



A Comparison of Methods for the Estimation of Body Composition in highly-trained Wheelchair Games Players

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Abstract:	<p>The purpose of this study was to assess the agreement in body composition measurements of wheelchair athletes using skinfolds, bio-impedance analysis (BIA) and air displacement plethysmography (ADP) with the criterion method of dual-energy X-ray absorptiometry (DXA). A secondary objective was to develop new skinfold prediction equations to estimate %fat for this sample. Thirty wheelchair games players were recruited and the body composition outcomes of BIA, ADP, and skinfolds were compared to the DXA outcomes by a paired-samples t-test (systematic bias), intraclass correlation (ICC, relative agreement) and Bland-Altman plots (absolute agreement). Regression models to predict the %fat as measured by DXA by the sum of skinfolds or BIA were calculated. Results showed that the predictions of %fat when using BIA, ADP or skinfolds systematically underestimated the %fat mass as measured by the DXA. All ICC values, except for the measurement of fat (kg) by ADP (ICC=0.702), were below 0.7. New prediction models found the $\Sigma 7$ skinfolds and calf circumference as the best model to predict %fat ($R^2=0.84$). In conclusion, BIA, ADP and existing skinfolds equations should be used with caution when estimating %fat of wheelchair athletes with substantial body asymmetry, lower body muscular atrophy and upper body muscular development.</p>

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A comparison of methods for the estimation of body composition in highly trained wheelchair games players

For Peer Review

Introduction

The assessment of body composition within both Olympic and Paralympic athletes is commonly used as a tool to help define the impact that sports training and dietary interventions have on adipose tissue. That said, when working with Paralympic athletes this becomes a challenging topic as the transferability of able-bodied athletes normative values are questionable due to the increased fat mass (FM) and decreased bone density and lean mass (fat-free mass (FFM)) [123,304,356]. Currently, the methods available to assess changes in adiposity in persons who participate in wheelchair sports (e.g. individuals with a spinal cord injury (SCI), polio, amputation or with a neurological disorder) have tended to include simple and relatively cheap field-based techniques, such as skinfold callipers and bioelectrical impedance (BIA). But for obvious reasons the suitability with respect to the physical impairment of the athlete must be carefully considered. For example, hand-to-foot BIA analysers cannot be used with double leg amputees; similarly, the number and location of skinfold sites measured may need to be reduced, depending on the physical impairment type. In spite of this, these techniques have reportedly been used in persons with these aforementioned physical impairments with some degree of satisfactory results [1,267,278]. However, previous studies are limited with small sample sizes (e.g. n=8 males [267]) or with heterogeneous impairment groups (e.g. wheelchair games players comprising of both amputee and persons with a low to mid-level SCI [356]). Moreover, practitioners are cautious when using skinfolds since FM is typically underestimated in individuals with a SCI when using skinfolds [254,356] and the general conclusions have stated the need for larger sample sizes so that an appropriate skinfold prediction equation can be developed.

With respect to other techniques, then to the authors' knowledge only one study has described the ability of air displacement plethysmography (ADP) to accurately assess body composition in persons with a SCI [56]. Their results suggested that ADP is a valid method

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3 for the calculation of total body volume and density in persons with a SCI below T3. That
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5 said, there may be problems with the measurement of thoracic gas volume of persons above a
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7 lesion of T6 which would result in the use of predicted values taken from the able-bodied
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9 norms [56]. Additionally, the theoretical problem with the use of ADP, is the assumption of a
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11 fixed density of FFM, implying that proportions of minerals, water and proteins remain
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13 constant and are not affected by sex, body mass, age, or body composition. However, the
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15 mass of bone mineral and skeletal muscle may be substantially reduced in wheelchair athletes,
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17 hence invalidating this assumption. The use of two compartmental models that make
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19 assumptions about FM and FFM may therefore not be suitable for the use in individuals who
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21 have significant deviations from the norms, such as individuals with a physical impairment.
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23 As a result three or more compartmental models are the preferred methods of assessment of
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25 body composition for accuracy and reliability, whilst methods that are not dependent upon
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27 body density, such as dual-energy X-ray absorptiometry (DXA), may offer greater accuracy.
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29 Despite the noted difficulties with the positioning of an individual with a physical impairment
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31 on the DXA couch, Keil et al. [189] recently found DXA to be a highly reproducible
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33 technique in the estimation of total and regional body composition of elite wheelchair
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35 basketball athletes.
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41 It is clear that many comparative studies exist, that have assessed the accuracy of a
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43 given body composition technique to a reference method such as DXA, in a number of
44
45 different cohorts, including healthy individuals [34,201,245], young children [101,2930], and
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47 athletes [23]. In contrast, to help inform the selection of methodology of athletes with a
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49 physical impairment then there is very little published data available [267,356]. Therefore, the
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51 main purpose of this study was to assess the agreement in body composition measurements of
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53 trained wheelchair athletes using skinfolds, BIA and ADP with the reference method of DXA.
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55 This was done for the total group as well as for those participants with a SCI (e.g., tetraplegia
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3 vs. paraplegia) on the agreement. Furthermore, the second purpose was to develop new
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5 skinfold prediction equations to estimate percentage fat in wheelchair athletes with a SCI.
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8 9 **Methods**

