Effect of Low-Compression Balls on Wheelchair Tennis Match-Play

Thieme

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Abstract

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The purpose of this study was to compare court-movement variables and physiological responses to wheelchair tennis match-play when using low vs. standard compression tennis balls. Eleven wheelchair basketball players were monitored during repeated bouts of tennis (20 min) using both ball types. Graded and peak exercise tests were completed. For match-play, a data logger was used to record distance and speed. Individual linear heart rate oxygen consumption relationships were used to estimate match-play oxygen uptake. Significant main effects for ball type revealed that total distance ($P < 0.05$), forward distance ($P < 0.05$), and average speed ($P < 0.05$) were higher for play using a low-compression ball. A lower percentage of total time was spent stationary ($P < 0.001$), with significantly more time spent at speeds of 1–1.49 ($P < 0.05$), 1.5–1.99 ($P < 0.05$) and 2.0–2.49 ($P < 0.05$) m·sec^{-1} when using the low-compression ball. Main effects for physiological variables were not significant. Greater total and forward distance, and higher average speeds are achieved using a low-compression ball. The absence of any difference in measured HR and estimated physiological responses would indicate that players move further and faster at no additional mean physiological cost. This type of ball will be useful for novice players in the early phases of skill development.

Introduction

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The link between tennis and health is well established [24,27]. Playing tennis can improve aerobic fitness, encourages a favourable lipid profile, improves bone health, and reduces the risk of cardiovascular morbidity and mortality [27]. While a cause and effect relationship cannot be confirmed, the health of tennis players is positively affected by lower body fat, greater strength, and less diminished cognitive function in comparison with less active controls [24].

For the wheelchair user, tennis provides potential for a stimulating and energetic environment. Even though tennis is less physiologically demanding than other wheelchair sports, most notably basketball [8], individuals with low level spinal cord injury can still maintain an intensity of 50% peak HR during on-court tennis activity [4]. Such a dose satisfies the exercise recommendations of the ACSM and AHA for improvements in health [2,27]. Approximately one hour of wheelchair tennis play is associated with an energy expenditure of between 300–350 kcal and thus a reduced risk of myocardial infarction [1]. Positive outcomes are not exclusively limited to highly competitive match play conditions, with both practice [4] and game play [4,29] scenarios eliciting sufficiently high HRs to be considered beneficial physical activity. Hence, to ensure that individuals gain from the benefits of the sport, and to maximise the impact on cardiovascular health, it is necessary to find new ways to increase participation and raise energy expenditure in wheelchair tennis.

The International Tennis Federation (ITF) aims to "increase the number of people playing tennis in their respective nations" [21] as "participating in sports, in particular in wheelchair tennis, increases self-belief and also provides people with a disability with the means and know-how for independent living and a more affirmative attitude towards their community and existence in general" [19]. As the psychological benefits of wheelchair tennis are more prominent when the frequency is at least three times per week [26], and tennis must be played regularly to influence fitness levels [27], the overarching aim is to promote the sport through on-going participation and long-term compliance.

However, as wheelchair tennis is associated with high levels of technical competence [28] and represents a significant physiological and skill challenge to the individual [9, 13, 14], participation and compliance are not guaranteed. Both experienced and inexperienced athletes have reported major problems in the learning and development of new skills associated with wheelchair tennis [34]. In addition, while relative playing intensity is similar, higher ranked players push faster and further than lower ranked counterparts, and are therefore more capable of responding to ball movement and the challenges of competitive match-play [31]. This, coupled with a moderate to high level of aerobic fitness required for competitive match-play [29], has resulted in a growing interest on how the game might be adjusted or adapted to promote skill development for developmental players.

While the ITF suggests that beginners of all ages would benefit from playing tennis with slow moving balls, the evidence to support this notion is limited. No significant difference was observed in skill learning between low (LCB) and standard compression (SCB) tennis balls in able-bodied children [15]. However, positive technique development, longer rallies and greater playing times were reported in beginners using an LCB [15]. Furthermore, using a larger than standard size ball results in delayed onset of volitional fatigue, increased ground stroke accuracy, lower HR, lower ratings of perceived exertion and lower blood lactate concentrations in healthy able-bodied tennis players [6]. Hence, while the physiological response of able-bodied participants has been considered, it remains unclear whether similar responses are to be expected in wheelchair users as a result of an extended playing time and rallies using modified balls. Court-movement variables have previously been reported for wheelchair tennis [31], but not for play using LCB's. Furthermore, skilled wheelchair users with no prior tennis playing experience have not yet been sampled.

