak workloads when the diagonal grip orientation was used, this was not statistically significant. Nonetheless, small reductions in oxygen uptake during laboratory tests may translate into important and significant improvements in economy during longer endurance activities such as a handcycling road race (Fischer et al., 2015). This time dependant relationship between work load and oxygen uptake has been identified in other studies (Verellen et al., 2004).

An unexpected finding was the higher blood lactate concentration during submaximal (60 and 100 W) handcycling when the vertical grip was used compared with both the diagonal and horizontal grips. As it is unlikely that lactate clearance would be different between the three test conditions (Heck et al., 1985; Mader, 2003), this elevation in lactate with the vertical grip indicates that there is likely to be a greater reliance on anaerobic metabolism by the working muscles. As these changes are unique to the vertical grip position, a plausible hypothesis could be that the vertical position requires increased static work, throughout the entire pedal stroke, to fix the hand at the handlebar. As sweat production, and the associated grip instability, increases with exercise intensity and time, this is likely to lead to further increases in static work and a greater reliance on local anaerobic metabolism. It is likely that this explains why many athletes avoid

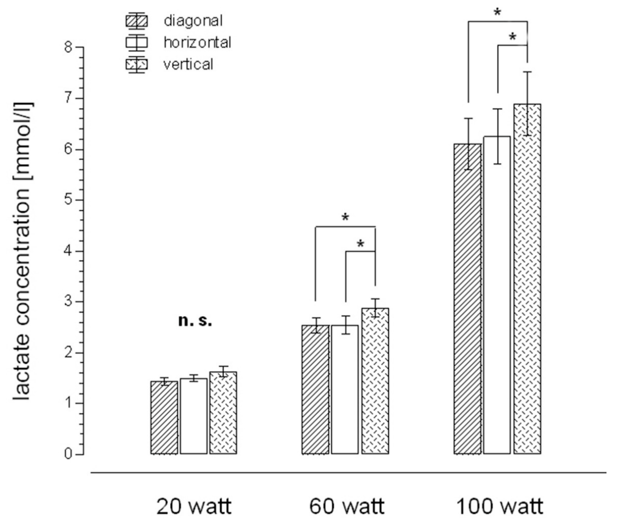

FIGURE 3 | Lactate concentrations at defined work loads of 20, 60, and 100 W for different grip angles. *Significant.

TABLE 2 | Peak and mean work load during the 20 s test.

	Horizontal	Vertical	Diagonal
Peak load (W)	589.73 ± 190.78	581.52 ± 188.24	583.67 ± 211.75
Relative peak load (W/kg)	7.74 ± 1.51	7.64 ± 1.59	7.59 ± 1.76
Mean load 20 s. (W)	350.17 ± 125.75	341.97 ± 116.18	344.02 ± 128.35
Mean relative load 20 s. (W/kg)	4.57 ± 1.08	4.48 ± 0.98	4.47 ± 1.10

using the vertical grip in practice, and instead adopt a grip with some degree of horizontal orientation.

In the present study a full 90° grip range was explored to ascertain the most appropriate orientation of the hand-crank grip. This complete range of movement was considered necessary, as previous cycling studies on crank length for example only considered small increments of change (Martin and Spirduso, 2001). Despite this maximum change in the range of motion of the grip orientation, there were no significant differences in force between the vertical, diagonal, and horizontal grip positions. The hypothesis that altering the grip orientation, and therefore altering the muscle length and specific load applied to the forearm and upper muscles, would result in a change in power generated as well as in efficiency related values was not supported. Based on the similar oxygen uptake and heart rate measures during each of the tests, the economy of the three different grip orientations showed no difference.

Training with the optimal hand-crank orientation is essential for efficiency of movement, performance and the prevention of overuse risks (Webborn and Van de Vliet, 2012; Arnet et al., 2014). As the economy of movement when handcycling with the diagonal grip was only slightly, and non-significantly, higher than the other grip orientations for the able-bodied population, it would also seem important to consider comfort when setting up the handcycle, particularly for individuals with a loss of lower limb function. Depending on the unique and individual anatomy and movement restrictions of the athlete with a disability, the optimal handcycle setup and grip orientation may alter significantly form individual to individual.

Limitations of the Study

The testing was done in a stationary laboratory situation using the Cyclus II ergometer. The absent of a need or possibility to steer the handcycling as well as the able-bodied participant with limited handcycling experience might have influenced test results. This restricts the transferability of the test results onto athletes with spinal cord injuries or other disabilities. A real competitive test setup during a handcycling race, including participants with disabilities would have simulated this more significantly, but tests like that are more or less impossible to be conducted.

Nevertheless, as all grip angles were tested under the same laboratory situation, the results allow claiming relevance for handcycling athletes.

CONCLUSION

In the present study there were no differences between three different grip positions (horizontal, vertical, and diagonal) when handcycling at maximum intensity during an incremental test and during a sprint test. There was also no difference in the economy of hand cycling during submaximal loads when each of the three grips was used. The vertical grip was associated with higher lactate concentrations during submaximal handcycling, and may be indicative of reduced efficiency caused by the static (continuous) activation of the working muscles. Further, studies should be conducted to verify these findings during prolonged exercise bouts and in athletes with a spinal cord injury or similar disabilities.

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frontiers in Physiology

ORIGINAL RESEARCH
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Comparison Between 30-15 Intermittent Fitness Test and Multistage Field Test on Physiological Responses in Wheelchair Basketball Players

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The intermittent nature of wheelchair court sports suggests using a similar protocol to assess repeated shuttles and recovery abilities. This study aimed to compare performances, physiological responses and perceived rating exertion obtained from the continuous multistage field test (MFT) and the 30-15 intermittent field test ($30\text{-}15_{IFT}$). Eighteen trained wheelchair basketball players (WBP) (WBP: 32.0 ± 5.7 y, IWBF classification: 2.9 ± 1.1 points) performed both incremental field tests in randomized order. Time to exhaustion, maximal rolling velocity (MRV), VO_{2peak} and the peak values of minute ventilation (V_{Epeak}), respiratory frequency (RF) and heart rate (HR_{peak}) were measured throughout both tests; peak and net blood lactate ($\Delta[Lact^-]$ = peak–rest values) and perceived rating exertion (RPE) values at the end of each exercise. No significant difference in VO_{2peak}, VE_{peak}, and RF was found between both tests. $30\text{-}15_{IFT}$ was shorter (12.4 ± 2.4 vs. 14.9 ± 5.1 min, $P < 0.05$) but induced higher values of MRV and $\Delta[Lact^-]$ compared to MFT (14.2 ± 1.8 vs. 11.1 ± 1.9 $km{\cdot}h^{-1}$ and 8.3 ± 4.2 vs. 6.9 ± 3.3 $mmol{\cdot}L^{-1}$, $P < 0.05$). However, HR_{peak} and RPE values were higher during MFT than $30\text{-}15_{IFT}$(172.8 ± 14.0 vs. 166.8 ± 13.8 bpm and 15.3 ± 3.8 vs.13.8 ± 3.5, respectively, $P < 0.05$). The intermittent shuttles intercepted with rest period occurred during the $30\text{-}15_{IFT}$ could explain a greater anaerobic solicitation. The higher HR and overall RPE values measured at the end of MFT could be explained by its longer duration and a continuous load stress compared to $30\text{-}15_{IFT}$. In conclusion, $30\text{-}15_{IFT}$ has some advantages over MFT for assess in addition physical fitness and technical performance in WBP.

Keywords: wheelchair, basketball, field test, aerobic fitness, evaluation

INTRODUCTION

Wheelchair basketball (WB) attracts many persons with different physical impairment and has great success at the Paralympic Games since 1960. WB has been described as intermittent aerobic-based sport scattered with short anaerobic bouts (Coutts, 1992; Bloxham et al., 2001). In their game analysis, Sporner et al. (2009) reported that the wheelchair basketball players (WBP) on average traveled 2679 ± 1103 m cut off by 239.8 ± 60.6 stops and starts during a match. Wheeling tasks including sprint, endurance, and slalom were strongly correlated with aerobic fitness in WBP (Hutzler, 1993; Vanlandewijck et al., 1999). WBP presented larger cardiac dimensions, greater power output and peak oxygen uptake (VO_{2peak}) values compared to untrained counterparts (Huonker et al., 1998; Schmid et al., 1998). Thus, maximal oxygen uptake was correlated to functional capacity and competition level in WBP (Schmid et al., 1998; De Lira et al., 2010).

Cardiorespiratory adaptation to exercise provided valuable information on training status. VO_{2peak} is generally assessed in laboratory condition during graded exercise performed on a wheelchair rolling on a motor driven treadmill and on an arm cycle ergometer. However, low correlations are obtained between peak cardiorespiratory values measured while pushing on the wheelchair and those measured with arm cranking on ergometer or in selected wheeling task (Hutzler, 1993; Rotstein et al., 1994). Standardized laboratory protocol tests can also provide higher VO_{2peak} reached at the end of test compared to field tests (Cunningham et al., 2000; Goosey-Tolfrey and Tolfrey, 2008). However, laboratory conditions did not take into account the natural environment (floor surface, specific wheelchair equipment) and not relate specific skills at the environment and ability to maneuver the wheelchair (Bernardi et al., 2010; Molik et al., 2010; De Groot et al., 2012; Goosey-Tolfrey and Leicht, 2013). Several authors adapted continuous (Vinet et al., 1996; Vanderthommen et al., 2002; Bernardi et al., 2010) and shuttle (Vanlandewijck et al., 1999; Cunningham et al., 2000; Goosey-Tolfrey and Tolfrey, 2008) tests for able-bodied players to assess aerobic fitness and predict the VO_{2peak} of disabled players. To assess agility, sprint recovery and endurance characteristics of WBP, Yanci et al. (2015) and Gil et al. (2015) also proposed a modified Yo-Yo intermittent recovery test (10-m instead of 20-m shuttle run). Yanci et al. (2015) showed a good test— retest reliability (ICC = 0.74–0.94; CV: ranged from 2.6 to 7.2%).

Buchheit (2008) developed for able-bodied athletes the 30-15 Intermittent Field Test ($30\text{-}15_{IFT}$), which aims to evaluate the maximal aerobic velocity in court sport players and acute responses to high-intensity intermittent shuttle-runs. The main interests of this test is the final speed reached at the end of the test which is well suited for training prescription and the rest time is longer than the Yo-Yo intermittent recovery test and more representative of defensive phase of WP (Buchheit and Rabbani, 2014). Nevertheless, wheelchair sports are distinct from those able-bodied due to functional impairment of the disabled and the displacement imposed by wheelchair (Goosey-Tolfrey and Leicht, 2013).

Previously, an incremental multistage field test (MFT) specific for disabled body wheelchair subjects was validated (Vanderthommen et al., 2002). It was observed that a slightly MFT adaptation—as alternating right and left turns vs. single direction—increase VO_{2peak} and peak minute ventilation (V_{Epeak}) responses without any significant differences in perceived exertion and maximal rolling velocity (MRV) reached at the end of the test (Weissland et al., 2015). These adjustments have no correspondence with the intermittent nature and the metabolic and cardio-respiratory responses induced by pivots, sprints and dribbles requested in WBP. Moreover, it has been observed, in able-bodied team sport players, that higher peak velocity were reached with a shorter time to exhaustion in intermittent shuttle vs. continuous running tests, with no significant difference in peak values of heart rate (HR_{peak}) and blood lactate (Carminatti et al., 2013).

Hence, the aim of the study was (i) to assess the aerobic fitness derived from an able-bodied intermittent field test in WBP (Buchheit, 2008) and (ii) to compare with a continuous and validated wheelchair field test. This study aimed to examine the end-test rolling velocity, the physiological responses and perceived exertion obtained from the continuous MFT and with the 30-15 intermittent field test ($30\text{-}15_{IFT}$).

METHODS

Subjects

Eighteen national WBP were recruited and all were engaged in national WB competitions every week, with several training sessions per week. Skinfolds thickness at four sites (triceps, subscapular, suprailiac, and abdominal) was measured using a Harpenden caliper. A summary of their characteristics, pathology and international classification (International Wheelchair Basketball Federation Web site, 2009) is presented in **Table 1**. For both tests, all players always used their own wheelchair. Before each test, the tire pressure was checked (Sawatzky et al., 2005). All procedures were conducted in accordance with approval of the "Fédération Française Handisport" medical committee, and in accordance with the Helsinki Declaration. All participants are fully informed of any risk giving and provided written informed consent.

Experimental Design

Testing for this study was conducted during the competitive period, in the middle of the season. Both tests replaced technical and physical training sessions during a week between competitive matches. Training load was reduced on the day preceding each test, which was performed between 9:00 a.m. and 4:00 p.m. Each WBP performed both tests within 48 h in a randomized order, in the same indoor hall: (i) the MFT which is an incremental continuous test (Vanderthommen et al., 2002) and (ii) the 30-15 intermittent fitness test ($30\text{-}15_{IFT}$) (Buchheit, 2008). Briefly, the MFT included wheeling around an octagon (15 × 15 m) at an initial speed of 6 $km \cdot h^{-1}$ during 1 min. Then, the speed increased by 0.37 $km \cdot h^{-1}$ every minute until exhaustion (Vanderthommen et al., 2002). The $30\text{-}15_{IFT}$ consisted of 40-m shuttle runs during 30-s with 15-s of passive recovery. The initial velocity was set at 6 $km \cdot h^{-1}$ (instead of 8 $km \cdot h^{-1}$ in the original protocol) for the first 30-s trial and was increased by 0.5 $km \cdot h^{-1}$ every 45-s

TABLE 1 | Individual Wheelchair basketball players' characteristics (gender, age, disability, sum of four skinfolds) according to International Wheelchair Basketball Federation classification (IWBF).

Player	Sex	Age (years)	Disability	IWBF classification	ΣSK (mm)
P1	M	29	Poliomyelitis	1.0	45.1
P2	F	28	Lower limb agenesis	1.0	76.2
P3	M	27	Spinal cord injury	1.5	52.2
P4	M	30	Spinal cord injury	2.0	42.9
P5	M	41	Spinal cord injury	2.0	27.2
P6	M	39	Spina bifida	2.5	33.7
P7	M	35	Hemiplegia	2.5	45.0
P8	M	36	Agenesis	3.0	44.9
P9	M	22	Larsen syndrome	3.0	30.8
P10	M	39	Spinal cord injury	3.0	39.1
P11	M	23	Spinal cord injury	3.0	37.9
P12	M	29	Cerebral palsy	3.0	44.1
P13	M	36	Spinal cord injury	4.0	48.3
P14	M	36	Spina bifida	4.0	54.5
P15	M	27	Cerebral palsy	4.0	23.1
P16	M	30	Above knee amputation	4.0	56.9
P17	F	38	Above knee amputation	4.5	34.1
P18	M	31	Orthopedic impairments	4.5	44.6
mean ± SD		32.0 ± 5.7		2.9 ± 1.1	43.5 ± 12.3

ΣSK represents the sum of four skinfolds (biceps, triceps, subscapular, supra-iliac).

(Buchheit, 2008). During the 15-s recovery period, the subjects rolled in the forward direction to join the closest line (at the middle or at one end of the area, depending on where they stopped) from where they started the next stage. No indication for the propulsion strategy was given for the two tests and WBP freely used their push rate and modality (synchronous and/or asynchronous).