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11 *Participants:* The study was approved by University Research Ethics Committee and the
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13 National Research Ethics Service and participants provided written informed consent prior to
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15 data collection. Participants included thirty male trained wheelchair games players from the
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17 sports of wheelchair basketball (n=19; 29 ±7yrs with a body mass of 72.1 ±13.1kg) and
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19 wheelchair rugby (n=11; 32 ±5yrs with a body mass of 68.2 ±10.7kg). Diagnoses were spinal
20
21 cord injury from the lumbar to cervical region (n=22), ~~diastrophic dysplasia dystrophie~~
22
23 ~~dysphasia~~(n=3), hip damage (n=1) and lower limb damage (amputation (n=4)), indicative of
24
25 physical disabilities that meet the eligibility criteria to participate in wheelchair basketball and
26
27 wheelchair rugby. All participants were considered trained having competed at a national
28
29 level on a regular basis. As body composition estimates may differ between individuals with a
30
31 high and low SCI, subgroups comprising of persons with paraplegia (n=11) and tetraplegia
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33 (n=11) were formed. This study has been performed in accordance with the ethical standards
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35 of the International Journal of Sports Medicine [145].
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44 *Experimental Design:* Each individual attended a single session in a euhydrated state having
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46 refrained from exercise and consuming alcohol and caffeine for 12 hours, and eating or
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48 drinking at least 2 hours before each testing session to minimise variation in gastrointestinal
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50 contents and hydration status. Urine osmolality was assessed using an Osmocheck (Vitech
51
52 Scientific Ltd, West Sussex, UK) to determine hydration status. Every participant underwent
53
54 a whole-body DXA scan and participated in an anthropometry session. Additional
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56 measurements using the techniques of air displacement plethysmography (ADP, also known
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3 by the commercial term BODPOD) and bioelectrical impedance analysis (BIA) were also
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5 undertaken for those participants where standard electrode placement sites were accessible
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7 and electrode placement was possible.
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11 *Dual-energy X-ray absorptiometry (DXA)*: Body composition was assessed using a Lunar
12 Prodigy Advance DXA scanner (GE Lunar, Madison, WI, USA) running version 12.20
13 enCORE 2006 software. Standard quality assurance and stability monitoring of the DXA
14 scanner was performed with daily measurement of the GE-Lunar calibration block and
15 aluminium/water bath spine phantom prior to the use of the machine to detect and correct for
16 any drift. The same trained operator performed all scans and analyses. Short-term precision
17 for DXA measurements were determined in a previous study [189], using the same scanner,
18 operators and in the same cohort as participants for the present study. CV values for all whole
19 body measurements were <2.0%, and, with the exception of arm FM (kg) (CV = 7.8%),
20 ranged between 0.1-3.7% for all segmental measures of bone mass, FM, and lean tissue mass
21 (LTM). Participants wore loose fitting, light-weight clothing with no metal or reflective
22 material, and all jewellery and prostheses were removed where possible. Participants were
23 asked to identify any metal fixtures (e.g. surgical pins) prior to the scans being performed and
24 such fixtures were flagged as artefact on analysis. Each individual was aligned supine on the
25 bed and appropriately positioned as closely as possible to the standard protocols. Positions
26 that may have produced spasms or other movement and any discomfort were minimized and
27 enough time allowed for any spasm generated on positioning to subside before scanning.
28 Velcro restraints were applied around participants' knees and ankles to minimise movement
29 during the scan, unless this was not possible because of the disability. Afterwards, the
30 participants were positioned on the DXA-bed in a supine position as close as possible to
31 standard positioning protocol, with Velcro straps used to help keep the legs still during
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3 measurement. The analyses of all scans were performed by the same operator to avoid any
4 inter-observer variability. The total body scan was used to gain the outcome measures which
5 were: total body FM, total body fat percentage (% fat), total LTM and bone mineral content
6 (BMC). To allow for comparison with other methods FFM was calculated as LTM +BMC.
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14 *Anthropometry:* For participants unable to assume a standing position, body height was
15 measured from the heel to the crown of the head in the supine position to the nearest 0.1 cm
16 with a Luftkin measuring tape (Cooper Tools, Apex, USA). For participants who had a double
17 amputation, height was measured using the same methodology, but to the point of amputation.
18 For participants who were unable to lie straight or who had chronic contractures, body height
19 was calculated from the sum of body segments.
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30 *Skinfolds:* Eight skinfold sites were obtained from all participants, unless access to specific
31 skinfold sites was inhibited due to disability or absence of limbs, in which case, as many
32 measurements were taken as possible. All measurements were made in accordance with the
33 guidelines stated by International Society for Advancement of Kinanthropometry (ISAK)
34 using Lohman et al. [212] for site locations, by the same trained investigator, using a set of
35 Harpenden Skinfold Callipers (Baty International, West Sussex, UK). The eight sites included
36 the following sites: biceps, triceps, subscapular, iliac crest, supraspinale, abdominal, ~~anterior~~
37 front thigh and medial calf. For non-wheelchair bound individuals, skinfold measurements
38 were taken in the anatomical reference position (standing up). For wheelchair-bound athletes,
39 skinfold measurements were taken in the seated position in a standardised seat without arm
40 rests to allow for better access to the iliac crest and supraspinale. Each measurement was
41 taken in duplicate and an average of the two measurements was recorded. Body density was
42 calculated using the equations from Katch and McArdle [178], Withers et al [37], the three
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3 and four skinfold equations of Durnin and Womersley [940] and Sloan and Weir [334]. Body
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5 fat percentage was then estimated using the Siri equation [323]: % fat = (4.95/density – 4.50)
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7 x 100.
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11 *Bioelectrical impedance:* Body composition was assessed using the Multiple Frequency
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13 Bioimpedance Meter (Bodystat 1500, Isle of Man, UK). Participants were asked to remove
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15 socks and jewellery before lying down in the supine position on a non-conductive surface for
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17 ten minutes, for standardisation purposes. Two electrodes were placed on the posterior surface
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19 of the right hand, at the distal end of the third metacarpal and between the styloid processes of
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21 the radius and ulna. Where possible, two electrodes were placed on the anterior surface of the
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23 right foot, at the end of the second metatarsal and between the medial and lateral malleoli of
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25 the ankle. For single leg amputees missing their right foot, the left foot was used instead and
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27 for double leg amputees, this technique was not used. Body composition was determined by
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29 the measurements of resistance made at 50kHz, using the previously validated prediction
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31 equations of Lukaski et al. [223].
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39 *Air displacement plethysmography:* Body composition was assessed using a commercially
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41 accessed BODPOD (BODPOD, Life Measurements, Concord, CA). Participants were asked
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43 to wear tight fitting swim wear or in the absence of such attire, small shorts were worn, all
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45 prostheses and items of jewellery were removed and participants were provided with a tight
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47 fitting nylon cap to cover their hair. A two-point calibration was conducted, using an empty
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49 chamber prior to each individual assessment. Participants who were able to stand were
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51 weighed using the BODPOD system's electronic scales. For those who could not stand, body
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53 weight was matched using free weights (to the nearest 0.25kg) and loaded onto the scales to
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55 give a reading. On instruction, each participant entered the chamber and was asked to remain
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3 still throughout the assessment. A single ADP procedure consisted of two measurements of
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5 body volume, unless they differed by more than 150ml, in which case, the system required a
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7 third measurement. Body volume was determined by the volume of air displaced, when the
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9 participant is secured in the chamber. The measured body volume was adjusted for thoracic
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11 gas volume, which was estimated according to the methods described by Dempster and
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13 Aitkens [78]. The corrected body volume was used in combination with body mass and height
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15 to determine body density, from which percentage FM was estimated. All estimations were
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17 calculated using prediction equations integral to the system's software. Data pertaining to fat
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19 and muscle mass in kilograms and percentages were displayed on the system's monitor and
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21 were recorded.
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27 **Statistical analysis**