Chair mobility has been described as the single-most important aspect of wheelchair tennis, providing a base and transition for timing, balance, motion and the execution of skills [11]. Without appropriate mobility skills, a player will be unable to respond to the movement of the ball and the challenges of match-play. Hence, for a study concerned with court-movement, selection of participants with no chair or tennis skills is problematic. Furthermore, tennis requires a modified propulsion technique, as players push while holding a racket. Such a technique requires additional skill [9], reduces maximum velocity [14], and is therefore physiologically and technically challenging [9, 14]. Those with sport-specific chair propulsion skills have an inherent ability to mobilise the chair in a sporting context, but are not skilled for tennis propulsion or play. Participants therefore appropriately skilled to perform court-movement, but display typical characteristics of the novice user. Additionally, a moderate to vigorous intensity is associated with match-play [29]. Hence, for comparisons between conditions for court-movement and resultant physiological responses, recruitment of participants with a good level of aerobic fitness is justified.

An investigation into the physiological demands and court-movement patterns monitored during wheelchair tennis play using an LCB is required to assess the value and impact of altering tennis ball characteristics for individuals taking up the sport and/or for recreational players with low skill levels. Lower average and minimum HR's were observed in low-ranking players who won sets of tennis, when compared with low-ranking players who lost during competitive match-play [31]. Hence, for low-skill players, better performance outcomes are associated with a lower physiological cost. However, such findings are currently limited to play with an SCB. Use of an LCB is likely to facilitate greater court movement and thereby increase the physiological cost of match-play. As more energetic play is likely to confer desirable cardiovascular health effects, it is important to identify the optimal playing conditions to maximise physiological cost.

It is likely that this investigation will pre-empt further studies in wheelchair tennis, and provide a case for increasing participation. Hence, the purpose of this study was to compare both the physiological responses and court-movement variables in wheelchair tennis match-play when using an LCB versus an SCB. We hypothesise that the LCB will result in greater distance and speed covered during 20-min of tennis match-play and subsequently increased HR responses (exercise intensity).

Methods
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Participants
11 wheelchair-dependent basketball players gave written consent to participate in the study (◉ Table 1). All participants had no previous tennis playing experience and hence, held no International Tennis Federation (ITF) world ranking. Players were recruited through contacts at the Lakeshore Foundation and the University of Alabama. Approval for the study procedures was obtained from the University Research Ethics Committee and was conducted in accordance with the Declaration of Helsinki and Ethical Standards in Sport and Exercise Science Research [16].

Procedures
All participants underwent initial anthropometric profiling, followed by graded and peak exercise tests in a controlled laboratory environment prior to involvement in tennis match-play (◉ Fig. 1). Physical characteristics were recorded (◉ Table 2). Harpenden skinfold callipers (British Indicators Ltd., Luton, UK) were used to measure skinfold thickness at 3 anatomical landmarks. Weight scales suitable for wheelchair access were used to assess body mass. An electromagnetically braked arm ergometer (Lode Angio, Groningen, The Netherlands) with adjustable cranks (80–170 mm range) was mounted to the floor using an automatic stand. Participants were seated in their own wheelchair, with adjustments made to arm-crank height to ensure scapula-humeral joint alignment with crank pedal axle and a slight elbow bend at maximal arm extension. Once baseline resting data for oxygen uptake were obtained, participants completed a 3-min familiarisation stage. Heart rate (HR) was monitored using radio telemetry (PE4000 Polar Sport Tester, Kempele, Finland).

Graded exercise test: The graded test protocol consisted of 4-6 3-min steady-state exercise stages (◉ Fig. 1). Power output for stage 1 was determined taking into consideration a) HR response during the familiarisation stage, b) level of disability, c) basketball classification and d) sex. Workload was thereafter increased in 20 W increments. As alterations in cadence influence oxygen consumption/efficiency during arm crank ergometry [32], crank rate was fixed at 75 rev·min^{-1}. Verbal feedback was given when crank rate deviated by ~5 rev·min^{-1}. The test was terminated after 3 warnings. Expired air was collected and analysed using a calibrated online metabolic cart (Parvomedics TrueOne 2 400 Metabolic Measurement System, Parvomedics Inc, Utah, USA). HR was monitored continuously

Table 1 Descriptive characteristics for wheelchair basketball players. Participants ordered by degree of physical impairment (ascending order), as indicated by International Basketball point classification.

Participant	Sex	Age (years)	Nature of disability	Injury level	Time since injury (years)	Wheelchair user for daily ambulation (years)	Wheelchair tennis experience (years)	International Basketball point classification
1	M	19	Amputee (both limbs: trans-femoral/trans-humeral)	n/a	18	0†	0	1.0
2	F	18	Caudal regression syndrome	T12*	18	18	0	1.0
3	F	18	Spina bifida	L3/4	18	18	0	1.5
4	M	22	SCI	T5	6	6	0	1.5
5	M	21	SCI	T12*	21	16	0	2.0
6	M	23	SCI	T12	6	6	0	2.0
7	F	28	Spina bifida	n/a	28	25	0	2.0
8	M	22	Spina bifida	L3/4*	22	22	0	2.0
9	M	24	Cerebral palsy	n/a	24	11	0	3.0
10	M	20	Spinal cord stroke	L3*	6	6	0	4.0
11	M	20	Amputee (right leg: transfemoral)	L1	20	0†	0	4.0
Mean		21			16.7	15.4	0	
SD		3			8.9	8.9	0	