All participants were instructed to complete as many stages as possible. The test ended when the participant could no longer be located within the turning zone (MFT) or consecutively to reach a 2-m zone around each line (30-15_{IFT}) at beep signal despite verbal encouragement. The time to exhaustion (TTE) was the longer time maintaining to the speed imposed on the last stage during each respective test. MRV was the velocity at the end of test reached at the TTE.

All subjects were advised to keep the same meals between both tests and to refrain from smoking and caffeinated drinks during the 2 h prior to testing.

Physiological and Perceived Responses Measurements

The resting oxygen uptake (VO_2), carbon dioxide production (VCO_2), respiratory frequency (RF), and minute ventilation (V_E) were measured breath-by-breath at rest and throughout both tests using Cosmed K4b^2 or Metamax 3B portable spirometric systems. To reduce the duration of the test time and the turnover subjects, two portable measurement systems were used. A previous study showed a satisfactory comparison between the two measuring devices with able-bodied cyclists (Leprêtre et al., 2012). Participants always used the same analyzer for both tests to repeat the mistake device. The turbines flow meters (with a 3-L syringe) and analysers were calibrated before each test, according to the constructor instruction manuals using a two-point calibration (calibration gas $O_2 = 16\%$ and $CO_2 = 5\%$ against room air). Then we used the software of each device to automatically eliminate ectopic values and average the data every 5 s. Heart rate (HR) was continuously recorded beat-to-beat (Polar RS800, Polar Electro, Kempele, Finland) and averaged every 5 s.

Small capillary blood samples (0.5 µL) were collected from finger to assess basal lactate concentration. A sample of lactate at rest was taken upon arrival of the player and before warm-up, immediately after the test and 3 min after during the passive recovery period. Net blood lactate values ($\Delta[Lact^-]$) were calculated by the difference between the peak $[Lact^-]$ values and rest values. All blood samples were analyzed using a portable lactate analyzer (Lactate Pro, Arkray, Japan) calibrated before each test using a standard strip of provided by the manufacturer (Pyne et al., 2000).

Immediately after the end of both tests, participants individually rated their overall perceived exertion (RPE) using the Borg's 6–20 scale (Borg, 1990).

Statistical Analysis

Descriptive data are presented as mean and standard deviation (mean ± SD). Normality and homogeneity of the distribution were verified via Shapiro Wilks and Levene tests, respectively. Student's *t*-test was used to compare the resting and peak values measured during MFT and 30-15$_{IFT}$. The determination of the Pearson correlation coefficients (R) were used to examine the relationship between TTE, MRV, VO2peak, and condition test. Absolute effect size (ES) and 95% confidence intervals of the differences (95% CI) were computed. An ES of 0.2 refers to a small effect, 0.5 a moderate effect, and 0.8 a large effect according to Cohen (Cohen, 1992). Agreements were sought by the Bland and Altman' method (Bland and Altman, 1986) between the peak values of VO_2 and V_E between the both tests. In all statistical analyses, the (alpha) level of significance was set at $P < 0.05$.

RESULTS

Peak values of cardiorespiratory responses and performance measured during MFT and 30-15$_{IFT}$ are shown in **Table 2**. Higher MRV values (14.2 ± 1.8 vs. 11.1 ± 1.9 km·h^{-1}, $P < 0.05$, $ES = 0.6$) and shorter TTE (12.4 ± 2.4 vs. 14.9 ± 5.1 min, $P < 0.05$, $ES = 0.3$) were observed during 30-15$_{IFT}$ compared to MFT. HR$_{peak}$and RPE values were significantly lower during 30-15$_{IFT}$ compared to MFT (166.8 ± 13.8 vs. 172.8 ± 14.0 bpm, $ES = 0.4$, and 13.8 ± 3.5 vs. 15.3 ± 3.8, $ES = 0.5$, $P < 0.05$, respectively). 30-15$_{IFT}$ induced a higher $\Delta[\text{Lact}^-]$ values compared to MFT (8.3 ± 4.2 vs. 6.9 ± 3.3 mmol·L^{-1}, $P < 0.05$, $ES = 0.4$) without any significant difference between rest ($P = 0.88$) and peak $[\text{Lact}^-]$ values (9.8 ± 4.4 mmol·L^{-1} vs. 8.5 ± 3.1, $P = 0.2$, $ES = 0.3$). No significant difference was found for VO_{2peak}, V_{Epeak}, and RF peak values between both tests.

A significant relationship for MRV ($r = 0.57$, $P < 0.05$) TTE ($r = 0.64$, $P < 0.05$), and VO2peak ($r = 0.84$, $P < 0.01$) was found between MFT and 30-15$_{IFT}$(**Figure 1**). The Bland–Altman plots showed that, for VO_{2peak} and V_{Epeak} measurements, the bias ± random error was acceptable with an acceptable agreement between both tests (-0.27 ± 6.81 ml.min.kg^{-1}; **Figure 2A** and 2.6 ± 34.8 L.min^{-1}; **Figure 2B**, respectively). Differences between MFT and 30-15$_{IFT}$ HR$_{peak}$ and $\Delta[\text{Lact}^-]$ per WBP were reported in **Figure 3**. Individual responses have reflected significant changes measured in HR (**Figure 4**) and $\Delta[\text{Lact}^-]$ for 30-15$_{IFT}$.

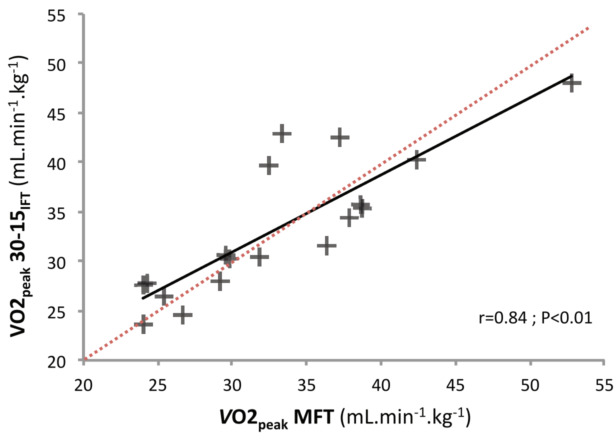

FIGURE 1 | Correlation between VO_{2peak} reached during MFT and 30-15$_{IFT}$ tests ($r = 0.54$, $r^2 = 0.71$, $P < 0.01$).

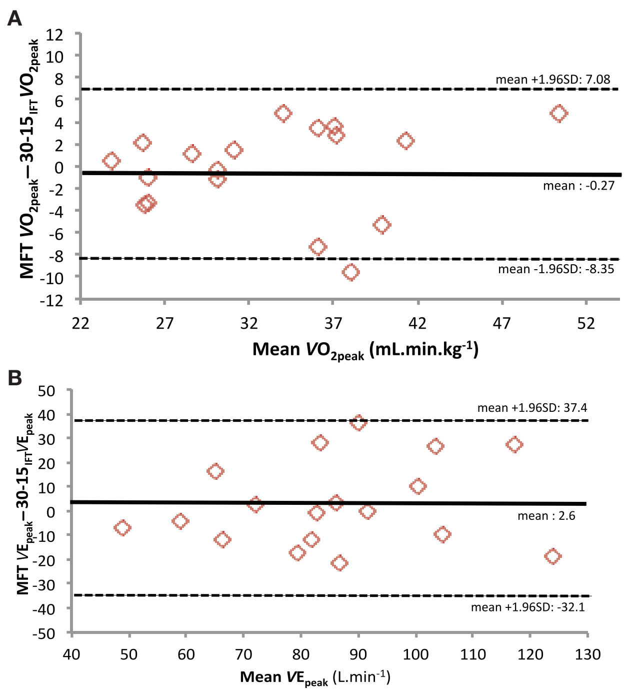

FIGURE 2 | Analysis of the individual difference by Bland-Altman method between MFT and 30-15$_{IFT}$ test and (A) peak oxygen consumption (VO_{2peak}) and (B) peak ventilation (V_{Epeak}).

DISCUSSION

The aim of this study was to compare a modified able-bodied field intermittent test with a validated standardized wheelchair-users field test. The observed performances at 30-15$_{IFT}$ were better with higher MRV associated with a shorter time to exhaustion ($P < 0.05$). However, no significant difference for peak oxygen uptake and ventilation values was noted between both tests (**Table 2**).

MFT is a validated field test to estimate VO_{2peak} for disabled body wheelchair subjects in indoor conditions (Vanderthommen et al., 2002). No significant difference was found for VO_{2peak} between MFT and 30-15$_{IFT}$ and a significant relationship for VO_{2peak} were found between the both tests ($r = 0.84$, $P < 0.01$) (**Figure 1**). We used Bland-Altman plots to graphically display the variability of VO_{2peak} and V_{Epeak} variables (**Figure 2**). In each case, the systematic bias is close to zero and the 95% limits of agreements are acceptable. Thus, we can conclude that the 30-15$_{IFT}$ is comparable to VO_{2peak} and V_{Epeak} encountered during the end of the test. Nevertheless, it would be necessary in the future to investigate the reliability and validity of the 30-15$_{IFT}$ with a standardized test on a wheelchair ergometer in the laboratory. However, the only valid option to confirm whether a "true" VO_{2max} has been reached during both tests is currently in a verification phase (VER) (Leicht et al., 2013), absent in our protocol.

TABLE 2 | Peak values and 95% confidence interval (CI) measured during the MFT and the 30-15$_{IFT}$, Mean ± SD.

	TTE min:s	MRV km.h^{-1}	RF b·min^{-1}	V_{Epeak} L·min^{-1}	VO_{2peak} mL·min^{-1}·kg^{-1}	HR$_{peak}$ bpm	peak [Lact$^-$] mmol·L^{-1}	Δ[Lact$^-$] mmol·L^{-1}	RPE
MFT	14:53 ± 5:04	11.1 ± 1.9	49.9 ± 11.4	87.0 ± 22.8	33.0 ± 7.5	172.8 ± 14.0	8.5 ± 3.1	6.9 ± 3.3	15.3 ± 3.8
CI	12:32–17:13	10.3–12.0	44.7–55.2	76.5–97.6	29.5–36.5	166.3–179.2	7.1–9.9	5.4–8.4	13.5–17
30-15$_{IFT}$	12:25 ± 2:21$^{*\gamma}$	14.2 ± 1.8$^{*\theta}$	48.4 ± 12.8$^{\theta}$	84.4 ± 20.1	33.3 ± 7	166.8 ± 13.8$^{*\theta}$	9.8 ± 4.4^{2}	8.3 ± 4.2$^{*\theta}$	13.5 ± 3.5$^{*\theta}$
CI	11:19–13:31	13.4–15.1	42.5–54.3	75.1–93.7	30.1–36.5	160.5–173.2	7.7–11.8	6.3–10.2	11.9–15.1

TTE, indicates Time To Exhaustion; MRV, Maximal Rolling Velocity; RF, peak respiratory frequency; V_{Epeak}, peak values of ventilation; VO_{2peak}, peak oxygen uptake; HR$_{peak}$, peak heart rate; peak [La$^-$], peak blood lactate value; Δ[La$^-$], the difference between rest and maximal blood lactate values; RPE, the rating of perceived exertion.
**Significantly different from MFT ($P < 0.05$); $^{\theta}$moderate effect size; $^{\gamma}$small effect size (Cohen, 1992).*

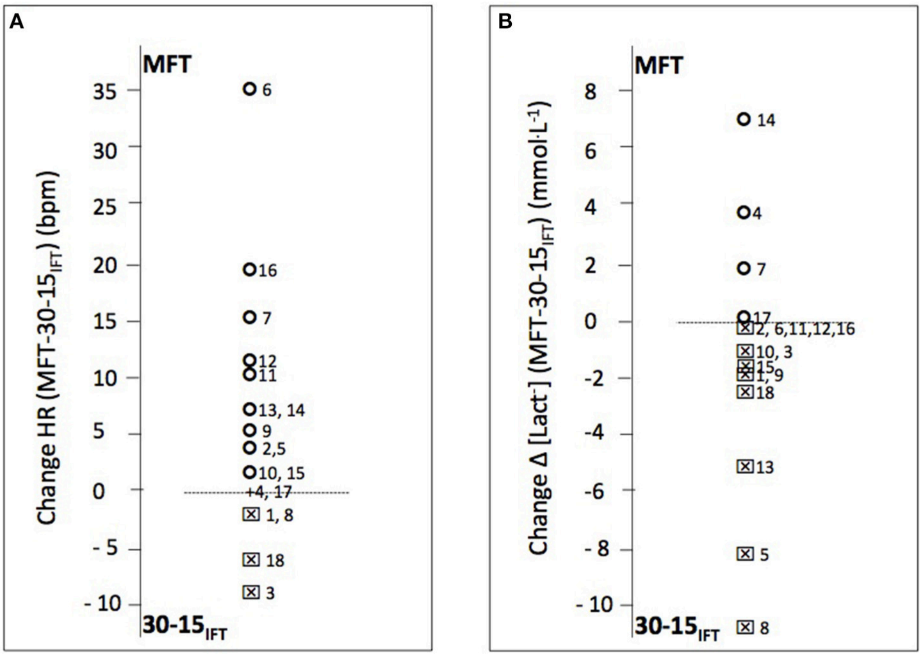

FIGURE 3 | Individual wheelchair basketball players difference in peak heart rate and blood lactate values between continuous multistage field test (MFT) and 30-15 intermittent field test (30-15$_{IFT}$) (n = 18). (A) Difference HR (bpm) and **(B)** Difference Δ[Lact$^-$], respectively represented the difference in peak values of heart rate (bpm) and Δ blood lactate (peak-rest values [La$^-$] mmol·L^{-1}). A circle plots indicated a difference between MFT and 30-15$_{IFT}$ values in favor of MFT; a square worth the 30-15$_{IFT}$.

TTE to reach VO_{2peak} is shorter during 30-15$_{IFT}$ than MFT (12.4 ± 2.4 vs. 14.9 ± 5.1 min, $P < 0.05$, $ES = 0.3$) and a significant correlation between both TTE tests was found ($r = 0.64$, $P < 0.05$). To reach VO_{2max}, Buchfuhrer et al. (1983) recommended a time span of 10 ± 2 min for an incremental ramp protocol. This widely cited recommendation is applied for incremental protocols with able-bodied participants but also for upper body exercises and disabled subjects. With 16 untrained able-bodied men, Smith et al. (2006) observed, during an incremental arm crank ergometry, the effects of two ramp rates (12W·min^{-1} vs. 6W·min^{-1}) on the attainment of peak physiological responses and power output (Smith et al., 2006). In this study, TTE was shorter for the 12W·min^{-1} protocol (within the range of 8–12 min) whereas, for the 6W·min^{-1} protocol, TTE extends to 15 ± 4 min. However, no significant difference was found for VO_2, V_E, and HR$_{peak}$ between both protocols. In wheelchair athletes, Vinet et al. (1997) adjusted the velocity increment from a progressive treadmill test to be within the limits defined by Buchfuhrer et al. (8:50 ± 1:24 min). The Modified Yo-Yo intermittent recovery test (10 m shuttle run) provides higher TTE (16.96 ± 1.14 min), as reported by Yanci et al. (2015) in WBP. Considering the recommendations of time span (between 8 and 12 min) and given the absence of differences in the peak physiological responses, IFT$_{30-15}$ would be more appropriate than MFT for the trained participants, due to the shorter TTE required for reaching VO_{2peak}.