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29 The assumption of normality was checked for the body composition outcome measures by a
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31 Shapiro-Wilk test and visual inspection of the q-q plot and the box plot of the data. A One-
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33 Way ANOVA and a Tukey post-hoc test were performed on [height, body mass, calf](#)
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35 [circumference and](#) the DXA outcomes to check for differences between athletes with a
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37 tetraplegia, paraplegia and other disability. A paired samples t-test was performed to test for
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39 systematic bias between the DXA outcomes and the other body composition outcomes (BIA,
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41 ADP, skinfolds). Intra-class correlations coefficients (ICC, two-way random, absolute
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43 agreement) were computed to test the relative reliability between the DXA outcomes and the
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45 outcomes of the other body composition measurement techniques. ICC's were considered
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47 sufficient when >0.8 , moderate when 0.7 to 0.8 , and insufficient when <0.7 [362]. Systematic
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49 bias and relative reliability were checked for the total group as well as for the groups with a
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51 paraplegia and tetraplegia separately. Bland-Altman plots with 95% limits of agreement were
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3 made to determine absolute reliability, i.e. underlying trends and within-subject differences in
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5 the results [45].
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8 Lastly, new equations for wheelchair games players to predict percentage body fat
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10 were developed using univariate regression analyses with percentage body fat measured by
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12 DXA as dependent variable and as independent variable one of the following variables: % fat
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14 measured by BIA, sum of three or four skinfolds used by Durnin and Womersley [910] or the
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16 sum of seven skinfolds as used by Withers et al. [37]. Different regression models were tested
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18 (e.g. linear, log, quadratic) and the models with the highest explained variance were finally
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20 chosen. In a secondary analysis, age or calf circumference (chosen as a measure indicative of
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22 muscle atrophy) were added to these models to check whether it improved the explained
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24 variance of the regression model. Level of significance was set at $p < 0.05$.
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29 Results