*Denotes an incomplete spinal lesion. † Wheelchair user for sport, but otherwise ambulant

and recorded at the end of each submaximal stage. A small capillary blood sample was obtained from the earlobe during a 1-min break between stages for determination of blood lactate concentration using a portable Lactate Pro™ analyser (KDK Corporation, Kyoto, Japan, Arkray factory inc., KDK Corporation, Shiga, Japan). Device application within sports research has been confirmed with good accuracy against reference measures and high reliability [3]. Ratings of perceived exertion (RPE) [5] were monitored throughout the test. Environmental temperature and atmospheric pressure was consistent across all tests (23.3 °C, 725 mmHg). Mean relative humidity was 24.4(0.5)%.

Peak exercise test: Following a 5-min rest, each participant performed a further test to determine peak oxygen uptake ($\dot{V}O_{2peak}$). The starting power output was ascertained from graded testing, with the work rate advanced in 10 W min^{-1} increments until volitional exhaustion. HR was monitored continuously. For $\dot{V}O_{2peak}$, expired air samples were collected and analysed using an online method. 3-min post-test, a capillary blood sample was obtained and analysed for blood lactate concentration. The final RPE was recorded. Criteria for a valid $\dot{V}O_{2peak}$ was: a peak RER value ≥1.10 and a peak HR ≥95% of age-predicted maximum (200 b·min^{-1} minus chronological age [23]). The same testing equipment was used for all participants and all tests.

Tennis match-play: A randomly assigned player number (1–11) was allocated and participants were assigned to one of 3 groups [n=4 (×2) and n=3 (×1)]. Each group underwent a habituation process prior to competitive match-play. Two 15-min practice sessions were played, one with an LCB and one with an SCB. An LCB is the same size and diameter as an SCB, but is softer and lighter [15]. Hence, average mass (g) of all balls used during match play were recorded. A single-blind design was adopted for ball type. The same colour [yellow ITF branded 'Play & Stay' (ITF)] balls were used, with LCBs marked with a small red circle. Players were not aware of the nature of this marking and hence, were blinded to ball compression rating. All matches were played indoors on a suspended floating hardwood floor. Playing area was defined, marked and checked in accordance with offi-

cial ITF court dimensions [17]. Ambient conditions were controlled across all matches (environmental temperature 21.0 °C; humidity 50–55%).

Following habituation, participants were invited to take part in competitive round-robin format match-play. Each player completed 2 or 3 matches, playing the other participants within their group once. Play was officiated in accordance with ITF rules [20] with two exceptions. First, matches involved two 20-min bouts of continuous play. Each bout involved play with either the LCB or SCB. Ball choice was randomised across bouts using a cross-matched design (players in matches A and B used the LCB in bout one, while players in matches C and D used the SCB first (○ **Fig. 1**). Second, players were only required to change ends after each 20-min bout.

The start and finish time for each game was recorded using a stopwatch. Actual playing time (APT) was defined as the 20-min bout and commenced from racket contact in the first service strike. Time limits for changeovers and breaks between bouts of play were strictly enforced. Each match was filmed using a Sony HDR HC7 Mini DV Handycam connected to a Raynox HD Superwide Angle Conversion Lens (0.5× conversion factor). Video footage was used to cross-check all recorded times.

Match-play intensity: Average HR during match-play was recorded in 5-sec intervals and expressed as an absolute value (HR$_{avg}$) and percentage of laboratory-measured maximum (%HR$_{labmax}$). Due to the intermittent nature of tennis, and to indicate the range of HR values during play, peak (HR$_{peak}$) and minimum (HR$_{min}$) were also noted. To determine actual playing intensity, HR and $\dot{V}O_2$ from laboratory testing were regressed against each other using a standard linear model. Values for average HR were then cross-compared to estimate average oxygen uptake during match-play ($\dot{V}O_{2match}$). This was also presented in relative terms (%$\dot{V}O_{2peak}$) using the following equation:

$$\%\dot{V}O_{2peak} = (\dot{V}O_{2match} \div \dot{V}O_{2peak}) \times 100$$

Energy expenditure was calculated on the assumption that one litre of oxygen is equivalent to 5 kcal.min^{-1} [29].
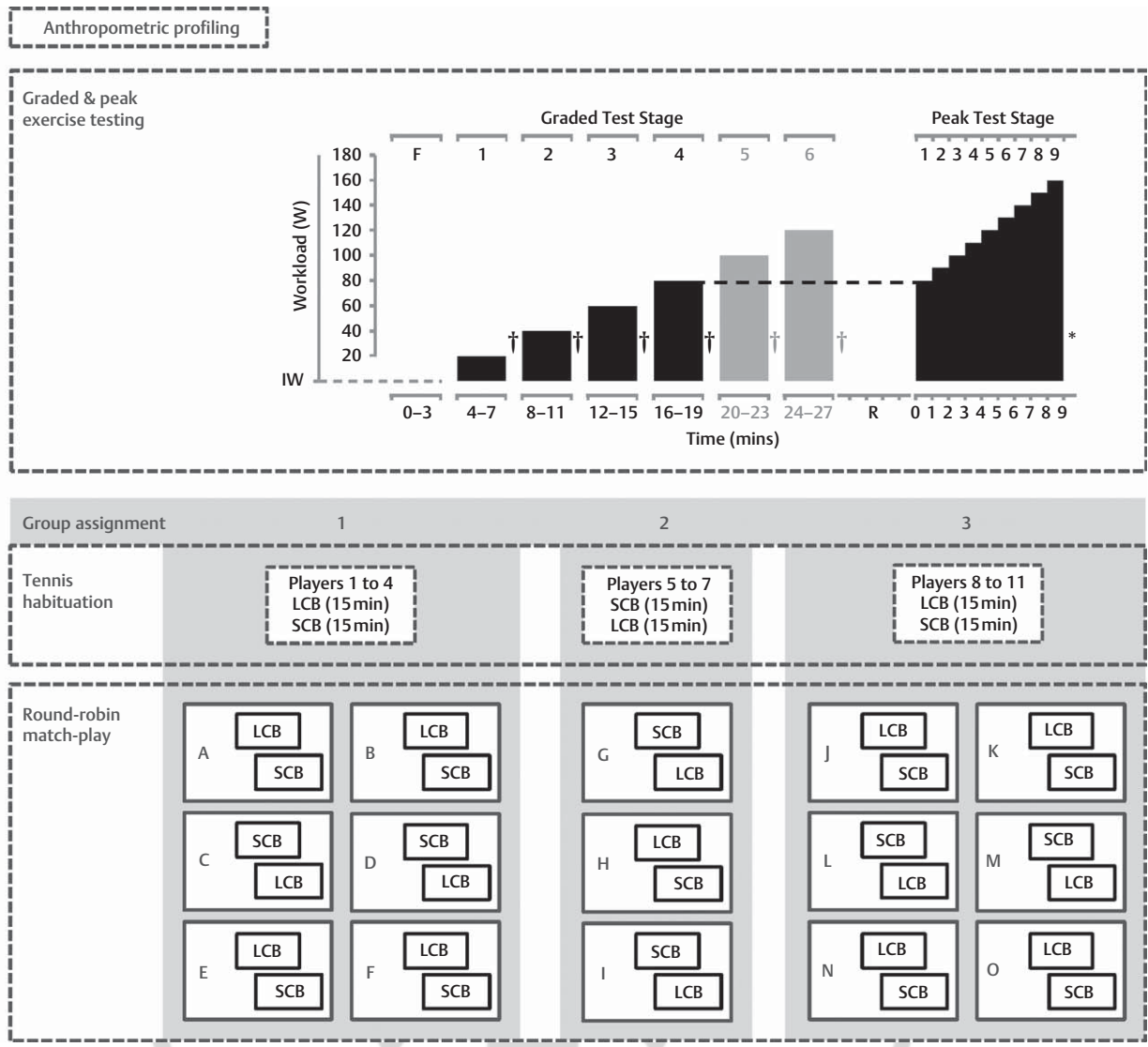
Fig. 1 Schematic representation of laboratory and tennis match-play testing protocols. Vertical arrow indicates sequence of tests. *Graded & peak exercise testing*: incremental exercise stages represented in chronological order (left to right). Initial workload (IW – grey dashed line) determined during familiarisation (F). Workload increased above IW in 20 W increments during graded testing. Minimum 4 stages, maximum 6 completed (black and grey blocks respectively). Post 5-min recovery period (R), peak testing commenced at an equivalent workload to final submaximal stage (black dashed line). 10 W increments applied at 1-min intervals until volitional exhaustion. † Submaximal and *peak values for HR, oxygen uptake, blood lactate and rating of perceived exertion recorded. *Group assignment and tennis habituation*: random player number (1–11) and groups (1–3) assigned, with 2×15-min bouts of organised practice. Round-robin match-play: competitive tennis matches (A–O), with 2×20-min bouts per match. Ball type randomly assigned: LCB (low-compression ball), SCB (standard compression ball).

Data logger: The data logger used in this study has been validated for distance and speed [33] and its role in the quantification of tennis court-movement has been described [31]. One data logger device was placed onto each wheel. Values for left and right wheels were averaged for calculation of total distance, forward distance, reverse distance, and forward-to-reverse distance (i.e., small movements incorporating intermittent forward and backward motion). Peak and average speed were determined, along with percentage of total time spent in eight discrete speed zones (0–3.99 m·sec^{-1}; at 0.5 m·sec^{-1} intervals).