The difference in HR$_{peak}$ measured at the end during both tests (166.8 ± 13.8 vs. 172.8 ± 14.0 bpm for 30-15$_{IFT}$ and MFT, respectively, $ES = 0.4$, $P < 0.05$) can be explained by the intermittent nature of the 30-15$_{IFT}$, which is based on

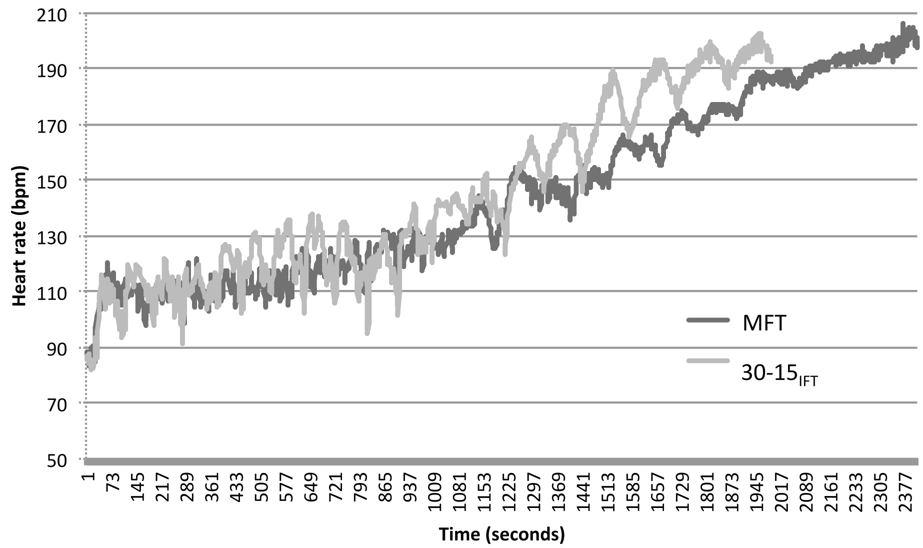

FIGURE 4 | Example data illustrating heart responses during 30-15$_{IFT}$ and MFT for participant 12 (three point, IWBF classification).

the use of 15-s passive rest periods between each stage. HR responses represented as an example in **Figure 4** for the 12 WBP clearly show the difference in HR evolution between the two tests. 30-15$_{IFT}$ therefore allows a discontinuous load stress for WBP. 30-15$_{IFT}$ does not elicit maximal HR and the maximal capabilities of the cardiovascular system while some other criteria for the attainment of a maximal exercise (like VO_2 plateau, RER > 1.1, lactate concentration accumulates $>$ 8 mmol.L^{-1}) were achieved. A peripheral limitation may explain the submaximal values for HR_{peak}. Vanlandewijck et al. (1999) has supported that shuttle test is not a direct measure of aerobic capacity but rather reflects ability and specific skills using the wheelchair. Indeed, Goosey-Tolfrey and Tolfrey (2008) showed that cardiorespiratory responses during a continuous shuttle multi-stage fitness test did not fully reflect those obtained during an exercise on arm crank ergometer. With WBP population, Yanci et al. (2015) reported greater HR_{peak} values (+4.7%) with a longest time (+36%) with Yo-Yo intermittent recovery test than the 30-15$_{IFT}$. One other explanation can be the disruption of the autonomic control of the HR in three subjects with high spinal cord lesion, which would control the cardiovascular function during exercise and rest (West et al., 2014).

Peak RPE measured during MFT are consistent with the level of cardio-respiratory solicitations but RPE should be used cautiously for spinal cord injury athletes and differentiated for high and low lesion (Goosey-Tolfrey et al., 2010). Test duration and monotony of continuous displacement in MFT could increase the overall rate of perceived exertion during MFT in comparison with 30-15$_{IFT}$ (15.3 ± 3.8 vs. 13.8 ± 3.5 $ES = 0.5$, $P < 0.05$). Turning in the same direction during MFT could induce premature tiredness and muscle fatigue in the upper limb of the external curve. This could be in relation to the great push power output and high arm frequency and the centrifugal force exerted on the wheelchair in the curve. With novice wheelchair users, Paulson et al. (2013) showed self-regulation of intermittent exercises based on the overall or peripheral perceptions. Dissociating muscular and respiratory RPE in order to analyze match load is a feasible method of quantification in monitoring the training of WBP (Iturricastillo et al., 2015). In our study, overall RPE did not provide information of the muscular load perceived by the succession of starts and changes of direction in the 30-15$_{IFT}$'s protocol. An evaluation of peripheral RPE would certainly have given additional information between the two tests.

Higher MRV values were reached in a shorter time during 30-15$_{IFT}$ compared to MFT (14.2 ± 1.8 vs. 11.1 ± 1.9 km·h^{-1}, $P < 0.05$, $ES = 0.6$). 30-15$_{IFT}$ adaptation by initially starting at 6 km·h^{-1} allowed to extend the standard protocol of 3-min, in order to have the same initial velocity between MFT and 30-15$_{IFT}$. Despite this modification, 30-15$_{IFT}$ induces shorter TTE. It is explained by the difference in less than 15-s and in addition to 0.13 km·h^{-1} per stage in detriment to MFT between the both tests. Also for these reasons, MRV attained higher values at 30-15$_{IFT}$that MFT for similar VO_{2peak}.

Higher 30-15$_{IFT}$'s MRV could explain the higher peak blood lactate values. Smith et al. (2006) measured higher peak [Lact$^-$] for 12 W·min^{-1} ramp protocol and had argued that the higher workload increment than 6 W·min^{-1} was linked with higher lactactes concentration. In this study, the workload during the graded exercise has an impact on the muscular component. Thus, compared with continuous octagonal line rolling in MFT, 30-15$_{IFT}$ with direction changes and multiple acceleration phases could present a greater physiological load, as supported by relative blood lactate concentration and the extra energy expended. Δ[Lact$^-$] 30-15$_{IFT}$ values compared to MFT were higher (8.3 ± 4.2 vs. 6.9 ± 3.3 mmol·L^{-1}, $P < 0.05$, $ES = 0.4$). The significant increase of velocity per 0.5 km·h^{-1} at IFT after rest period, added to direction changes, deceleration and acceleration phase generate significant muscular efforts and greater anaerobic solicitation. However, Yanci et al.

(2015) reported, for the modified Yo-Yo protocol, lower peak [Lact$^-$] values than our data (7.21 $\pm$ 2.4 mmol·L^{-1} vs. 9.8 $\pm$ 4.4 mmol·L^{-1}). Intermittent field tests correspond to the nature of the court sport in WB. Comparing Yo-Yo and 30-15$_{IFT}$ with young soccer players, Buchheit and Rabbani (2014) have noted a large correlation ($r = 0.75$) between both tests, with 30-15$_{IFT}$ being more related to maximal sprinting speed and Yo-Yo being more associated with aerobic endurance. Bloxham et al. (2001) showed with the Canadian team that 28% of the WB playtime was spent at high anaerobic intensities and estimated 20% above the ventilatory threshold. But, 48.3% of playtime concerns recovery and low-speed replacement periods. Considering these aspects, 30-15$_{IFT}$ could be closer to the WB conditions than the Yo-Yo intermittent test. Intermittent field testing would also have the advantage in determining the BLa threshold rather than ventilatory data collection (Leicht et al., 2014) with the sample blood lactate at each level.

Using able-bodied field tests to assess the physical condition of athletes with disabilities remains difficult and even imperfect (Goosey-Tolfrey and Leicht, 2013). First, pushing for inducing wheelchair rolling is not comparable to running. The amount of energy required for the inertia of the wheelchair are different, especially to start, to turn or to glide at half turn. Secondly, the initial rolling velocity is often inappropriate and the increment may be too important. In these conditions, shuttle protocols need a great technique or ability to maneuver the wheelchair and could limit the wheelchair novices and players with a low classification point (IWBF) that have more significant disabilities than the others. Shuttle tests could be more disadvantageous for athletes with greater disabilities than MFT in which the participants determine their preferred direction of rotation (Vanlandewijck et al., 1999). Functional asymmetry with a dominant side and contralateral side deficit in strength, imbalance had low impact for the physiological responses and MRV that are related between both tests ($r = 0.57$, $P < 0.05$). Heterogeneity of pathologies and residual functional capabilities represented in our study provide individual responses as shown in **Figure 3**.

Maneuvering a wheelchair during acceleration-deceleration phases, slide and half turns requires specific skills, considering individual muscular impairments and trunk imbalance. A moderate to high level of expertise of these techniques is essential for not stopping prematurely in 30-15$_{IFT}$. It would be useful to compare our results during 30-15$_{IFT}$ with other untrained or novice wheelchair users in order to determine if 30-15$_{IFT}$ is also adaptable to various populations like MFT. Sprinting ability and wheelchair maneuverability are probably important predictors of performance in WBP (Vanlandewijck et al., 1999; Granados et al., 2015; Yanci et al., 2015). Thus, the 30-15$_{IFT}$ has the advantage to assess, in addition to physical fitness, the technical performance to maintain wheeling velocity with succession of alternating turns. MFT was originally developed to assess aerobic fitness of the wheelchair users without a GTX laboratory protocol. MFT is validated and the VO_{2peak} extrapolation equation from MFT-score is reliable, repeatable and similar to VO_{2peak} measured (Vanderthommen et al., 2002; Weissland et al., 2015). However, MFT protocol is not representative of the WB nature while intermittent field tests are more similar but would need assessment to determine their level of reliability, validity and sensitivity.

As a take home message, the MFT test is more appropriate for the determination of maximal physiological capacities of WBP and the associated MRV can be used for the individualization of pre-season training programs. However, with a shorter time to exhaustion, 30-15$_{IFT}$ is also really interesting and relevant for the evaluation of the WBP. This intermittent field test allows reaching VO_{2peak} with a higher contribution of the anaerobic metabolism, while also assessing and taking into account the specific technical characteristics of WB. The important differences for peak HR, [Lact$^-$] and MRV values between both tests emphasize the importance of an adequate and relevant test selection, according to the parameter of interest.

CONCLUSION

The 30-15 Intermittent Fitness Test induced a higher MRV with a greater blood lactate value but lower heart rate and perceived exertion compared to the original continuous MFT. Moreover, time of exhaustion is shorter for 30-15$_{IFT}$ with similar peak oxygen uptake reached at the end of both test. Intermittent field test has some advantages over MFT for jointly assessing physical fitness and technical ability of WBP. It would be necessary in the future to investigate the reliability and validity from a standardized test on wheelchair ergometer in the laboratory.

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Performance changes and relationship between vertical jump measures and actual sprint performance in elite sprinters with visual impairment throughout a Parapan American games training season

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The aims of this study were to estimate the magnitude of variability and progression in actual competitive and field vertical jump test performances in elite Paralympic sprinters with visual impairment in the year leading up to the 2015 Parapan American Games, and to investigate the relationships between loaded and unloaded vertical jumping test results and actual competitive sprinting performance. Fifteen Brazilian Paralympic sprinters with visual impairment attended seven official competitions (four national, two international and the Parapan American Games 2015) between April 2014 and August 2015, in the 100- and 200-m dash. In addition, they were tested in five different periods using loaded (mean propulsive power [MPP] in jump squat [JS] exercise) and unloaded (squat jump [SJ] height) vertical jumps within the 3 weeks immediately prior to the main competitions. The smallest important effect on performances was calculated as half of the within-athlete race-to-race (or test-to-test) variability and a multiple regression analysis was performed to predict the 100- and 200-m dash performances using the vertical jump test results. Competitive performance was enhanced during the Parapan American Games in comparison to the previous competition averages, overcoming the smallest worthwhile enhancement in both the 100- (0.9%) and 200-m dash (1.43%). In addition, The SJ and JS explained 66% of the performance variance in the competitive results. This study showed that vertical jump tests, in loaded and unloaded conditions, could be good predictors of the athletes' sprinting performance, and that during the Parapan American Games the Brazilian team reached its peak competitive performance.

Keywords: Paralympics, track and field, muscle power, physical disability, blind athletes

INTRODUCTION

In general, the public is astonished by the performance of Paralympic athletes, given their extreme physical and technical capacities in spite of the presence of mild to severe physical disabilities. Although it is known that sprinting performance in Paralympic Track and Field has improved at a higher rate than the Olympic results (Grobler et al., 2015), there has been no systematic analysis of the variability and progression in competitive performance of successful teams in the months of preparation leading up to a main competition (e.g., Parapan American Games).

It has been suggested that the smallest important effect in performance at a target international event is one-half of the typical within-athlete random variability between events (Hopkins et al., 1999). An important performance progression to enhance the chances of a medal for Olympic and Paralympic swimmers in the year leading up to the main competition has been estimated to be ≈1–2% (Pyne et al., 2004; Fulton et al., 2009). In addition, in elite Olympic track athletes (including sprinters), an improvement of as little as 0.3–0.5% is considered meaningful (Hopkins, 2005). Calculating the smallest important change in Paralympic sprinters may help coaches to define targets for performance improvements in the year of preparation for the upcoming Paralympic Games.

Importantly, although the actual performance is considered the "gold standard" to assess elite athletes, simple and field based tests assessing key components of competitive outcomes can be considered as important evaluation and monitoring tools. For instance, it has been shown that loaded and unloaded vertical jumping performances are largely correlated with sprinting speed in elite sprinters (Loturco et al., 2015a,b). Confirmation of these associations between loaded/unloaded jumps (or even in combination) and sprinting performance in Paralympic athletes may help coaches to choose appropriate tests in order to evaluate and monitor Paralympic sprinters. This is particularly relevant to athletes with visual impairments as vertical jumping tests may be executed without the need for much assistance, enabling easy implementation in the training routines.

In this regard, it is important to know the within-athlete variability and progression in vertical jumping performance, to allow coaches to effectively decide whether a given change in testing performance might be considered meaningful or within the trivial variation caused by biological and/or technical factors. Based on this information, coaches can better select training strategies to optimize athletes' sports form, without necessarily assessing the actual competitive performance. Furthermore, simple tests can be used on a daily basis, thus providing fine feedback for training adjustments.

Therefore, the aim of this study was to estimate the magnitude of variability and progression in actual competitive and field vertical jump test performances in elite Paralympic sprinters with visual impairment in the year leading up to the 2015 Parapan American Games. Furthermore, we aimed to investigate the relationships between loaded and unloaded vertical jumping test results and the actual competitive sprinting performance, through the use of simple and multiple linear regression analyses.

MATERIALS AND METHODS

Seven official competitions were analyzed (four national, two international and the Parapan American Games 2015) between April 2014 and August 2015. The competitions were sanctioned by the Brazilian Paralympic Committee (CPB), International Paralympic Committee (IPC), and Americas Paralympic Committee (APC), respectively. The physical assessments were performed close to the competitions (up to 3 weeks prior to the main competitions) in five different periods (between April 2014 and July 2015) scheduled by the High Performance Programs of CPB, as part of the athletes' monitoring during the competitive season. Fifteen Brazilian Paralympic sprinters with visual impairment, from 18 to 36 years old, took part of the study (seven men and eight women, classes: T11 [$n = 9$]; T12 [$n = 3$]; and T13 [$n = 3$]). All athletes were part of the permanent Brazilian team, frequently involved in national and international competitions. This elite sample comprised four world champions, two Paralympic champions, four world record holders, two Paralympic record holders, eight world medalists, 11 Paralympic medalists, 12 top-five athletes and two top-ten athletes in the 2015 world ranking, thus attesting their high level of competitiveness.