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32 Height ($p=0.31$) and body mass ($p=0.31$) were not significantly different between the groups
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34 with a tetraplegia, paraplegia and other disability. The calf circumference of athletes with
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36 another disability was significantly different compared to the SCI groups ($p=0.01$). Post-hoc
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38 test results showed that athletes with another disability showed a larger calf circumference
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40 compared to athletes with a tetraplegia. All participants ($n=30$) underwent a DXA scan, yet
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42 due to the array of physical impairments not all participants were able to be measured via all
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44 the body composition field-based methods due to the limitations described previously and
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46 problems accounted with access to the BODPOD by the athletes with tetraplegia. This
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48 resulted in 28 participants being measured via the methods of BIA, 18 via the methods of
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50 ADP and up to 27 participants were able to have all the skinfold sites taken. Importantly, all
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52 participants were noted as being euhydrated as determined via the osmolality of the waking
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54 urine sample that was analysed on arrival to the laboratory prior undertaking the BIA
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3 measurement. The DXA assessment showed a total body fat percentage for the total group of
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5 wheelchair games players as $25.0 \pm 6.6\%$. No significant differences were found in DXA
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7 outcomes between athletes with a tetraplegia and paraplegia or between tetraplegia and the
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9 group with another disability. However, athletes with paraplegia had a significantly higher
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11 %fat and significantly lower FFM (kg) compared to the group with another disability.
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16 *Systematic bias:* Table 1 shows the mean and standard deviations of all body composition
17
18 outcome measures and the results of the systematic bias testing. Compared to the DXA, the
19
20 BIA and ADP techniques systematically overestimated FFM while they systematically
21
22 underestimated FM and percentage FM. The predictions of % fat of all skinfold measurement
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24 formulas also systematically underestimated the percentage FM as measured by the DXA.
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26 These results were similar for the total group as well as for those with tetra- and paraplegia.
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31 *Agreement:* Table 1 shows the results for relative agreement between DXA outcomes and the
32
33 other body composition measurement techniques. All ICC values, except for the measurement
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35 of FFM (kg) by BIA and ADP (resp, ICC=0.824 and 0.877) and fat (kg) by ADP
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37 (ICC=0.702), were below 0.7, indicating that the relative agreement of FM measured by BIA,
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39 % fat measured by BIA and ADP and skinfold body composition outcomes with the reference
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41 DXA measurement was insufficient. Similar results were found for people with a tetra- and
42
43 paraplegia. Figures 1A-F show the absolute agreement between % fat measured by the DXA
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45 measurement and measured by the BIA, ADP or skinfolds formulas. The Bland-Altman plots
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47 clearly show that the % fat measured by the DXA is systematically higher for almost all
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49 participants with all body composition measuring technique. The smallest mean difference
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51 with the DXA was found for the ADP and three skinfolds formula of Durnin and Womersley
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[910] (both a mean difference of 6.1%) but with high 95% confidence intervals of the difference: -3.4 to 15.5 and -2.2 to 14.4, respectively.

New equations: The relationship between skinfold thicknesses and % fat by DXA seemed curvilinear (Figure 2) and The quadratic regression equations showed the best explained variances. Table 2 shows the regression models to predict the % fat as measured by DXA by the sum of three, four or seven skinfolds or the % fat measured by BIA in wheelchair games players. Furthermore, the effect of adding age or calf circumference to the models is shown. The best model, with the highest R^2 , to predict % fat is the one with the 7 skinfolds and calf circumference ($R^2=0.84$), see formula 1 below.