Statistical analysis

The SPSS 19.0 statistical package (SPSS Inc., Chicago, IL, USA) was used for all statistical analyses. Descriptive statistics [mean (SD)] were obtained for all participants and presented as 20-min average values. For all court-movement variables, an average value for logged data from left and right wheels was used. Normality and homogeneity of variance were confirmed by Shapiro-Wilk and Mauchley's tests respectively. Distance data were presented in absolute terms (per 20-min bout). HR values were adjusted and presented as relative playing intensities (minimum, average and peak recorded values expressed as a percentage of laboratory-based-maximum). Separate 2×3 (ball by bout) within measures ANOVA were used to examine the following dependent variables (average HR; %HR$_{labmax}$; peak and minimum HR; $\dot{V}O_{2match}$; %$\dot{V}O_{2peak}$; energy expenditure; total distance; total forward distance; total reverse distance; total forward-to-reverse distance; peak and average speed; and percentage of time in speed zones 0–8). Simple main effect analyses were used to fol-

Participant	Sex	Age (years)	Body Mass (Kg)	Sum of skinfolds (mm)	$\dot{V}O_{2peak}$ (L·min^{-1})	HR$_{labmax}$ (b·min^{-1})	Peak Power Output (W)
1	M	19	61.1	71.9	1.78	161	80
2	F	18	35.7	42.5	1.13	188	80
3	F	18	47.3	58.1	1.57	182	90
4	M	22	61.9	25.1	1.99	177	140
5	M	21	57.4	32.4	2.51	206	170
6	M	23	73.4	29.1	2.85	190	230
7	F	28	56.0	71.6	1.60	178	90
8	M	22	69.8	45.5	2.79	208	200
9	M	24	66.9	59.5	2.34	191	110
10	M	20	78.8	58.2	2.84	184	160
11	M	20	69.8	49.9	2.85	188	160
Mean		21	61.6	49.4	2.34	187	137
SD		3	12.3	16.2	0.62	13	51

Table 2 Anthropometric and peak physical characteristics for all participants based on initial laboratory profiling. Participants ordered by degree of physical impairment (ascending order), as indicated by International Basketball point classification.

*Physiological measures: $\dot{V}O_{2peak}$ = peak oxygen uptake; %HR$_{labmax}$ = average HR during match-play as a percentage of laboratory-measured maximum

Table 3 Comparison of ball type for court-movement and physiological variables during 20-min bouts of wheelchair tennis match-play.

	LCB		SCB		P
	Mean	**SD**	**Mean**	**SD**	
total distance (m)	956	383	859	339	0.013*
forwards distance (m)	835	374	741	323	0.021*
reverse distance (m)	29	13	32	15	0.312
forwards to reverse distance (m)	61	16	58	12	0.366
peak speed (m·sec^{-1})	2.34	0.52	2.36	0.48	0.751
average speed (m·sec^{-1})	0.80	0.32	0.72	0.28	0.011*
HR$_{avg}$ (b·min^{-1})	109	18	107	17	0.223
%HR$_{labmax}$	58	9	57	9	0.219
HR$_{peak}$ (b·min^{-1})	136	20	132	18	0.089
HR$_{min}$ (b·min^{-1})	84	15	85	15	0.354
%$\dot{V}O_{2match}$ (L·min^{-1})	0.91	0.41	0.88	0.37	0.205
%$\dot{V}O_{2peak}$	39	13	38	12	0.225
energy expenditure (Kcal)†	90.5	39.6	87.7	36.6	0.230

*Physiological measures: HR$_{avg}$ = average HR during match-play; %HR$_{labmax}$ = average HR as a percentage of laboratory-measured maximum; HR$_{peak}$ = peak HR; HR$_{min}$ = minimum HR; $\dot{V}O_{2match}$ = estimated oxygen uptake during match-play; %$\dot{V}O_{2peak}$ = percentage of laboratory measured peak oxygen uptake. * Significant main effect for ball (P<0.05). †Average value for a 20-min bout of activity

low-up significant ball by bout interactions. Values for each individual bout of tennis match-play were used to form the basis of the statistical analysis. Statistical significance was accepted at a level of P<0.05.

Results

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Court-movement variables
The main effect for ball revealed that total distance during 20-min bouts of wheelchair tennis was significantly greater for LCB than SCB [956 (383) vs. 859 (339) m respectively; P=0.013]. Consequently, distance per minute was also greater for LCB [48 (19) vs. 43 (17) m respectively; P=0.013]. Forward distance was higher for LCB [835 (374) vs. 741 (323) m, P=0.021], as was average speed [0.80 (0.32) vs. 0.72 (0.28) m·sec^{-1}, P=0.011]. There was no significant difference in mean peak speed (○ **Table 3**).
Forward propulsion was the dominant movement strategy (87 to 88% of total distance). Less distance was covered using a for-

ward-to-reverse (8–10%) and reverse (3–4%) propulsion strategy. ○ **Fig. 2** presents the results of time spent in specific speed zones and indicates a greater percentage of total time in zones 3, 4 and 5 for LCB (21.2 vs. 19.4%, P=0.029; 9.3 vs. 7.3%, P=0.019; 3.7 vs. 2.6%; P=0.012). Comparatively less time was spent stationary (speed zone 0) for play using an LCB (11.1 vs. 13.9%, P=0.001). No main effect for bout or ball by bout interaction was noted for court-movement variables.