For analysis purposes, only the times attained in the finals were retained. Across the seven competitions, a total of 120 official times (68 from the 100-m and 52 from the 200-m dash) were included in the analyses. Additionally, 192 test results in the five different periods using loaded (mean propulsive power [MPP] in jump squat [JS] exercise) and unloaded (squat jump [SJ] height) vertical jumps were analyzed. All the athletes had been previously familiarized with the testing procedures. This study was approved by the Ethics Committee of the Bandeirantes Anhanguera University. Prior to study participation, all the athletes signed an informed consent form.

Vertical Jumping Ability

Vertical jumping ability was assessed using SJ. To perform the SJ, a static position with a 90° knee flexion angle was maintained for 2-s before every jump attempt. No preparatory movement was allowed and an experienced researcher visually inspected for proper technique. Five attempts were performed interspersed by 15-s intervals. All attempts were executed with the hands on the hips. The jumps were performed on a contact platform (Smart Jump; Fusion Sport, Coopers Plains, Australia) with the obtained flight time (t) being used to estimate the height of the rise of the body's center of gravity (h) during the vertical jump (i.e., $h = gt^2/8$, where $g = 9.81\ m \cdot s^{-2}$. The best attempt was used for data analysis purposes. The athletes executed the attempts without assistance.

Bar Mean Propulsive Power in Jump Squat

Bar MPP in the JS exercise was assessed on a customized Smith machine (adapted by Hammer Strength, Rosemont, IL, USA). The athletes were instructed to execute three repetitions at maximal velocity for each load, starting at 40% of their body mass (BM). The athletes with visual impairment executed a knee flexion until the thigh was parallel to the ground (≈100°

knee angle for 2-s) and, after a command, jumped as fast as possible without losing contact between their shoulder and the bar. A load of 10% BM was gradually added in each set until a decrease in MPP was observed. A 5-min interval was provided between sets. All athletes attained their maximum values of MPP during the execution of the tests, within 4–5 attempts. Of note, the athletes achieved their highest MPP outputs at a load corresponding to ≈100% BM. To determine MPP, a linear transducer (T-Force, Dynamic Measurement System; Ergotech Consulting S.L., Murcia, Spain) was attached to the Smith machine bar. The finite differentiation technique was used to calculate bar velocity (Sanchez-Medina et al., 2010). As Sanchez-Medina et al. (2010) demonstrated that mean mechanical values during the propulsive phase better reflect the differences in the neuromuscular potential between two given individuals, MPP rather than peak power was used in the JS. The bar maximum MPP value obtained was considered for data analysis purposes. In order to consider the differences in BM between the athletes and avoid misinterpretation of the power outputs, these values were normalized by dividing the absolute power value by the BM (i.e., relative power = $W.kg^{-1}$) (MPP REL). All the tests were performed by the athletes with no assistance.

Statistical Analysis

The normality of data was confirmed using the Shapiro-Wilk test. Data are presented as means ± standard deviations (SD). The smallest important effect on performances was calculated as half of the within-athlete race-to-race (or test-to-test) variability (Hopkins et al., 1999). Additionally, the within-subject coefficient of variation (CV), with 90% confidence intervals (CI), was calculated as a measure of competitive and testing performance variability. A Pearson product-moment coefficient of correlation was used to analyze the relationships between SJ and MPP REL in the JS and sprinting time in the 100- and 200-m. The vertical jumping tests took place in close proximity to five of the seven competitions. A multiple regression analysis was performed using the vertical jump test results as predictors of 100- and 200-m dash performances. The possibility of collinearity between the predictive variables in multiple regression models was examined using variance inflation factor (VIF) and tolerance (i.e., VIF < 10 and tolerance > 0.2; Kennedy, 1992; Hair et al., 1995; Tabachnick and Fidell, 2001). Intraclass correlation coefficients (ICCs) were used to indicate the relationship within SJ and JS for, respectively, jumping height and MPP. The significance level was set as $P < 0.05$.

RESULTS

All data presented herein showed normal distribution. The VIF and tolerance values were 2.43 and 0.42, respectively, attesting that the independent variables (i.e., SJ and JS) were not collinear. The characteristics of the subjects are presented in the **Table 1**. The BM of the athletes did not vary substantially across the five evaluation moments (varying from 61.41 ± 9.76 to 63.84 ± 10.66). **Figure 1A** displays the means of the 100-m dash performances in the seven competitions. The mean CV (90% CI) over the competitions was 1.79% (1.47; 2.24). Meanwhile, **Figure 1B** depicts the mean performance in the 200-m events. The mean CV (90% CI) across the seven competitions was 1.35% (0.83; 1.88). The performance variation in the SJ and JS over the five moments is displayed in **Figures 2A,B**, respectively. Importantly, the ICC was 0.94 for the SJ and 0.92 for the loaded JS. The mean CVs (90% CI) for SJ and JS were 5.58% (4.18; 6.99) and 7.97% (5.91; 10.02), respectively.

The correlations (90% CI) between SJ and JS test results and 100- and 200-m dash performances were −0.80 (−0.71; −0.88) and −0.71 (−0.61; −0.81) for SJ and JS with 100-m, respectively, and; −0.81 (−0.72; −0.89) and −0.65 (−0.48; −0.79) for SJ and JS with 200-m, respectively ($P < 0.01$ for all correlations; **Figure 3**). The multiple regression analysis using SJ and JS test results as predictors of 100- and 200-m dash performances is presented in **Table 2**. The SJ and JS explained 66% of the performance variance in both 100- and 200-m dash performances.

DISCUSSION

This is the first study to investigate the relationships between loaded/unloaded vertical jump tests and the actual performance obtained by top-level Paralympic sprinters in 100 and 200 m dash events. The main finding reported herein is that, providing they are executed only a few weeks before the official tournaments (i.e., from 1 to 3 weeks), SJs and loaded JSs—when combined in a multiple linear regression model—can be good predictors of the actual competitive performance of top-level athletes with visual impairment. In addition, during a given training period, the dynamics of the performance in these specific jump tests seem to be analogous to the dynamics of the actual results obtained in 100 and 200 m dash events.

Another study has already reported strong correlations between sprinting performance (i.e., measured in time) and SJ height ($r = -0.82$) in elite sprinters who compete in 100 m dash events (Loturco et al., 2015b). This "close relationship" can be explained when analyzing the mechanical aspects of unloaded SJs. In order to jump higher, an athlete has to apply a substantial amount of force against the ground—and against his/her own BM (Loturco et al., 2015a,b). Thus, this measurement is already normalized by the subject's weight, being able to express his/her relative neuromuscular potential (i.e., relative values of muscle force and muscle power; Bosco et al., 1983; Copi et al., 2014). Furthermore, from a mechanical perspective, athletes with better performances in vertical jumps are possibly more efficient at overcoming the inertia and accelerating their bodies vertically (Bunton et al., 1993; Loturco et al., 2015b). Importantly, as the ground reaction forces increase, the vertical jump height increases (Loturco et al., 2015b). The same occurs in sprinting, during the transition from lower to higher velocities

TABLE 1 | Characteristics of the subjects (mean ± SD).

Age (years)	Weight (kg)	Height (cm)
26.5 ± 6.2	63.3 ± 10.6	169 ± 0.9

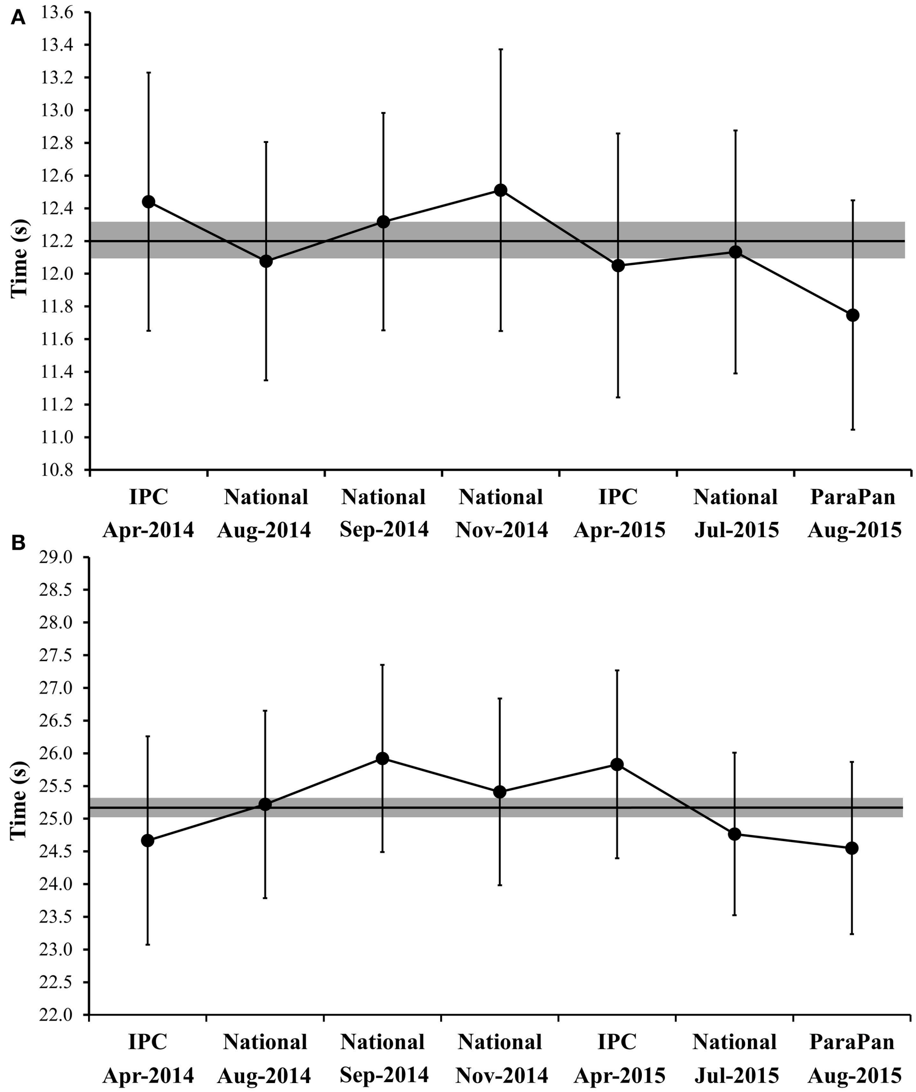

FIGURE 1 | Variation in 100- (A) and 200-m (B) dash performances across seven official competitions. The black line represent the mean individual performances, and the gray area represent the smallest important effect on performances (i.e., calculated as half of the within-athlete race-to-race variability). *National* corresponds to competitions organized by the local Paralympic Committee; *IPC* corresponds to international competitions organized by the International Paralympic Committee; *ParaPan* corresponds to the ParaPan American Games.

(i.e., top-speed sprinting), which results in shorter support phases with simultaneous increases in vertical peak force (Nilsson and Thorstensson, 1989). Curiously, even in sprinters with visual impairment, this mechanical similarity seems to be capable of influencing the specific performance in 100 and 200 m dash events. Certainly, the user-friendly characteristic and practicality of SJ facilitates its execution by athletes with visual impairment, thus reinforcing its use as a tool to control/monitor the variation in sprinting performance presented by this specific group of Paralympics.

Loaded JSs are usually performed with moderate training loads, moved as rapidly as possible (Cormie et al., 2011; Loturco et al., 2015d). In this study, the athletes executed an *optimal loading test* in order to determine their individual *optimal power loads* (i.e., loads capable of generating higher values of muscle power). The maximal JS power has been extensively related to a variety of specific sports measures, including speed and acceleration abilities (Sleivert and Taingahue, 2004; Cronin and Hansen, 2005; Loturco et al., 2015a,b,d). Interestingly, the athletes also presented significant correlations between MPP and actual sprinting time, both in 100 and 200 m dash events ($r = -0.71$ and -0.65, for 100- and 200-m). Of note, the athletes reached their highest MPP at ≈100% of their BM, which represents a substantial amount of external overloading. At this loading condition, movement performance is possibly associated with maximum dynamic strength (i.e., ability to apply high force at low velocity; Baker and Nance, 1999; Young et al., 2001; Stone et al., 2003). Similarly, to start from

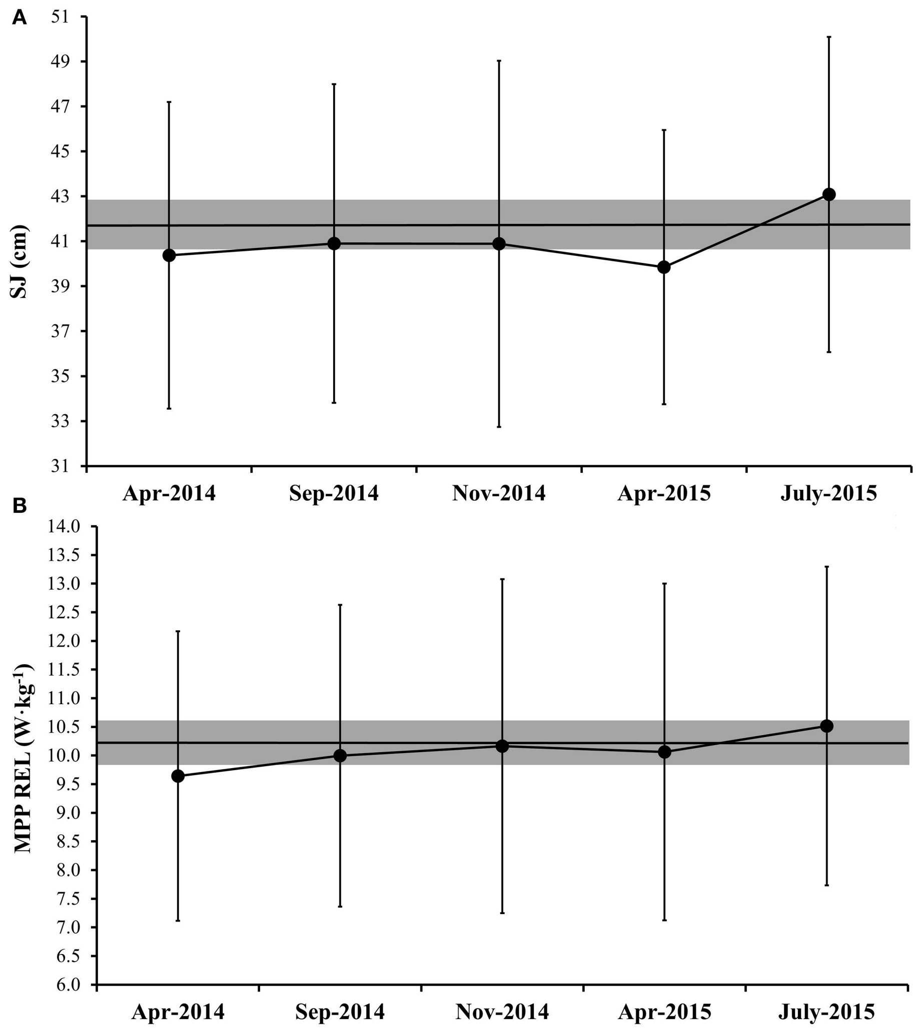

FIGURE 2 | Variation in squat jump (SJ) (A) and relative mean propulsive power in jump squat exercise (MPP REL JS) (B) test results across the five periods. The black line represents the mean individual performances, and the gray area represents the smallest important effect on performances (i.e., calculated as half of the within-athlete test-to-test variability).

zero-velocity and achieve higher accelerations in very-short periods, the athletes have to apply greater amounts of force (at lower velocities) against the ground (Wisløff et al., 2004; Loturco et al., 2014). More importantly, based on the parametric relationship between force and velocity (Cronin et al., 2002; Loturco et al., 2015c), these higher rates of acceleration can only be attained if the accelerated mass (i.e., athlete's BM) represents a relatively low resistance for the athlete involved (when compared to his/her maximum dynamic strength; Moss et al., 1997; Cormie et al., 2007; Loturco et al., 2014). Therefore, although we did not have the "partial times" of the actual competitions to perform additional correlational analysis in this study, it is highly conceivable that the more powerful athletes presented superior performance in the acceleration phases of sprinting, in both the 100 and 200 m dash. Undoubtedly, this issue should receive priority in future investigations, in spite of the difficulty in obtaining partial times in official competitions.