Formula 1: %Body fat = -3.04 + 0.41 · Σ SF7 - 0.001 · Σ SF7² + 0.03 · Calf circumference

The models using the sum of three skinfolds showed also a quite high explained variance ($R^2=0.74-0.75$), see formula 2 below, and were better compared to the models using four skinfolds ($R^2=0.62-0.70$) or the % fat measured by BIA as independent variable ($R^2=0.46-0.51$).

Formula 2: %Body fat = -5.04 + 1.46 · Σ SF3 - 0.001 · Σ SF3²

Discussion

This study contributes to the search for a valid field-based body composition technique in highly trained male wheelchair games players and extends previous studies to include the methods of ADP and identifies the suitability of methods with respect to SCI lesion level. In the present study we employed DXA as the criterion method and the mean % fat of $25 \pm 7\%$ is similar to those values reported for other USA and Japanese male wheelchair athletes [156,256,267] and male athletes from other British cohorts [112]. Furthermore, this

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3 data demonstrates how high training loads have a positive influence on % fat since the
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data demonstrates how high training loads have a positive influence on % fat since the
aforementioned value is substantially lower than the ~30% body fat that has been reported in
sedentary, disabled participants [167,234]. However, % fat estimates in disabled athletes may
not be comparable with those in other populations. In wheelchair athletes, body FM may be
typical relative to sedentary controls [356]. However, muscle atrophy and the related low
FFM contribute to a lower body mass, and hence an artefactually high estimate of % fat. As
such % fat is probably a less appropriate measure of obesity in wheelchair athletes.

No difference in body composition was found between players with tetraplegia and
paraplegia while a difference was found between players with paraplegia and other disability.
This difference could result partly from muscle atrophy and hence lower FFM in the
paraplegic athletes, whilst athletes with other disability (e.g. amputation) are likely to exhibit
much less muscle atrophy. A comparable % fat in those with tetraplegia and paraplegia was
found before [345].

This study found each technique showed substantial systematic error and significantly
underestimated FM (% and kg) and overestimated FFM (kg) relative to DXA. The mean bias
for ADP, BIA and both Durmin skinfold formulae was 5.8-6.8%, whilst that for the other
skinfold techniques was 9.9-11.6%. This systematic bias was observed in both people with a
high and low lesion level, confirming previous literature [267]. The Bland Altman plots
demonstrated a large variability at both the individual and the group level in estimating FM
(%) in all techniques when compared to DXA. The limits of agreement for all techniques (e.g.
from -2.2 to 14.4% for the Durmin & Womersley [940] 3 skinfolds formula but with
comparable limits of agreement for the other techniques) were not particularly wide compared
to other studies on able-bodied participants [67]. However, substantial underestimation in FM
(% and kg) in comparison to DXA demonstrated that these methods cannot be used

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3 interchangeably at the group level and individual values should always be interpreted with
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5 caution.
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7 Explanations for the underestimation of % fat reported via the skinfold technique
8 relative to DXA may be attributable to both theoretical and technical issues. Assessment of
9 body fat from skinfold thicknesses assumes that the skinfold thicknesses at measured sites are
10 proportional to the total body fat content. However, subcutaneous fat levels are particularly
11 high around the waist in persons with a SCI, which could have affected the accuracy of the
12 measures [134]. It is not known whether the proportion of fat situated subcutaneously differs
13 between SCI and healthy controls. Moreover, assessment of some skinfold sites may not be
14 feasible in this group due to e.g. amputation, whilst landmarks used for locating
15 anthropometric sites may be altered. The need to make measurements in the seated position in
16 wheelchair athletes may have affected some skinfold thicknesses (e.g. iliac crest).
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30 Mojahedi et al. [278] stated that BIA may be a more reliable field measure than
31 skinfolds since it measures resistance to electrical current through the body. Our data showed
32 that BIA consistently underestimated FM (% and kg) and overestimated FFM (kg) when
33 compared to DXA which supports previous findings [278]. These findings are not surprising,
34 as the measurement is influenced by the geometric proportions of the body, which may be
35 altered in wheelchair athletes. Furthermore, it has previously been reported that BIA
36 measurements are affected by a variety of factors such as nutritional status, hydration and
37 electrolyte balance [89], body position [312] and disease [123]. In the present study, there was
38 an attempt to control for training, caffeine, alcohol, food and general fluids, prior to
39 assessments, to reduce the impact that such factors would have on the assessment of body
40 composition. Participants were all confirmed as being in a euhydrated state, nonetheless, it is
41 highly likely that variability in the data was predominantly due to the significant body
42 asymmetry in amputees, and muscle wastage and altered extracellular fluid distribution in the
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3 lower limbs of wheelchair-bound athletes [1920,234,356], making this technique potentially
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5 less accurate in this cohort.