HR and estimated physiological variables
Physiological data for participant 9 (cerebral palsy) were found to be within the 14th–50th percentile of the studied population. Therefore, all data were entered for analysis. No significant main effect or ball by bout interaction was observed for measured HR (HR$_{avg}$, HR$_{peak}$, HR$_{min}$, %HR$_{labmax}$) or estimated physiological variables ($\dot{V}O_{2match}$, %$\dot{V}O_{2peak}$ and EE). A similar average HR response was observed for ball type (LCB vs. SCB; 109 vs. 107 b·min^{-1}) with large variation in average (LCB; 72–131, SCB; 70–130 b·min^{-1}), peak (LCB; 97–161, SCB; 92–153 b·min^{-1}) and minimum (LCB; 52–109, SCB; 53–110 b·min^{-1}) HR. Relative playing intensity was similar when HR was expressed as a percentage of HR$_{labmax}$ (LCB: 58 (9) %, range 45–77%; SCB: 57 (9) %, range 48–73%). Further analysis revealed that HR$_{min}$ and HR$_{peak}$ relative to laboratory-measured maximum were almost identical (LCB: 46–74%; SCB: 46–72%). Peak testing produced a mean $\dot{V}O_2$ of 2.20 (0.62) L·min^{-1} [range 1.13–2.85], HR$_{labmax}$ of 187 (13) b·min^{-1} [range 161–208] and a peak power output of 137 (51) W [range 80–230] (○ **Table 2**).

Discussion

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The purpose of this study was to compare physiological responses and court-movement variables during wheelchair tennis match-play when using an LCB vs. an SCB. Such comparisons allow for greater understanding of methods for increasing participation and raising energy expenditure in wheelchair tennis.
Significant main effects for ball revealed that total distance (P=0.013), forward distance (P=0.021) and average speed (P=0.011) were higher for LCB tennis play. While players moved further and faster, our data reveals no significant differences in the physiological response for match-play using balls of different compression levels. Additional significant main effects for ball
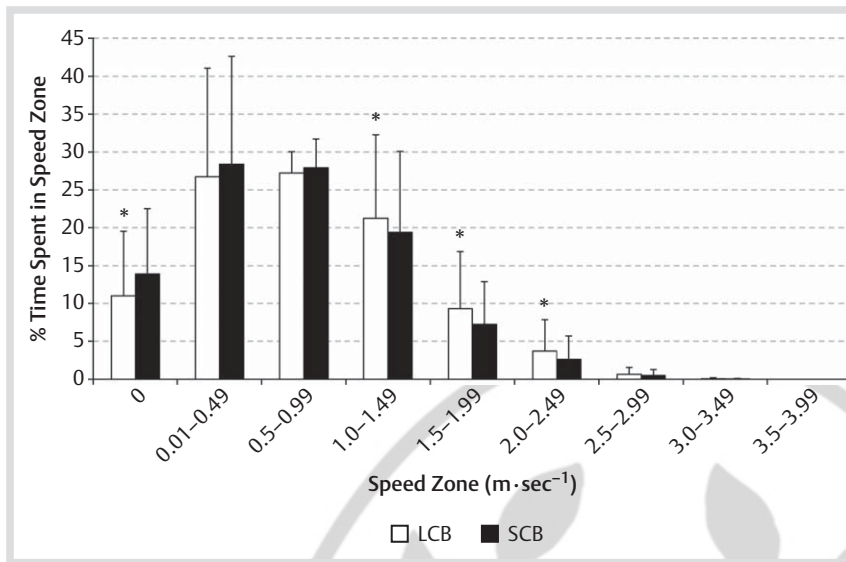
Fig. 2 Percentage of time spent in speed zones during 20-min bouts of tennis match-play using the low (LCB) and standard (SCB) compression ball. Speed zones: $0 \, m \cdot sec^{-1}$ denotes percentage of time spent stationary; 8 discrete zones ($0.5 \, m \cdot sec^{-1}$ increments). *Significant main effect for ball type (LCB vs. SCB, $P < 0.05$)

revealed that less time was spent stationary (speed zone 0), and more time was spent in zones 3, 4 and 5 ($1.00–2.49 \, m \cdot sec^{-1}$) when players used the LCB. Previous work has found play involving the LCB to be associated with extended playing time, longer rallies and enhanced technique [15]. However, this is the first study to consider court-movement and its impact on the physiological demands of match-play using modified tennis balls.