In this study, the possibility of combining two independent variables (i.e., SJ and JS) in a multiple linear regression model to more accurately predict the athletes' actual performance was considered due to the distinct importance of each one of these measures in sprinting mechanics and due to the high levels of competitiveness found in Paralympic track and field competitions. As aforementioned, whereas JS is probably more related to the accelerating phases of sprinting (Wisløff et al., 2004; Loturco et al., 2014), SJ may be more associated with the "top-speed" phases of both the 100- and 200-m dash (Loturco et al., 2015b). Therefore, since individual performance in top-level sports depends on very fine adjustments, it is worth considering novel and better models/strategies to predict results and enhance performance. Still, although the use of multiple

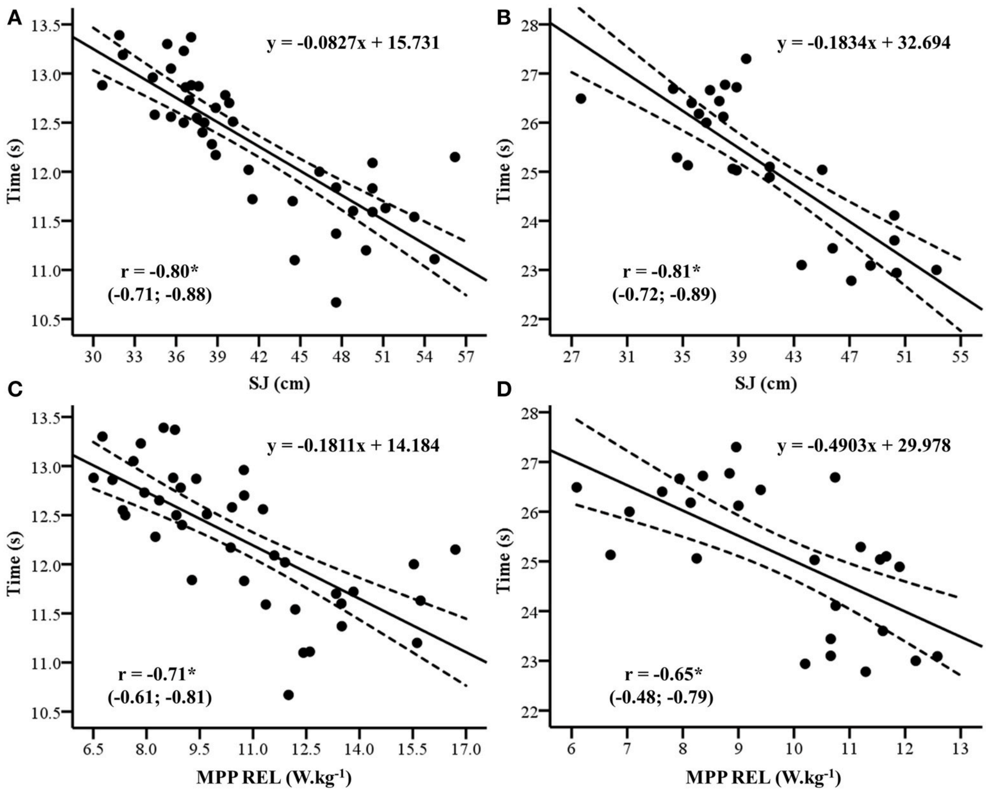

FIGURE 3 | Linear regression between 100 (A,C) and 200-m (B,D) dash performances and the squat jump (SJ) height and relative mean propulsive power (MPP REL) in the jump squat (JS) exercise; *$P < 0.01$.

regression models have increased only (on average) ∼1.2% of the explained variance between dependent (actual sprint times) and independent variables (SJ and JS), we considered relevant to carry out this calculation, since slight differences between individuals in 100- and 200-m dash events might significantly affect their competitive results. Observing the data reported here, from this point on, Paralympic coaches can better estimate the actual performance of their top-level athletes in official sprint competitions. Furthermore, by understanding the importance of this specific "mechanical combination" (i.e., SJ and JS) in sprinting performance, they will be able to develop more effective and specific training programs.

Concerning the within-subject variability, the smallest worthwhile enhancements in the 100- (0.9%) and 200-m dash (1.43%) were comparable to those reported in Olympic and Paralympic swimmers (Pyne et al., 2004). However, these values were higher than the estimates provided by elite track athletes without disabilities (Hopkins, 2005). The greater variability in athletes with visual impairment's performances may be associated with their disabilities (Fulton et al., 2009) and the possible influence of their respective guides on the individuals' sprinting mechanics (unpublished data). Importantly, the smallest worthwhile enhancement provides the coach with an idea of the meaningfulness of a given change in an athlete's performance. In general, an enhancement needs to be higher than the smallest worthwhile enhancement to affect the results (i.e., medal prospects; Fulton et al., 2009). Curiously, in the 100-m dash, the athletes presented worse sprinting times than their mean times during the period of observation, but during the Parapan American Games they achieved their "performance peak." Although in the 200-m the times were close to the mean performance throughout the observation, during the Parapan American Games, they reached a meaningful performance change (in comparison to the previous analyzed competitions). To some extent, this explains the outstanding results obtained by the Brazilian team during the 2015 Pan American Games (three gold, six silver, and two bronze medals in the 100- and 200-m races).

TABLE 2 | Predictions of 100- and 200-m dash performances using multiple regression analysis.

	R^2	Equation
100-m	0.66*	$y = 15.558 – (0.063 \times SJ) – (0.061 \times JS)$
200-m	0.66*	$y = 32.918 – (0.167 \times SJ) – (0.098 \times JS)$

*SJ, squat jump; JS, jump squat; *P < 0.01.*

The jumping test results were substantially more variable than the actual competitive performances in the 100- and 200-m dash (CV of SJ = 5.58% and JS = 7.97%), which implies the need for larger improvements in jumping tests, in order to consider these enhancements as meaningful. The general dynamics of the vertical jumping performance were similar to the sprinting performance; nevertheless, only SJ (change > 2.79%) attained a meaningful enhancement prior to the Parapan American Games. Accordingly, while monitoring SJ and JS in Paralympic athletes, coaches need to be aware that the meaningful performance changes should be greater than ≈2.79–3.98%; smaller changes can be considered within the range of the inherent measurement variability. The advantage of these practical and timesaving tests is that they can be easily implemented in the athletes' routines, for finely adjusting the training strategies and, therefore, improving sprinting performance (e.g., stretch-shortening cycle efficiency).

Future studies are necessary in order to determine other factors involved in the non-explained variance of sprinting ability in athletes with visual impairment (e.g., anthropometric characteristics of the subjects and coordination between the athletes with visual impairment and their respective guides, etc). Possibly, some factors related to jumping and running mechanics will reveal more movement similarities and additional associations between their respective kinetic and kinematic parameters.

CONCLUSION

Performance in Paralympic elite sprinting depends on a series of neuromuscular, physiological and technical factors. This study showed that vertical jump tests, in loaded and unloaded conditions, could be good predictors of athletes' sprinting performance, mainly when combined in a multiple linear regression equation. Furthermore, in this specific group of top-level Paralympic athletes, the dynamics of SJ and JS performances seem to follow the same variation as 100- and 200-m actual times. These findings may have important implications in athletes with visual impairment's training and testing methodology, since vertical jump tests can be easily performed by subjects with total or partial visual impairments. In addition, Paralympic track and field coaches can use these simple field assessments to specifically monitor their elite athletes close to official competitions, adjusting the training contents in order to optimize each athlete's performance peak. Finally, further studies should be conducted to investigate the chronic effects of training athletes with visual impairment using exclusively loaded and unloaded vertical jumps.

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Individualized Internal and External Training Load Relationships in Elite Wheelchair Rugby Players

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Aim: The quantification and longitudinal monitoring of athlete training load (TL) provides a scientific explanation for changes in performance and helps manage injury/illness risk. Therefore, accurate and reliable monitoring tools are essential for the optimization of athletic performance. The aim of the present study was to establish the relationship between measures of internal [heart rate (HR) and session RPE (sRPE)] and external TL specific to wheelchair rugby (WR).

Methods: Fourteen international WR athletes (age $= 29 \pm 7$ years; body mass $= 58.9 \pm 10.9$ kg) were monitored during 18 training sessions over a 3 month period during the competitive phase of the season. Activity profiles were collected during each training session using a radio-frequency based indoor tracking system (ITS). External TL was quantified by total distance (m) covered as well as time spent and distance covered in a range of classification-specific arbitrary speed zones. Banister's TRIMP, Edwards's summated HR zone (SHRZ), and Lucia's TRIMP methods were used to quantify physiological internal TL. sRPE was calculated as the product of session duration multiplied by perceived exertion using the Borg CR10 scale. Relationships between external and internal TL were examined using correlation coefficients and the 90% confidence intervals (90% CI).

Results: sRPE ($r = 0.59$) and all HR-based ($r > 0.80$) methods showed large and very large relationships with the total distance covered during training sessions, respectively. Large and very large correlations ($r = 0.56 - 0.82$) were also observed between all measures of internal TL and times spent and distances covered in low and moderate intensity speed zones. HR-based methods showed very large relationships with time ($r = 0.71 - 0.75$) and distance ($r = 0.70 - 0.73$) in the very high speed zone and a large relationship with the number of high intensity activities (HIA) performed ($r = 0.56 - 0.62$). Weaker relationships ($r = 0.32 - 0.35$) were observed between sRPE and all measures of high intensity activity. A large variation of individual correlation co-efficient was observed between sRPE and all external TL measures.

Conclusion: The current findings suggest that sRPE and HR-based internal TL measures provide a valid tool for quantifying volume of external TL during WR training but may underestimate HIA. It is recommended that both internal and external TL measures are employed for the monitoring of overall TL during court-based training in elite WR athletes.

Keywords: paralympic, performance, perceived exertion, exercise prescription, heart rate, speed zones

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INTRODUCTION

Coaches and sports science practitioners continue to take an increasingly scientific approach to the prescription and monitoring of athlete training (Malone et al., 2015; McLaren et al., 2015). The longitudinal monitoring of individual training load (TL) provides a quantifiable explanation for changes in performance, ensures target doses are achieved, and helps manage illness/injury risk. External TL describes the work completed by the athlete in terms of distance, speed or power using micro-technologies including time-motion analysis, accelerometers or power-meters, respectively (Lambert and Borresen, 2010; Halson, 2014; McLaren et al., 2015). The resultant physiological or psychological stress imposed, described as internal TL, drives adaptation in the relevant metabolic, cardiovascular and neurological systems (Halson, 2014). The outcome of any training intervention is therefore the consequence of both external and internal stimuli and reliable monitoring tools are vital for the optimization of athletic performance.

Like basketball and its wheelchair-based equivalent, wheelchair rugby (WR) is a court-based, intermittent sport characterized by frequent high intensity accelerations and decelerations (Barfield et al., 2010; Rhodes et al., 2015a). Eligibility for WR classification requires a functional impairment in all four limbs and encompasses a range of physical impairments including cervical level spinal cord injury (SCI), amputees, and cerebral palsy. Recently a novel radio-frequency based indoor tracking system (ITS) has been employed to quantify the external demands of competition (Rhodes et al., 2015a) and key determinants of successful performance during WR match-play (Rhodes et al., 2015b). Athletes typically cover distances ranging between 3500–4600 m during matches (Sarro et al., 2010; Rhodes et al., 2015a) with the majority of time spent (∼75%) performing low intensity activities interspersed with short, frequent bouts of high intensity activity (Rhodes et al., 2015a). The ability to reach high peak speeds and perform a greater number of high intensity activities (HIA) are key indicators of mobility associated with successful performance, as determined by team rank (Rhodes et al., 2015b).

WR squads are characterized by a large heterogeneity in athlete impairment which may result in a range of internal TL responses to the same dose of external load. Yet, training within a team sport environment is frequently prescribed on a squad-basis to develop sport-specific, technical, and tactical competences, thereby increasing the risk of non-functional over-reaching or under-training. Currently no research has investigated the use of internal TL measures during WR training in relation to commonly used measures of external TL. Barfield et al. (2010) attempted to quantify the exercise intensity of WR training sessions for a group of athletes with a cervical SCI using heart rate (HR) as a measure of internal load. However, HR is considered an ineffective tool for monitoring TL in some athletes with a cervical level SCI due the reduction in maximal HR responses (120–150 bpm^{-1}) associated with impaired autonomic function (Valent et al., 2007; Paulson et al., 2013). An increasing number of non-SCI athletes now compete in WR, therefore, HR-based methods maybe suitable for these individuals. Banister's TRIMP, Edwards' summated HR zone (SHRZ), and Lucia's TRIMP are HR-based methods that have been utilized to quantify physiological load in able-bodied sports (Banister, 1991; Edwards, 1993; Lucia et al., 2003; Waldron et al., 2011; Scanlan et al., 2014). However, the use of these HR-based methods in intermittent sports may underestimate near maximal short high and very high intensity efforts due to the heavy reliance on anaerobic metabolism (Alexiou and Coutts, 2008; Akubat and Abt, 2011).

The session rating of perceived exertion (sRPE) provides an alternative method of quantifying internal TL, which describes a subjective, global rating of intensity and is the product of training duration, and perceived exertion using Borgs CR10 scale (Borg, 1998; Foster et al., 2001). Very large linear relationships are observed between HR and RPE-based methods in field and indoor intermittent sports supporting sRPE as a valid alternative for the quantification of internal TL (Impellizzeri et al., 2004; Manzi et al., 2010; Waldron et al., 2011; Scott et al., 2013; Lupo et al., 2014; Scanlan et al., 2014). Lovell et al. (2013) and Scott et al. (2013) have also observed large relationships between sRPE and external TL indices, including total distance covered, during elite Rugby League and Football training, respectively. In contrast, Weston et al. (2015) report only small relationships between overall match RPE and GPS-derived measures of external load in Australian League Football. Currently no "gold standard" method currently exists for the quantification of internal TL during high intensity/intermittent activities representative of WR. The aim of this study was to establish the relationship between traditional measures of internal TL (HR and sRPE) and external TL measures specific to WR.

METHODS

Participants

Fourteen international WR players (age = 29 ± 7 years; body mass = 58.9 ± 10.9 kg; time in sport = 9 ± 2 years; training hours = 9 ± 2 h.wk^{-1}; n = 1 female) with a cervical SCI (n = 9) and non-SCI (n = 5) volunteered to participate in the current study. Ethical approval for the study was obtained through Loughborough University's ethics committee. Prior to participation, all players provided their written, informed consent.