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7 This is the first study to assess the validity of ADP, using the commercially available
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9 BODPOD in elite wheelchair athletes as to the author's knowledge only one study has
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11 compared ADP with DXA within a clinical SCI population (n=13 mixed gender). Mean body
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13 fat estimates were substantially and significantly lower than those by DXA, whilst 95%
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15 confidence limits were high, suggesting that this technique is not a valid measure of body
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17 composition in this athletic cohort. Ballard et al [23] reported ADP to be an accurate
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19 technique in the estimation of body composition in female athletes. However, densitometric
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21 techniques such as ADP assume a constant density of the FM and FFM. In wheelchair
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23 athletes, particularly those with SCI, the substantial losses of skeletal muscle and bone will
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25 affect the FFM density in particular, hence affecting estimates of % fat. However, FFM
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27 density may have been expected to be lower in those with SCI, which would result in
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29 overestimation of fat content as opposed to the underestimation seen here. It is important to
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31 note that we used the commercially available BODPOD so were unable to input directly the
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33 measured thoracic gas volume and our calculations were reliant on predicted able-bodied
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35 normative data. That said, for persons above a T6 lesion it has been suggested that there may
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37 be problems with directly measuring V_{TG} and therefore normative values may be
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39 recommended [56]. This does open the debate to how transferable the normative thoracic gas
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41 volume values are for persons with a SCI – there may be consistent differences that would
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43 further affect the estimate of body fat content. Further research is needed in this area.
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49 We used DXA as the reference technique in this study, but the errors associated with
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51 DXA may also be greater in this population. The technique makes assumptions about the
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53 relative attenuation of X-ray by fat and LTM [289]; but the skeletal muscle atrophy in
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55 wheelchair athletes may make these assumptions less reliable. Furthermore, the technique can
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3 only resolve two components in each pixel. In pixels containing bone, fat and LTM²s cannot
4 be resolved and are estimated based upon the composition of surrounding pixels, weighted to
5 account for differences in distribution of fat and lean relative to the bone. In wheelchair
6 athletes, there may be a smaller proportion of non-bone pixels in regions affected by atrophy,
7 producing greater error in estimating soft tissue composition. Further, this atrophy will alter
8 the distribution of fat and lean which could also make soft tissue composition estimates less
9 reliable. As such, it is important to remember that the differences between techniques
10 observed in this study will arise from errors in DXA as well as those in the other methods,
11 and the errors in DXA estimates may also be larger in this population. It would thus be
12 particularly important to evaluate techniques against a multi-component model, which allows
13 measurements of more of the components that may vary in this population.
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27 This study has attempted to develop a skinfold model for trained wheelchair games
28 players. We determined that a model containing only the three upper body skinfold sites of
29 the biceps, triceps and subscapular is similar to that containing the additional four sites of the
30 supraspinale, abdominal, front thigh and medial calf. The former model showed an explained
31 variance of $R^2=0.75$ compared to $R^2=0.69$. Theoretically, an equation including a broader
32 range of sites should be able to take more account of inter-individual variation in fat
33 distribution, although this advantage may be counteracted by practical limitations at some of
34 the lower body sites. This may explain why the 7 skinfold equation explained only a little
35 more of the variance in %fat. However, when adding calf circumference to the model with the
36 seven skinfold sites, this model was the best ($R^2=0.84$). As a practitioner the additional
37 benefit of the model with three skinfold sites is convenience and less intrusiveness since
38 wheelchair athletes tend to wear training trousers rather than shorts due to muscle atrophy of
39 the lower limbs. Further validation of these predictive models is warranted.
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Conclusion

Based on the findings in this study, the agreement between the methods employed to estimate body composition at both the group and SCI impairment level, when compared to the reference method of DXA, is comparable to the agreement found in able-bodied populations. It is clear from the data presented that BIA, ADP and skinfolds should be used with caution in the estimation of body composition of elite wheelchair athletes with substantial body asymmetry, lower body muscular atrophy and upper body muscular development. Further studies need to validate the prediction equations that were derived from this study.

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Table 1. Descriptives, systematic bias (p-value t-test) and relative agreement (ICC) of the different body composition measurement techniques compared to DXA for the total group, group with a tetraplegia and with a paraplegia.