In comparison to low ranked counterparts, higher total distance, forward distance and average speed are associated with highly ranked wheelchair tennis players [31]. Hence, better players typically cover greater distances and operate at higher speeds. Successful court-movement is essential in tennis. Players are required to respond to the unique patterns of opponent and ball movement. Our data suggest that greater total and forward distance, and higher average speeds are achieved using the LCB. These data indicate that movement activity increases when using the modified ball. In addition, no differences were observed between the observed HR variables and estimated physiological variables. Hence, while play with an LCB prompted increased court-movement, this occurred with little or no additional physiological cost. The ability to cover greater distance and speeds with no associated increase in physical demand is likely to be highly advantageous, particularly for the inexperienced or developmental player. For such individuals, tennis is a highly complex sport. The significant physiological and skill requirement for wheelchair propulsion while interfacing with a racket [9,14], intermittent, multidirectional nature of the sport [29] and vigorous intensity [31] combine to create a challenging activity environment.

The present study revealed that a lower percentage of total time was spent stationary (speed zone 0; $P = 0.001$), and a higher percentage of time in speed zones 3 ($P = 0.029$), 4 ($P = 0.019$) and 5 ($P = 0.012$) while using the LCB. These data suggest that use of an LCB a) reduces inactive time and b) prompts a more consistent and frequent movement response during match-play. Increased activity is most likely linked to a response to ball placement. An LCB is softer, lighter and has a lower bounce [15]. Therefore, players are more likely to propel the chair towards the ball in an attempt to make a return shot. Collectively, these data suggest that the ball is in play for longer when an LCB is used. The LCB could therefore have a positive role in the development of both technical skill and aerobic fitness.

With respect to a single 20-min bout of tennis activity, our data suggests that LCB and SCB use does not alter physiological cost. However, it is important to note that the relative exercise intensity in the present study was considerably lower than reported previously for tennis [4,8,29,30]. Indeed, when compared with established guidelines on exercise quantity and quality [2], our study reports a light activity classification for relative intensity (HR: 57–63%, and $\dot{V}O_{2peak}$: 37–45%). As no physiological differences were observed for ball type, this light intensity environment is most likely explained by playing experience and skill. While all were skilled wheelchair users, participants were novice players (no prior tennis experience for either practice or match-play). Hence, intensity was limited by player skill development within each discrete 20-min bout. However, because no previous studies have targeted novices for assessment of court-movement and physiological demands, sampling strategy was a strength of the study. In addition, the ITF maintains that players should be able to 'play and stay' (i.e., serve, rally and score) from the first session, and that slower moving balls are 'essential kit for introducing disabled people to wheelchair tennis' [18]. To assess the accuracy of this statement, recruitment of novice players (but skilled wheelchair users) was warranted. Light activity is associated with lower energy expenditure than more intense exercise and is therefore less conducive to health enhancement. However, such conditions are likely to be advantageous for the novice, who is focused on skill development and chair propulsion while holding a racket in the palm of the hand. Our data shows greater total and forward distance and average speeds for the LCB. Hence, using the LCB influences court-movement. In turn, this suggests that performance was enhanced using the modified ball.

Actual playing time ranges from 40–75 min in wheelchair tennis [31]. In the present study, players completed 20-min bouts of exercise. While this closely resembles the amount of time spent in one single set of match-play [31], further research should consider the influence of ball type over a longer duration. As the physiological response increases over an extended duration in tennis [31], but has also been shown to decrease in other wheelchair sports [30], accurate conclusions about the nature of the physiological response should be reserved for further investigation. However, it is plausible to assume that increased physiological demand is likely to be associated with increased duration.

Hence, more apparent differences for ball type may be observed during longer matches. In addition, breaks in-play and during play were not recorded and hence were variable in length. The precise nature of these physiological changes should be reserved for further research.

Our study revealed no significant differences for court-movement or physiological variables for bout. This suggests that participants covered similar distances and speeds, and experienced equivalent physiological demands across multiple bouts of play. Peak oxygen consumption is lower for exercise testing modes involving reduced active muscle mass [12]. In the present study, $\dot{V}O_{2peak}$ was assessed using an arm-crank, as opposed to a wheelchair ergometer. Consequently, peak values, and hence, relative playing intensity, may have been underestimated. However, for all conditions and participants, laboratory measures for HR and $\dot{V}O_2$ during the graded test were used to estimate relative playing intensity. Hence any underestimations would not have confounded comparisons for ball type or bout. Furthermore, while our data reveals lower values for $\dot{V}O_{2peak}$ than those reported for elite basketball players [8], values are consistent with those reported for elite tennis [8]. Hence, the aerobic fitness level of participants was not a likely explanation for the lack of significance for ball type.

Recruitment for studies involving wheelchair sports is challenging due to the small populations [8], and participation in wheelchair tennis is typically low [13]. Furthermore, participants with a range of disabilities are often recruited. Disturbed cardiac innervation and/or a disturbed peripheral reflex response are associated with lesions at T5 or above and may have influenced the HR response during match-play in those individuals with spinal cord injury. 1 participant had cerebral palsy and as such, motor control and hence, rate of skill development, may have been disproportionately affected. This condition is not associated with an abnormal or blunted HR response. However, with physiological responses at ~50th percentile, half of all participants achieved higher physiological responses than this participant. Reduced court-movement as a result of a greater proportion of total time spent stationary is a possible explanation for this outcome. Players are largely inactive during the serve, and serving times were not standardised. This skill is complex and requires successful ball toss to racket-swing coordination and timing. General observation indicated that some participants were able to coordinate this action effectively, while others needed to repeat the ball toss action. Prolonged inactivity caused by a lack of tennis-specific skills may therefore have contributed to the relatively low average exercise intensities observed in the present study. The focus should therefore be on the development of core skills in early phases to ensure that court-movement and thereby health effects are maximised.