Design

The study employed a single cohort observation with data collected during a total of 18 WR training sessions performed over a 3 month period during the competitive phase of the season. Prior to the training phase all participants performed an initial laboratory exercise test for the determination of resting (HR_{rest}) and peak (HR_{peak}) HR and peak oxygen uptake ($\dot{V}O_{2peak}$). During training sessions external and internal TL data were collected for all athletes using the ITS and sRPE, respectively. HR was only collected during training from the non-SCI players. All training sessions were performed at the same indoor venue on wooden sprung flooring. Data were only analyzed for individuals completing whole training sessions.

Submaximal Test and Graded-Exercise Test to Exhaustion (GXT)

HR_{rest} was determined following a 10-min rest in a semi-supine position using radio telemetry (Polar PE 4000, Kempele, Finland). All participants' performed the tests in their competition sports wheelchair on a motorized treadmill (HP Cosmos, Traunstein, Germany). The submaximal test and GXT were performed according to the protocols described by Leicht et al. (2012). Briefly, participants performed six to eight submaximal constant-load 4-min exercise blocks at ascending speeds at a fixed gradient of 1.0%, in order to elicit physiological responses covering a range from 40 to 80% $\dot{V}O_{2peak}$ (Leicht et al., 2012). This was followed by a 15-min passive recovery. The gradient at the start of the GXT was 1.0% with subsequent increases of 0.1% every 40 s to ensure a minimum GXT duration of ~8 min. After the GXT, participants recovered actively at a low intensity (1.2 ms^{-1}) at a 1.0% gradient for 5 min. Participants then performed a verification test, designed as a test to exhaustion at the same constant speed but 0.1% higher than the maximal gradient achieved during the GXT. The GXT and the verification test were terminated when participants were unable to maintain the speed of the treadmill. HR was measured throughout the test with the highest 5 s rolling average used to establish HR_{peak}. On-line respiratory gas analysis was carried out throughout the GXT and verification stage via a breath-by-breath system (Cortex metalyser 3B, Cortex, Leipzig, Germany). Before the test, gases were calibrated according to the manufacturer's recommendations using a 2-point calibration ($O_2 = 17.0\%$, $CO_2 = 5.0\%$ against room air) and volumes with a 3-L syringe at flow rates of 0.5–3.0 $L\cdot s^{-1}$. Breath-by-breath data allowed the highest 30 s rolling average $\dot{V}O_2$ value recorded and was taken as the $\dot{V}O_{2peak}$.

External TL

Activity profiles were quantified during each training session using a radio-frequency based ITS (Ubisense, Cambridge, UK) described previously (Rhodes et al., 2014; Perrat et al., 2015). Each participant was equipped with a small lightweight tag (25 g), which was attached on or near the foot-strap of athletes own rugby wheelchairs. Tags communicate wirelessly at a frequency of 8 Hz via ultra wideband radio signals with six sensors elevated around the perimeter of the court (28 × 15 m) to provide time and location data in three dimensions. The reliability of tags operating at this sampling frequency range between a coefficient of variation of 0.5% for distance covered and mean speed reached and never exceeded 2.0% for peak speed detection (Rhodes et al., 2014).

External TL was quantified by the total distance (m) covered during each training session. The time spent and distance covered in a range of classification-specific arbitrary speed zones, determined by the mean, peak speed (V_{max}) of each class, as previously defined by Rhodes et al. (2015a) were also reported. These speed zones were based on a percentage of the peak speed ($\%V_{max}$) for each classification group and were categorized as the following intensities: zone 1 = very low speed ($\leq 20\%V_{max}$), zone 2 = low speed (21–50%V_{max}), zone 3 = moderate speed (51–80%V_{max}), zone 4 = high speed (81–95%V_{max}), and zone 5 = very high speed ($>95\%V_{max}$). The number of HIA, as defined by the frequency of bouts performed in both high and very high speed zones, were also recorded.

Internal TL

HR-Based Methods

During training HR was collected via a Polar team system (Polar Team[2], Kempele, Finland) sampling at 5 s intervals. This HR data were incorporated into the Banister's TRIMP (Banister, 1991), Edwards SHRZ (Edwards, 1993) and Lucia's TRIMP to provide physiological measures of internal TL and are quantified in arbitrary units (AU). Banisters' TRIMP combines predetermined, individualized HR_{peak} and HR_{rest} measures, as well as the average HR during training (HR_{ex}). The activity intensity is weighted using a fixed exponential relationship between changes in HR and blood lactate concentration during incremental exercise (Banister, 1991). The formula to determine TL in males using the TRIMP model proposed by Banister is as follows:

$$\begin{aligned} \text{TRIMP training load (AU)} &= [\text{duration (min)}](HR_{ex} - HR_{rest})/ \\ &\quad (HR_{peak} - HR_{rest}) \times 0.64e^{1.92x} \\ \text{where} \quad e = 2.712, \text{ and } x &= (HR_{ex} - HR_{rest})/ \\ &\quad (HR_{peak} - HR_{rest}). \end{aligned}$$

The SHRZ model proposed by Edwards determines internal TL by multiplying the accumulated training duration in five discrete HR zones relative to HR_{peak} by a coefficient relative to each zone and summating the results. The formula to determine TL using the SHRZ model is represented as:

$$\begin{aligned} \text{SHRZ training load (AU)} &= (\text{duration in zone 1} \times 1) \\ &\quad +(\text{duration in zone 2} \times 2) \\ &\quad +(\text{duration in zone 3} \times 3) \\ &\quad +(\text{duration in zone 4} \times 4) \\ &\quad +(\text{duration in zone 5} \times 5) \\ \text{where} \quad \text{zone 1} &= 50 - 60\%\, HR_{peak}; \\ \text{zone 2} &= 60 - 70\%\, HR_{peak}; \\ \text{zone 3} &= 70 - 80\%\, HR_{peak}; \\ \text{zone 4} &= 80 - 90\%\, HR_{peak}; \\ \text{and} \quad \text{zone 5} &= 90 - 100\%\, HR_{peak}. \end{aligned}$$

Lucia's TRIMP method was calculated by multiplying the time spent in three different HR zones (zone 1 = below the ventilatory threshold, zone 2 = between the ventilatory threshold and the compensation point, zone 3 = above the respiratory compensation point) by a co-efficient for each zone (zone 1 = 1, zone 2 = 2, zone 3 = 3) and summating the results. HR zones are therefore defined on individual parameters obtained in the laboratory (Lucia et al., 2003). Lactate thresholds were employed as previously indicated (Impellizzeri et al., 2004) due to the more frequent threshold determination using BLa over ventilatory data in wheelchair athletes reported by Leicht et al. (2014).

Session RPE

The session RPE represents a single global rating of the intensity of a training session as described previously by Foster et al. (2001). Prior to the study all training participants were familiarized with the Borg CR10 scales and the associated verbal anchors (Borg, 1998). Within 30 min of a training session being completed participants were shown the scale and asked to provide a rating of the overall perceived intensity of the session. The sRPE was then calculated by multiplying the duration of the session in minutes by the individual RPE for that training session and was again presented as AU.

Statistical Analyses

Participants completing <5 training sessions were excluded from the statistical analysis leaving a total number of 78 observations from nine participants ($n = 6$ cervical SCI). All data were analyzed using the Statistical package for the Social Sciences (SPSS version 21.0, Chicago, Illinois, USA). The mean ± SD were calculated for each measure of external and internal TL. A within-measures design was used to determine if high internal load measures (Banister's, Edwards, Lucia's, sRPE) were associated with higher ITS-derived TL measures for the whole group as described previously (Bland and Altman, 1995). Confidence intervals (90% CI) for the within-player correlations were calculated. Individual relationships between external and internal TL measures were examined using Pearson correlation coefficients and the 90% CI. The magnitude of all correlations were categorized as trivial ($r < 0.1$), small ($r = 0.1$–0.3), moderate ($r = 0.3$–0.5), large (0.5–0.7), very large ($r = 0.7$–0.9), nearly perfect ($r > 0.9$), and perfect ($r = 1$; Hopkins et al., 2009). Statistical significance was set at $P < 0.05$.

RESULTS

The mean duration of all training sessions was 143 ± 40 min and ranged from 84 to 230 min. The mean external load measures of all training sessions are presented in **Table 1**. Mean internal TL was 97 ± 38 AU (Banisters), 310 ± 119 AU (Edwards), 247 ± 74 (Lucia's), and 934 ± 359 AU (sRPE). A large correlation was found between sRPE and both Banisters TRIMP ($r = 0.62$), Edwards SHRZ ($r = 0.64$). In addition, a very large correlation was found between sRPE and Lucia's TRIMP ($r = 0.81$).

HR and sRPE-based methods of internal TL showed a very large and large correlation with the total distance covered during training sessions, respectively. **Table 2** demonstrates the relationship between measures of external TL associated with exercise intensity and internal TL. Very large correlations were observed between Banisters TRIMP, Edwards SHRZ and Lucia's TRIMP and the times spent and distances covered in speed zones 2, 3, and 5. Large, significant correlations were observed between sRPE and the time spent and distance covered in zones 2 and 3. All HR-based methods demonstrated a large relationship (0.56–0.62) with the number of HIA performed. No significant correlation was identified between the number of HIA performed and sRPE.

Individual correlation coefficients between sRPE and measures of external TL are presented in **Table 3**. The only measures of external TL that demonstrated a positive correlation with sRPE for all individuals were the times spent in speed zone 2 and the distances covered in speed zones 1 and 2.

DISCUSSION

The individualization of athlete training is vital to optimize physical preparation within a team environment. Reliable and valid tools are required to accurately quantify intermittent, court-based TL involving athletes with the range of physical impairments displayed in WR. An interesting finding of the current study was the large relationships between all internal TL measures and total distance covered during training as previously observed in the able-bodied sports of elite football (Casamichana et al., 2013; Scott et al., 2013) and rugby league (Lovell et al., 2013). All internal TL measures demonstrated large or very large correlations with time spent and distance covered in speed zones 2 (low) and 3 (moderate). Also in accordance with previous findings (Casamichana et al., 2013; Scott et al., 2013), weaker relationships were observed between internal TL and external TL measures of high intensity training, including the number of HIA performed. The current observations suggest sRPE and HR-based measures of internal TL provide a valid tool for quantifying volume measures of external TL during WR training but sRPE may underestimate high intensity training doses. Large ranges in within-individual sRPE-external TL relationships suggest a variety of perceptual cues are responsible for determining sRPE during WR training. It is recommended that both internal and external TL measures are employed for the monitoring of overall TL during court-based training in elite WR athletes.

Coaches and Sport Science practitioners prescribe external TLs to replicate or exceed competition intensities and induce physiological and/or psychological stress (i.e. internal TL) that drives subsequent training adaptation. The use of HR in intermittent sports is less straightforward than for endurance/aerobic-based sports, due to the heavy reliance on

TABLE 1 | Descriptive statistics of external load measures during wheelchair rugby training sessions measured by the ITS ($n = 9$).

	Mean (SD)	Range	% of training session
Total distance (m)	4511 (1666)	1678–8694	–
Time in Zone 1	24:23 (12:13)	05:27–52:51	38.4
Time in Zone 2	24:05 (11:01)	07:41–54:21	38.0
Time in Zone 3	11:49 (04:08)	04:02–25:12	18.6
Time in Zone 4	02:23 (01:22)	00:34–06:00	3.8
Time in Zone 5	00:38 (00:33)	00:00–02:46	1.0
Distance in Zone 1	458 (193)	113–962	10.2
Distance in Zone 2	1781 (851)	589–4113	39.5
Distance in Zone 3	1655 (597)	569–3463	36.7
Distance in Zone 4	462 (269)	107–1164	10.2
Distance in Zone 5	147 (134)	0–674	3.3
HIA (n)	53 (29)	14–127	–

All distances (m) and times (mm:ss).

TABLE 2 | Within-individual correlation coefficients (90% confidence interval) for relationship between intensity measures of external load and internal training load.

External load	Internal load			
	Banisters TRIMP ($n = 31$)	Edwards SHRZ ($n = 31$)	Lucias TRIMP ($n = 31$)	sRPE ($n = 78$)
Total Distance	0.81** (0.67–0.89)	0.84** (0.72–0.91)	0.82** (0.69–0.90)	0.59* (0.47–0.70)
Time in Zone 1	0.37 (0.08–0.60)	0.40 (0.22–0.63)	0.39 (0.10–0.62)	0.37 (0.20–0.53)
Time in Zone 2	0.85** (0.74–0.92)	0.87** (0.77–0.93)	0.83** (0.69–0.90)	0.56* (0.42–0.68)
Time in Zone 3	0.66* (0.46–0.81)	0.72** (0.53–0.84)	0.75** (0.59–0.86)	0.59* (0.45–0.70)
Time in Zone 4	0.41 (0.12–0.63)	0.41 (0.13–0.63)	0.37 (0.08–0.60)	0.22 (0.03–0.39)
Time in Zone 5	0.75** (0.58–0.86)	0.75** (0.57–0.85)	0.71** (0.52–0.83)	0.33 (0.15–0.49)
Distance in Zone 1	0.52* (0.26–0.71)	0.52* (0.26–0.71)	0.51* (0.25–0.71)	0.45 (0.28–0.59)
Distance in Zone 2	0.82** (0.69–0.90)	0.84** (0.72–0.91)	0.81** (0.67–0.89)	0.56* (0.42–0.68)
Distance in Zone 3	0.67* (0.46–0.81)	0.72** (0.53–0.84)	0.74** (0.56–0.85)	0.58* (0.55–0.69)
Distance in Zone 4	0.43 (0.15–0.65)	0.43 (0.15–0.65)	0.39 (0.10–0.62)	0.22 (0.03–0.39)
Distance in Zone 5	0.72** (0.53–0.84)	0.73** (0.54–0.84)	0.70* (0.10–0.62)	0.35 (0.18–0.51)
No. of HIA	0.62* (0.39–0.78)	0.61* (0.38–0.77)	0.56* (0.50–0.83)	0.32 (0.14–0.48)

*Large within-individual correlation ($r = 0.5$–0.7).
**Very large within-individual correlation ($r = 0.7$–0.9).

TABLE 3 | Individual correlation coefficients between sRPE and measures of external training load.

Participant			Time in speed zones					Distance in speed zones					
	n	*TD*	1	2	3	4	5	1	2	3	4	5	HIA
1	8	0.44	0.81	0.65	−0.22	−0.43	0.32	0.80	0.63	−0.25	−0.42	0.29	−0.54
2	11	0.52	0.50	0.46	0.54	0.04	0.44	0.59	0.41	0.55	0.04	0.53	0.07
3	7	−0.03	0.62	0.43	−0.03	−0.69	0.12	0.42	0.41	−0.28	−0.69	0.02	−0.70
4	8	0.82	0.26	0.79	0.77	0.76	0.82	0.27	0.79	0.79	0.77	0.78	0.72
5	7	0.39	0.49	0.62	0.46	−0.58	−0.13	0.56	0.58	0.40	−0.58	0.06	−0.55
6	7	0.61	0.83	0.71	0.47	−0.39	0.60	0.81	0.72	0.43	−0.40	0.62	−0.09
7	16	0.38	0.23	0.24	0.56	0.04	−0.08	0.19	0.25	0.57	0.04	−0.05	0.17
8	9	0.70	0.71	0.74	0.55	0.28	0.33	0.72	0.73	0.43	0.25	0.33	0.16
9	5	0.82	0.97	0.67	0.68	0.85	0.67	0.96	0.67	0.69	0.83	0.67	0.68
Min	5	−0.03	0.23	0.24	−0.22	−0.69	−0.13	0.19	0.25	−0.28	−0.69	−0.05	−0.70
Max	16	0.82	0.97	0.79	0.77	0.85	0.82	0.96	0.79	0.79	0.83	0.78	0.72
Range	11	0.85	0.74	0.55	0.99	1.54	0.95	0.77	0.54	1.07	1.52	0.83	1.42

anaerobic metabolism and the associated delay in HR response with short duration, high intensity efforts (Alexiou and Coutts, 2008; Akubat and Abt, 2011). sRPE has been proposed as a cost-effective alternative to HR-based methods as a global measure of training intensity that may more accurately quantify internal TL in intermittent sports. In accordance with previous findings in football (Impellizzeri et al., 2004; Alexiou and Coutts, 2008), rugby union (Waldron et al., 2011), and basketball (Manzi et al., 2010), **Table 2** displays large and very large relationships between sRPE and Banisters TRIMP, Edward's SHRZ, and Lucia's TRIMP.