	Total group				Paraplegia (basketball)				Tetraplegia (rugby)			
	n	Mean ± SD	p-value	ICC	n	Mean ± SD	p-value	ICC	n	Mean ± SD	p-value	ICC
Height (m)	29	1.74 ± 0.14	-	-	10	1.68 ± 0.10	-	-	11	1.77 ± 0.09	-	-
Body mass (kg)	30	70.7 ± 12.2	-	-	11	68.9 ± 9.3	-	-	11	68.2 ± 10.7	-	-
Calf circumference (cm)	27	30.8 ± 5.1	-	-	9	28.1 ± 4.6	-	-	11	30.3 ± 2.6	-	-
DXA fat-free mass (kg)	27	53.7 ± 8.9	-	-	10	50.5 ± 6.2	-	-	11	52.3 ± 8.8	-	-
BIA fat-free mass (kg)	27	58.1 ± 9.7	<0.001	0.824	10	54.4 ± 7.1	0.020	0.689	11	57.7 ± 10.4	<0.001	0.827
ADP fat-free mass (kg)	17	57.1 ± 9.8	0.002	0.877	10	55.1 ± 8.5	0.003	0.718	-	-	-	-
DXA fat mass (kg)	28	17.2 ± 6.1	-	-	11	19.1 ± 5.4	-	-	11	15.9 ± 5.6	-	-
BIA fat mass (kg)	28	13.3 ± 4.4	<0.001	0.572	10	15.4 ± 3.9	0.011	0.434	11	12.0 ± 3.6	0.003	0.565
ADP fat mass (kg)	18	14.0 ± 5.6	<0.001	0.702	10	13.8 ± 5.5	0.001	0.557	-	-	-	-
DXA fat (%)	30	25.0 ± 6.6	-	-	11	28.4 ± 5.6	-	-	11	24.3 ± 6.9	-	-
BIA fat (%)	28	18.4 ± 5.5	<0.001	0.410	10	21.9 ± 5.8	0.009	0.130	11	17.4 ± 5.2	<0.001	0.482
ADP fat (%)	18	19.2 ± 5.9	<0.001	0.488	10	19.9 ± 5.9	<0.001	0.385	-	-	-	-
Skinfolds fat (%)												
• Katch & McArdle	29	14.3 ± 4.2	<0.001	0.278	10	15.5 ± 4.1	<0.001	0.173	11	14.0 ± 5.3	<0.001	0.380
• Sloan & Weir	27	14.0 ± 5.7	<0.001	0.294	10	17.8 ± 6.1	<0.001	0.336	11	11.6 ± 4.1	<0.001	0.162
• Durnin & Womersley (3 sites)	30	18.0 ± 4.7	<0.001	0.468	11	19.9 ± 4.5	<0.001	0.272	11	19.2 ± 5.4	0.001	0.610
• Durnin & Womersley (4 sites)	30	19.1 ± 4.7	<0.001	0.443	11	19.7 ± 5.4	<0.001	0.306	11	18.9 ± 4.5	0.001	0.543
• Withers et al.	30	15.1 ± 5.3	<0.001	0.342	11	17.4 ± 6.3	<0.001	0.275	11	13.9 ± 4.8	<0.001	0.339

Table 2. Newly developed regression equations for wheelchair games athletes (n=27) to predict percentage body fat measured by DXA from sum of three or four skinfolds, sum of seven skinfolds or percentage fat measured by BIA.

	Constant		SF		SF ²		Age		Calf circumference		R ²	SEE
	Beta (SE)	p-value	Beta (SE)	p-value	Beta (SE)	p-value	Beta (SE)	p-value	Beta (SE)	p-value		
SF3	-5.04 (5.00)	0.32	1.46 (0.30)	<0.001	-0.01 (0.004)	0.003	-	-	-	-	.752	3.40
SF3	-5.54 (5.67)	0.34	1.45 (0.30)	<0.001	-0.01 (0.004)	0.003	0.02 (0.11)	0.84	-	-	.752	3.47
SF3	-4.56 (6.44)	0.49	1.36 (0.32)	<0.001	-0.01 (0.004)	0.01	-	-	0.04 (0.14)	0.80	.741	3.54
SF4	4.92 (7.16)	0.50	0.52 (0.27)	0.07	-0.002 (0.002)	0.45	-	-	-	-	.616	4.23
SF4	4.75 (7.76)	0.55	0.51 (0.28)	0.08	-0.002 (0.002)	0.46	0.009 (0.144)	0.95	-	-	.616	4.31
SF4	0.09 (7.46)	0.99	0.90 (0.30)	0.006	-0.005 (0.003)	0.06	-	-	-0.19 (0.163)	0.26	.700	3.81
SF7	11.67 (4.69)	0.02	0.13 (0.11)	0.25	0.00 (0.001)	0.58	-	-	-	-	.691	3.80
SF7	9.98 (5.56)	0.08	0.12 (0.11)	0.28	0.00 (0.001)	0.58	0.07 (0.12)	0.56	-	-	.695	3.84
SF7	-3.04 (5.36)	0.58	0.41 (0.10)	<0.001	-0.001 (0.001)	0.06	-	-	0.03 (0.11)	0.82	.841	2.78
BIA	4.58 (7.50)	0.55	1.52 (0.85)	0.09	-0.02 (0.02)	0.41	-	-	-	-	.459	5.16
BIA	2.60 (7.81)	0.74	1.23 (0.91)	0.19	-0.01 (0.03)	0.60	0.16 (0.17)	0.36	-	-	.478	5.17
BIA	-8.90 (9.32)	0.35	1.24 (0.87)	0.17	-0.008 (0.03)	0.75	-	-	0.46 (0.23)	0.05	.514	4.86