While there are limitations in HR data collection, HR is an accurate and non-invasive means of reporting exercise intensity for the quantification of physiological demands. Coupled with laboratory measures, HR monitoring allows for the prediction of $\%\dot{V}O_{2peak}$ and an estimation of absolute $\dot{V}O_2$ during performance. While alternative methods are available for the direct assessment of $\dot{V}O_2$, and these are likely to provide more accurate determinations for intensity, they are cumbersome and thus inappropriate for competitive sport scenarios. For tennis monitoring, consideration must be given to the constraints of match-play. Player ability to manoeuvre the chair into an appropriate position for shot play is critical [25]. Consequently, the sports scientist must avoid invasive monitoring. Players participate in

the Open Class or Quad Division. Men and women with a permanent physical disability and substantial loss of function in one or both lower extremities (Open) and 1 or both upper and lower extremities (Quad) are eligible to play. Hence, it is important to capture data that are representative of the spectrum of players who may choose to play tennis. Therefore, exclusion of individual player data is not justified and collection of HR is appropriate for relevance, accuracy and ease of application.

Comparisons in performance variables for play with modified balls are currently limited to 2 studies involving able-bodied participants [6, 15]. In both cases, participants had some degree of tennis playing experience. In a study involving young players (~6 to 10 years), the SCB group were older and more experienced than the sample selected to use the LCB [15]. In more recent work, participants were experienced tennis players but had no experience in using a modified ball [6]. As stated previously, the strength of the present study was that wheelchair basketball players with no experience playing tennis with any type of ball were sampled. Consequently, tennis-specific skill levels were controlled. Chair-propulsion skills were not subject to the same level of control, as a degree of experience was considered favourable to ensure successful completion of 20-min bouts of tennis. However, while participants were skilled in sport-specific chair propulsion, they were unskilled in pushing while holding a racket. Furthermore, as basketball is classified based on degree of physical impairment, there is expected intra-team variance in physical fitness profiles. In the present study, peak values for $\dot{V}O_2$ and peak power output ranged from 1.13 to 2.85 L·min^{-1} and 80 to 230W, respectively. Hence, not all players were highly conditioned. Sampling of basketball players therefore allows for consideration of performance variables across a range of fitness levels, with good scope for generalisations on novice users and appropriately conditioned beginners.

Chair configurations were not manipulated by the investigators, and players participated in tennis using their own sports wheelchair. Hence, there may have been inter-individual differences in rolling resistance due to self-selection of tire type and pressure [22]. However, all chair tires were inflated to a level suitable for competitive play. Furthermore, players used the same chair for both conditions, and thereby the same configuration. Instrumented wheels provide additional kinetic information for wheelchair propulsion [7], but are heavier than the data logger device used in the present study (4.9 vs. 0.01 kg). The latter are therefore more suitable for logging movement during competitive match-play conditions.

The present study involved the use of the red LCB. Recent advances have seen developments in ball configurations and design, with a modified green ball now being trialled. This is noteworthy given that the current study reports the red LCB is ineffective in raising physiological cost. Both red and green balls are the same size and diameter as the SCB, but have different bounce and speed characteristics, with the latter bouncing higher than the former [10]. It has been proposed that the red ball can sit low after a second bounce, making shot play difficult for the wheelchair user [10]. In contrast, green balls have similar speed and balance characteristics as an SCB and may hence offer a better success rate for the beginner [10]. It is important to note that such propositions are yet to be investigated via an appropriately formulated research design. It is therefore necessary to proceed with caution. However, this is an interesting line of investigation, and further research should consider differences in novice performance when using a range of available ball

types. Additional strategies for the elevation of physiological cost during match-play should also be explored to ensure that the many health benefits of match-play are realised for the wheelchair user.

Conclusion
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Our study presents data to show that the use of an LCB allows for greater movement and the generation of higher average speeds during tennis match-play. While this is case for court-movement, our data shows no difference in the physiological response for separate bouts of play, or between ball types. An LCB is both softer and lighter than an SCB, and hence is known to move more slowly through the air [15]. Such characteristics may have a positive impact on a player's perceptual ability to reach the ball after an opponent's shot. If a player considers that he is likely to reach the ball, then he is more more likely to propel the chair. While increased movement activity was noted in the current study, this was not reflected in any increases in the physiological demands of the tennis match-play. Given that the match length in the current study was standardised to 20-min bouts, longer matches should be the focus for future work. However, this study presents important findings on the impact and potential role of the LCB for player development in tennis.

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