An interesting finding of the present study was the large relationships between all internal TL measures and total distance covered during intermittent, court-based WR training. Scott et al. (2013) previously observed very large ($r = 0.71$–0.84) correlations between internal TL measures (sRPE, Bansiters TRIMP, Edwards SHRZ) and total distance covered and volume of low speed activity during in-season training of 15 professional football players. Similarly, Casamichana et al. (2013) found large to very large associations between total distance and both sRPE and Edwards SHRZ in 28 semi-professional football players over 44 training sessions. Lovell et al. (2013) investigated the validity of sRPE for quantifying overall TL in 32 professional rugby league players. A very large correlation was observed between sRPE and total distance ($r = 0.69$–0.80) in conditioning, skills-conditioning, and speed-based training (Lovell et al., 2013). A large significant correlation was also observed in the present study between the time spent and distance covered in low and moderate speed zones, with stronger relationships between HR-based methods ($r = 0.63$–0.84) than sRPE ($r = 0.54$–0.59). The present findings support both internal TL variants as a marker of volume (total distance covered) and low/moderate intensity activity. This is significant as WR match-play and training are frequently characterized by large volumes of low intensity movements (∼75%) interspersed with short, frequent bouts of high intensity activity (Sarro et al., 2010; Rhodes et al., 2015a).

Weaker relationships were observed between sRPE (∼0.30) distance covered and time spent in high (zone 4) and very high (zone 5) speed zones vs. all HR-based methods. Previously, sRPE has been found to display weaker relationships to high/very high speed running activity ($r = 0.40$–0.67) in professional football (Scott et al., 2013) and high intensity-based measures of rugby league TL (Lovell et al., 2013). As the criterion speed of external TL increases, the strength of relationship to sRPE becomes weaker (Scott et al., 2013). This may represent the small window in which RPE can change (1–10) and the lack of sensitivity to small manipulations in training intensity. Also high speed activities interspersed with long periods of rest may reduce RPE despite high activity levels. Typically less than 5% of time during WR match-play is spent at speeds above 80% Vmax (Rhodes et al., 2015a,b). However, the sRPE-based relationships described above may under-estimate large volumes of time spent/distance covered in high or very high speed zones that accumulate during intensive training periods.

A novel finding of the present work was the large variation observed in individual relationships between sRPE and all external TL measures times spent in low intensity speed zones (zone 2) and the distances covered in very low (zone 1) and low intensity speed zones (zone 2). Perceived exertion is a subjective global rating of intensity governed by a multitude of physiological, psychological, and environmental perceptual cues (Hampson et al., 2001). While the subjective range of intensity (from min to max effort) is known to be equal between individuals, the dominant cues determining perceptions of effort may differ greatly (Lambert and Borresen, 2010). Interestingly, Weston et al. (2015) observed only small to moderate relationships between differentiated and overall sRPE and match-play movement demands in Australian League Football. By analysing the intra-individual correlation co-efficient it is clear a wide range of relationships are present between sRPE and external load measures (i.e. total distance $r = -0.03$–0.82). All participants were familiarized in using the scale prior to the study using standardized instructions (Borg, 1998). However, factors including technical role on court, accumulated fatigue, or psychological stress could all influence an individual athlete's perception of effort during a training session. As previously described, players performing very defensive roles on court may spend a large portion of training performing low-volume activity, including blocking maneuvers, with a high physiological cost. Therefore, baselines of RPE for distinct training intensities should be established by practitioners prior to any longitudinal monitoring in order to gain an insight into intra-individual variations in RPE.

A limitation of the current methodology was that no distinction was made between on-court training modes during the correlation analysis. Weaving et al. (2014) recently employed principle component analysis to explore the influence of training modality on relationships between TL measures during sport-specific training modes 32 rugby league players. For skills training, external measures of body load and total impacts explained the greatest proportion of variance in TL (Weaving et al., 2014). Internal measures of sRPE and Banisters TRIMP explained the greatest variance in speed-based training (Weaving et al., 2014). HIA including jumping, turning, physical contact, or resistance training may be recorded as low speed activity but demand a high physiological load (Scott et al., 2013; Weaving et al., 2014). The metabolic cost of sport-specific skills, including dribbling and kicking in football and tackling in rugby, is also greater than running alone at the same speed (Scott et al., 2013). It is therefore recommended that external TL data are considered within the context of the training environment and a combination of internal and external load measures employed to accurately quantify across training modes (Weaving et al., 2014). Future research should explore the individual internal TL responses to external TL doses experienced during individual WR-specific training drills with a larger cohort of participants.

In conclusion, methods for quantifying external TL, particularly the no. of HIA performed, should always be employed for monitoring overall TL in elite WR athletes. sRPE provides a valid alternative to HR-based methods for assessing distance covered and low to moderate intensity activity in individuals with an impaired HR response. However, sRPE-based measures may underestimate the dose of external TL performed at high or very high intensities. The intra-individual relationships between external TL measures and sRPE should be assessed for each athlete prior to performing any systematic longitudinal monitoring.

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OPINION
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Preparation of Paralympic Athletes; Environmental Concerns and Heat Acclimation

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High ambient temperature and relative humidity (rh) are of great importance when considering athletic performance. Such factors are of particular interest when considering that the majority of Paralympic Games have been hosted at locations with potentially challenging environmental conditions (e.g., Atlanta, Sydney, Athens, Beijing) and a range of Paralympic athletes exhibit conditions manifesting thermal dysfunction. Prior to the Atlanta Games in 1996, Nielsen (1996) considered the "fight against physics" with respect to high ambient temperature (30–38°C) and relative humidity (rh; 40–80%) on endurance performance for able-bodied athletes. It was noted that with such potentially severe conditions outdoor endurance based performances could be severely reduced, especially in spells of high humidity. Strategies to prevent heat illness were recommended including events being scheduled at times of lower thermal stress or re-scheduled if temperatures were above 35°C. However, how these conditions may affect Paralympic athletes has not yet been reported. This article will consider what is known regarding enhancing (or maintaining) performance in the heat in athletes with motor disabilities in preparation for Rio 2016.

LIKELY CONDITIONS FOR RIO, 2016

Average daily environmental temperatures expected for Rio during August are ∼28°C. However, at the time of writing (August, 2015), peak daily environmental temperatures at the four Paralympic venues (Deodoro, Maracana, Copacabana, and Barra) were between 32 and 36°C (35–50% rh) at 12:00–15:00 h. Furthermore, peak humidity rose to 70–75% during early to late evening (18:00–21:00 h) with some early morning humidity values reaching 100% (Worldwideweather, August 2015)[1]. As optimal environmental temperatures for endurance performance in those with intact thermoregulatory systems are between 6–10°C (Galloway and Maughan, 1997) and uncompensable heat stress occurs at environmental temperatures of ∼35°C and >60% rh (Nielsen, 1996) these conditions are challenging at best. For Paralympic athletes with thermal dysfunction performance, as well as daily activities and health, may well be negatively affected.

PARALYMPIC POPULATIONS AT RISK

Paralympic classifications for competition include spinal cord impairment, visual impairment, cerebral palsy, amputees, and Les Autres. Athletes with motor disabilities are reflected across a number of classifications. Contributing causes of motor disabilities include traumatic (spinal cord injury or loss of limbs) and disease or congenital conditions (cerebral palsy, muscular dystrophy,

[1] Worldweatheronline (2015). Available online at: http://www.worldweatheronline.com/Rio-De-Janeiro-weather-averages/Rio-De-Janeiro/BR.aspx (Accessed August 16, 2015).

multiple sclerosis, or spina bifida). The greatest amount of literature pertaining to thermoregulatory responses during exercise for any group of Paralympic related conditions is for athletes with spinal cord injury (SCI) who demonstrate both motor and neurological deficits. This body of literature most likely reflects the clear thermal dysfunction of this population in proportion to the level of spinal cord injury (For review see Price, 2006). Literature concerning thermoregulatory responses of other Paralympic conditions is unfortunately lacking.

Spinal cord injury results in a loss of motor function and neurological innervation below the level of injury (Price, 2006). In general, athletes with paraplegia (i.e., thoracic and lumbar spinal injuries) demonstrate reduced recruitable muscle mass and a sympathetic nervous system in proportion to the level of lesion. Those athletes with tetraplegia (i.e., cervical spinal injuries) demonstrate the smallest amount of recruitable muscle mass, characterized by upper limb dysfunction due to the injury occurring at a level within the brachial plexus which serves the upper limb. Athletes with tetraplegia also generally demonstrate no sympathetic nervous system innervation due to the level of injury also being above the thoracolumbar sympathetic outflow. As the key thermoregulatory effectors for heat dissipation, namely sweating, and changes in cutaneous blood flow, are sympathetically driven athletes with tetraplegia demonstrate an absent or much reduced sweating capacity. As the imbalance between rate of heat production and heat dissipation determines the magnitude of heat storage and increases in core temperature (Kenny and Jay, 2013) athletes with tetraplegia demonstrate continual increases in body temperature during continuous submaximal exercise in both cool and warm conditions (Price and Campbell, 1999, 2006). For athletes with paraplegia, the reduced sweating capacity appears reasonably matched by the reduction in metabolic heat production as evidenced by similar increases in body temperature for athletes with high level lesion paraplegia (T1–T6) and lower level paraplegia (T7 and below) (Price and Campbell, 2003). Athletes with tetraplegia are thus considered to be at a greater risk of heat injury when compared to athletes with paraplegia who, in turn, have a greater risk of heat injury when compared to able-bodied athletes.

CLASSICAL APPROACHES TO REDUCE HEAT STRAIN

In preparation for competition in hot conditions, athletes generally consider heat acclimation (HA) or various cooling techniques to reduce heat strain and the subsequent risk of heat injury. Although HA is the key method recommended to optimize performance in hot conditions (Racinais et al., 2015) recommendations for reducing exertional heat injury for athletes with SCI are brief (Binkley et al., 2002) with no update in recent years (National Athletic Trainers' Association (NATA), 2014). Conversely, Griggs et al. (2015) recently reviewed cooling strategies in athletes with SCI concluding that due to the athletes reduced heat dissipation potential, using water sprays and cooling garments may be of great benefit. Furthermore, the majority of studies had not simulated true competitive situations and factors to optimize cooling potential within the constraints of competitive regulations have yet to be established. This is also true for cold slurry ingestion which may provide a useful heat sink for this population. Therefore, this article will focus on heat acclimation.

Heat acclimation refers to procedures to elicit favorable physiological adaptations to heat stress using artificial conditions whereas heat acclimatization involves natural conditions. Heat acclimation usually occurs as part of the athlete's preparation prior to traveling to holding camps where the more natural heat acclimatization can be undertaken prior to the competitive event. Heat acclimation (and heat acclimatization) classically occurs from repeated exposure to exercise in the heat over 5–14 days (Armstrong and Maresh, 1991). More recently, intermittent and shorter duration heat acclimation procedures as well as a "thermal clamp" method, where core temperature is increased during heat stress trials and maintained at a desired level, have been considered (Garrett et al., 2009; Chen et al., 2013). Nevertheless, whichever methods are utilized, HA and acclimatization result in a number of key physiological adaptations to improve heat dissipation (Armstrong and Maresh, 1991). In able-bodied athletes with an unaffected thermoregulatory system HA adaptations typically include; reduced deep body ("core") temperature at rest as well as reduced deep body temperature, reduced skin temperature (and therefore reduced heat storage), increased skin blood flow and increased sweat rates at a given exercise intensity (Armstrong and Maresh, 1991; Armstrong, 2000; Lorenzo and Minson, 2010).

Sweating capacity and dynamic skin blood flow changes are well-known to be reduced or absent below the level of lesion in persons with SCI (Hopman, 1994; Price, 2006). Furthermore, similar deep body temperature and whole body sweat losses have been observed for both able-bodied upper body trained athletes and athletes with SCI during 60–90 min of arm crank exercise at the same relative exercise intensity (~60% peak oxygen uptake) in cool conditions (Price and Campbell, 1997, 1999). As these athletes with SCI would have had ~50% of their body surface area available for sweating these data suggest a greater sweat output per gland under the same exercise conditions and thermal strain. Subsequently, maximal sweat rates are potentially being achieved during exercise in cool environmental conditions by athletes with SCI (Price and Campbell, 2006). Alternatively, persons with SCI could demonstrate increased sweat gland activity and local sweat rates with heat acclimation. However, those persons with higher lesions levels (and lower whole body sweat rates) may not be able elicit a great enough increase in whole body sweat rate to affect core temperature responses. An athlete's remaining sweating capacity may subsequently be of key importance to heat acclimation success in this population.

HEAT ACCLIMATION STUDIES IN PERSONS WITH SCI

Two studies have reported the responses of persons with SCI to a period of HA. Although it is difficult to conclude any specific HA outcomes in this population from such a small body of literature it is important to consider what is currently known to stimulate future research. Castle et al. (2013) examined a 7 day period of HA (33°C, 65% rh) in a mixed group of Paralympic shooters ($n =$ 5) comprising of one athlete with tetraplegia (C4/5) two athletes with paraplegia (T9/10), one athlete with spina bifida (T6), and one athlete with Polio. Each day athletes undertook 60 min of heat exposure including 20 min of arm crank ergometry at 50 W followed by passive heat exposure or simulated shooting practice. Heat acclimation was partially evidenced as a reduction in resting and exercising aural temperature on day 7 compared to day 1 as well as decreased perceptions of effort, thermal strain, and increased plasma volume, thus supporting expected able-bodied adaptations.

Conversely, observations from our laboratory (Price et al., 2011) observed no typical HA responses for participants with tetraplegia ($n = 5$; C5–C7) or paraplegia ($n = 5$; T7-L1) also undertaking 7 days of HA, The protocol was similar to Castle et al. (2013) consisting of daily exercise in the heat (35°C, 40% rh) for 30 min at 50% peak aerobic power output followed by 30 min of passive recovery in the heat. Although the expected differences between groups for aural temperature were observed during exercise in the heat (Price and Campbell, 2003) no changes in aural temperature were observed between day 1 and day 7 for either group. A lack of HA may have been expected for the persons with tetraplegia with an absence of sweating, but not for the persons with paraplegia who demonstrated visible sweating capacity. It is possible that the exercise intensity, and thus body temperature stimulus, was not great enough to elicit heat acclimation however, the intensity was comparable to that of Castle et al. In addition both studies reported aural temperature as the deep body temperature estimate, with similar magnitudes of increase, so differences in deep body temperature site cannot solely explain the difference in results. Inter- and intra-individual variation in thermal responses, which are known to be large in the SCI population, along with differing lesion levels and disabilities may be key contributing factors between these studies observations.

Interestingly, reductions in perceived thermal strain on day 7 compared to day 1 with no change in aural temperature were observed for the group with paraplegia (Price et al., 2011). Such a response though may not be an advantageous adaptation as those individuals who cannot accurately assess their thermal status may be at a greater risk of heat injury (Goosey-Tolfrey et al., 2008). The group with tetraplegia showed no change in perceptions of thermal strain between day 1 and day 7, although thermal strain values were perceived at a similar level to the group with paraplegia even though aural temperatures during exercise were consistently greater. These responses suggest differences in the perception of thermal stimuli to those individuals with paraplegia and may potentially be due to much reduced surface area for afferent thermal information with tetraplegia when compared to paraplegia. Such responses should be examined in further detail. Although our data were collected from predominantly recreationally active, non-athlete participants such a population may represent athletes in sports where aerobic capacity and associated partial acclimation (as observed in able-bodied athletes; Piwonka et al., 1965) are not fully developed, coaches, or spectators. All of whom may be exposed to environmental stressors.

In addition to outdoor performances, indoor performances such as wheelchair basketball, rugby, and fencing may be of concern for some athletes. For example, a number of athletes, particularly those with tetraplegia, are unaware of the magnitude of rising body temperature during competitions undertaken in air-conditioned venues. Elevated "on court" body temperatures for some such players have been reported anecdotally by support staff and are similar to those observed during exercise in the heat or indeed the safety limits utilized in laboratory based thermoregulation studies. As heat acclimation has been shown to improve performance in cool conditions in able-bodied athletes (Lorenzo et al., 2010) this procedure may be of value for those athletes with lower level SCI and a significant sweating area, competing in indoor venues. However, the potential of reduced perceived thermal strain with no change in deep body temperature should always be considered. It should also be noted that other authors have observed no effect of heat acclimation on performance in cool conditions (Karlsen et al., 2015).

PRACTICAL CONSIDERATIONS

As can be gleaned from the above review, our knowledge of heat acclimation in athletes with SCI is considerably lacking. In addition, the wide range of individual responses to exercise in the heat, including skin temperature and sweating (Goosey-Tolfrey et al., 2008), makes general heat acclimation recommendations for this population difficult. It is possible that if athletes are educated regarding awareness of their thermal state during repeated exposure to heat and, importantly, have access to temperature monitoring devices for enhanced thermal safety assessment, such procedures may have performance benefits. As yet, few studies have considered performance aspects of thermal physiology in athletes with SCI so we are unfortunately unable to determine the efficacy of heat acclimation in this population with confidence. The same can also be stated for other groups of Paralympic athletes. As with most aspects of performance optimization, a considered individual approach needs to be taken with respect to environmental challenges. Appropriate medical back up and monitoring should always to available in such instances.

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Thermoregulation in wheelchair tennis—How to manage heat stress?

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Founded in 1976 and having become a full medal sport at the 1992 Barcelona Paralympics, the popularity of wheelchair tennis continues to grow. With the exception of the "double-bounce rule," wheelchair and able-bodied tennis follow the same rules. Most of tennis matches are played in cool outdoor conditions or climate-controlled indoor venues. Nonetheless, it is common for top-level players to be exposed to hot (>30°C) and/or humid (>70% rH) conditions during competition or training [Wet Bulb Globe Temperature (WBGT) of 28°C or greater]. At the 2009 Australian Open championship, Australia's former world No 1 Daniela Di Toro, spoke about the high court temperatures (often above 40°C)—"*You've got the direct heat overhead as well as radiant heat all around you that has been absorbed by the court and your chair, and it really is extremely full-on.*" Heat stress may not only threaten the quality of play, but could potentially pose a risk to the players' health. Detailed description of thermal, physiological and perceptual responses of able-bodied players to simulated competitions can be found in the literature (Fernandez Fernandez et al., 2006), while the investigations that have involved Paralympic tennis players are rare. Evaluating the specific game requirements is a prerequisite of more thoroughly understanding the physiology of wheelchair tennis. This task is, however, not easy due to numerous modulating internal (i.e., variety of physiological impairment, competitive standard, playing style, gender and body composition) and external (i.e., environmental conditions, ball type and court surface) factors of tennis match intensity, in addition to high individual variability in physiological responses to match play. Moreover, it is difficult to develop and implement universal safety standards and guidelines to account for all of the environmental scenarios. Well aware of potential health risks, the International Tennis Federation (ITF) medical commission has implemented policies for effectively reducing heat illness risk to safeguard wheelchair tennis players' health when competing in environmentally challenging conditions (http://www.itftennis.com/media/166656/166656.pdf). In addition to these existing procedures in wheelchair tennis the question still exist as to what preventive countermeasures can be implemented when it gets hot.

Current Regulations/Guidelines for Preventing Heat Injury in Wheelchair Tennis

To date, different rules and regulations are dictated by various tennis organizations (ATP, WTA, ITF, and Grand Slams) and even within the same governing body (ITF) recommendations for preventing heat injury are not uniformly applied between men, women, juniors or wheelchair tennis players. Curiously, no heat rule prevails in general in the able-bodied ITF men's circuit or ITF seniors. In extraordinary circumstances only, the referee in consultation with the tournament director and/or ITF supervisor may suspend play or adjust a tournament's schedule in the case of darkness, weather or adverse court conditions. In other categories including ITF Juniors, ITF Women's circuit and Fed Cup, the starting time of matches scheduled for play may be delayed where, in the opinions of tennis officials, extreme weather conditions are likely to come into effect.

For WTA matches already in progress where WBGT ≥ 30°C, a 10 min break in play between the second and third sets has recently been implemented, with immediate suspension of play in extreme conditions (WBGT ≥ 32°C). The current rules for wheelchair tennis (ITF) are:

- 28°C ≤ WBGT ≤ 30°C—15-min break between the second and third sets.
- 30°C ≤ WBGT ≤ 32°C—Suspension of play at the end of the set in progress and will not resume until WBGT falls below 30.1°C.
- WBGT ≥ 32°C—Immediate suspension of play that will not resume until WBGT falls below 30.1°C.

WBGT is an index calculated from wet-bulb, dry-bulb, and black-globe temperatures that is commonly used to quantify heat stress in occupational, military and sports context. Despite not being an actual representation of players' heat strain, WBGT is largely recommended by the most prestigious sport organizations (IOC) and endorsed by leading international sports federations (FIFA, IAAF, ITF) (Bergeron et al., 2012; Mountjoy et al., 2012). These recommendations that are based on WBGT cut-offs address the potential risks for a broad range of players without taking into consideration their individual characteristics (e.g., fitness level, acclimatization). Moreover, with obvious variation in worldwide climatology, the use of this index that neglects the influence of cloud cover (affecting the intensity of solar radiation) and wind speed is not without limitations (Brocherie et al., 2014). Given that metabolic rate determines exercise-induced heat strain in sports, regardless of the environmental conditions (Brotherhood, 2008) it is evident that heat dissipation cannot be predicted from WBGT measurements. This implies that, in decision on when to suspend the play, quantifying metabolic heat gain might be a more suitable approach rather than using universal fixed cut-offs based solely on the WBGT index or air temperature.

What Does Research Tell Us about Able-Bodied Tennis in the Heat?

Competitive match-play tennis in the heat leads to significantly greater levels of thermal, physiological and perceptual strain compared to cooler conditions where steady core temperatures, (i.e., fluctuating around 38.5°C), are recorded (Périard et al., 2014). In hot ambient conditions core temperatures above 39°C have been reported during play (Bergeron et al., 2007; Morante and Brotherhood, 2008; Périard et al., 2014), suggesting that contrary to temperate environments, the efficiency of autonomic (e.g., cutaneous vasodilatation, active sweat secretion) and behavioral (e.g., adjustments in play and recovery) thermoregulatory mechanisms cannot successfully regulate the rate of heat gain. For example, when competing in hot conditions (∼37°C, ∼36% relative humidity, ∼34°C WBGT and ∼0.5 m/s wind velocity), players' rectal and thigh skin temperatures increased to ∼39.4°C and ∼37.5°C, respectively, leading to exacerbation of the perception of effort and thermal perception (Périard et al., 2014).

Body heat storage capacity, influencing changes in core temperature, is determined by the cumulative imbalance between metabolic heat gain and net heat loss to the environment (Cramer and Jay, 2014). Heat balance is easily disturbed as a result of changes in metabolic heat gain due to intense physical activity and/or exposure to a warmer environment. Thermoregulatory differences between men, women and children wheelchair tennis players may relate to substantial inter-individual variability (Goosey-Tolfrey et al., 2008b) and/or the influence of independent factors (e.g., body mass or body composition) on thermoregulatory outcomes during exercise (Havenith et al., 1998). Generally speaking, players with larger body and muscle masses are characterized by greater heat gain that must be dissipated to maintain "safe" body temperatures. An increased thermal strain in hot playing conditions, that is also associated with warmer skin temperature readings (Morante and Brotherhood, 2008), induces behavioral adaptations, as thermal sensation become less comfortable. For instance, in able-bodied tennis, adjustment of match-play characteristics in hot conditions comes from evidence of shorter points durations (Morante and Brotherhood, 2008) or longer rest periods between points (Périard et al., 2014), in turn reducing the effective playing time (i.e., the percentage of total match time spent with the ball in play).

Thermoregulation in Wheelchair Tennis

Few studies have examined thermoregulatory responses during the wheelchair game (Veltmeijer et al., 2014; Griggs et al., 2015), yet the prevailing view is that individuals with a spinal cord injury (SCI) demonstrate impaired thermoregulatory function compared to able-bodied peers. This puts them at a higher risk (proportional to the injury level) of developing heat illnesses (Price, 2006). In one such study, thermoregulatory responses in wheelchair tennis players with and without a SCI were compared during a 45 min tennis match (WBGT = 18–20°C) (Veltmeijer et al., 2014). Confirming previous laboratory findings (Price, 2006), increases in core temperature were larger in the SCI (+0.6 ± 0.1°C; $n = 2$) compared to the non-SCI (+0.3 ± 0.1°C; $n = 4$) players, whereas mean skin temperature (30–31°C), match characteristics and exercise intensity were similar between groups. The common view is that regulation of body temperatures in SCI players is impaired because of the loss of normal blood-flow regulation via the central nervous system and by the inability to sweat or shiver below the neurological level (Webborn, 1996). In addition to disrupted autonomic nervous system function, loss of skin temperature sensation (i.e., smaller body surface area available for sweating and therefore restrictive evaporative cooling of the skin) also characterizing SCI players shouldn't be overlooked. Such impaired ability to detect thermal injury would indicate that individuals with spinal cord-related lesions (T6 and above) are more prone to heat illness due to increased lower body heat storage (Veltmeijer et al., 2014).

What Preventive Countermeasures are Potentially Useful to Minimize Heat Strain during the Wheelchair Game?

Cooling strategies (Griggs et al., 2015), structured heat acclimatization (Castle et al., 2013) and hydration interventions

(Goosey-Tolfrey et al., 2008a) are well-established methods for improving exercise performance in SCI players competing in warm-to-hot conditions. These strategies are helpful in reducing thermal and cardiovascular strain, while ameliorating perceptual responses and improving exercise tolerance. In one case study, for instance, one female player, a member of the Great Britain national team involved in the preparation of Athens 2004 Paralympics, underwent a simulated 1-h wheelchair tennis protocol in hot conditions (30°C, 54% rH) (Diaper and Goosey-Tolfrey, 2009). Peak sprinting speeds were better maintained when 30 min precooling (cooling vest) was combined with head and neck cooling (cooling hats and neck bands) during exercise. This occurred together with an improvement in thermal sensation and slower rise of aural temperature toward the latter exercise stages. Partial heat acclimation may also be beneficial for athletes with an SCI, as demonstrated by lower resting core temperature and increased plasma volume (yet without any improvement in sweat response) following 7 days of heat acclimation (Castle et al., 2013).

Creating universal guidelines on preventive countermeasures for wheelchair tennis players is challenging, as success will both depend on the environmental conditions of the competition venue and the level of SCI. Hence, individuals with high-level lesions (tetraplegia) possess a greater thermoregulatory impairment (i.e., impaired ability to dissipate heat due to a larger body surface area that cannot actively regulate body temperatures) than individuals with lower-level lesions (paraplegia). Reportedly, tetraplegic compared to paraplegic athletes display disproportionate increases in core temperature and body heat storage in spite of producing similar external work during the completion of an intermittent-sprint protocol in cool conditions (Griggs et al., 2015). Variation in the degree of sweating and blood flow redistribution between SCI individuals implies that preventive strategies should be individualized. For instance, it is recommended to determine the acclimatization response of each SCI player individually by recording the changes in haematocrit concentration after a heat-response test (Racinais et al., 2012). Furthermore, implementation of more "aggressive" cooling strategies (i.e., combined methods and/or larger surface area coverage) likely improves thermal comfort and eventually functional capacity (Minett et al., 2011).

Although non-SCI players may be able to cool down during the rest periods in between rallies, games or sets, the SCI players might not be able to do so as effectively. Well aware that SCI tennis players have an elevated risk of developing heat illness, tournament organizers and governing bodies have the responsibility to support the implementation of countermeasures to prevent hyperthermia (e.g., allowing extra time for cooling the body). Investigating the thermal effect of a 10-min break between the 2nd and 3rd sets during a game raising core temperature to ∼1.3°C after ∼80 min of play showed encouraging results; i.e., core temperature decreased by 0.25 ± 0.20°C for 6 of the 7 able-bodied women participants including all whose temperatures were above 39.0°C (Tippet et al., 2011). Whether there is enough scientific merit of using these results to support the implementation of 15 min break between the second and third set when the WBGT hits 28°C in the wheelchair game is still unknown. Perhaps ingestion of an intestinal pill or a radio-pill suppository for continuous monitoring of core temperature (e.g., gastrointestinal and rectal measurements, respectively) would enable informed decision on when to suspend play for games scheduled in hot ambient conditions. Simultaneous computations of deep-body temperature at various measurement sites (e.g., sublingual, aural, esophagus) could also be obtained by trained users (Taylor et al., 2014). While research has shown that it is possible to achieve greater cooling ability in individuals with SCI through the use of specific cooling garments (ice-packed vests; Webborn et al., 2005), the implementation of such strategies (i.e., at least during play) remains a challenge within the current laws that govern wheelchair tennis.

Conclusion

Substantial inter-individual variability that modulate thermal strain certainly represent barriers to develop uniform guidelines for minimizing heat stress during wheelchair tennis competitions. A more appropriate approach, than using fixed WBGT cut-off values, would probably mean that the play must be stopped when the body cannot compensate for the environmental conditions (i.e., cardiovascular drift). As of today, however, the internal metabolic load cannot be easily quantified, but deep core temperature can, to enable individual recommendations on when it is too hot to train or compete safely. Therefore, SCI players are strongly encouraged to implement a range of preventive strategies (e.g., acclimation, cooling, hydration), for instance in view of the 2016 Paralympics in Brazil, to more efficiently regulate their body temperatures. Supporting behavioral thermoregulatory strategies in wheelchair tennis would also imply adjustments in play and/or recovery. In doing so, however, it is crucial that the "game momentum" is not disrupted so as to preserve its popularity.

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