SF3: Sum of skinfolds of Biceps, Triceps, Subscapular [10]

SF4: Sum of skinfolds of Biceps, Triceps, Subscapular, Iliac Crest [10]

SF7: Sum of skinfolds of Triceps, Subscapular, Biceps, Supraspinale, Abdominal, Front Thigh, Medial Calf [37]

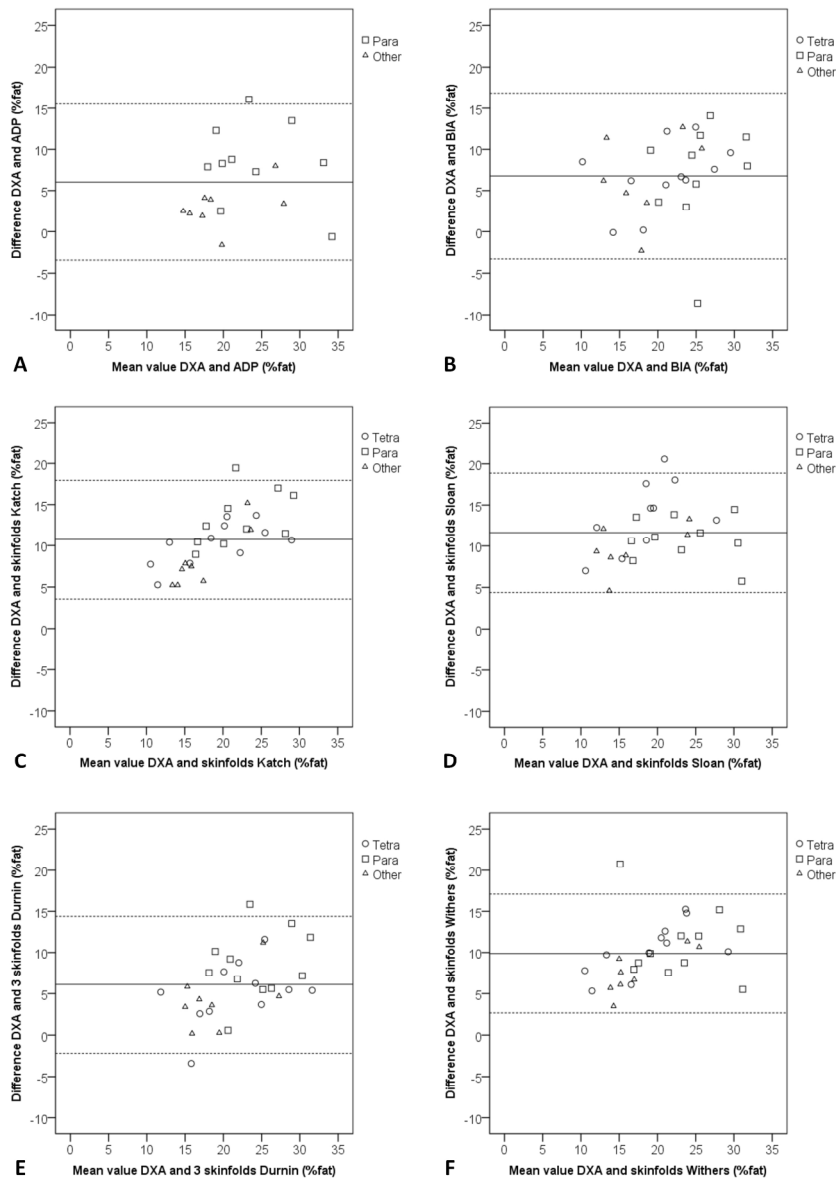


Fig. 1: Bland-Altman plots to show absolute agreement between percentage fat measured by DXA and ADP (A), BIA (B), skinfold equations of Katch & McArdle (C), Sloan and Weir (D), Durnin and Womersley (E), and Withers et al. (F). Mean values between DXA and the other technique are on the x-axis, and the differences between protocols are on the y-axis. The solid line is the mean difference across the data set for each variable. 95% Confidence intervals are the dotted lines above and below the means. The different groups are indicated by different signs.

254x338mm (300 x 300 DPI)

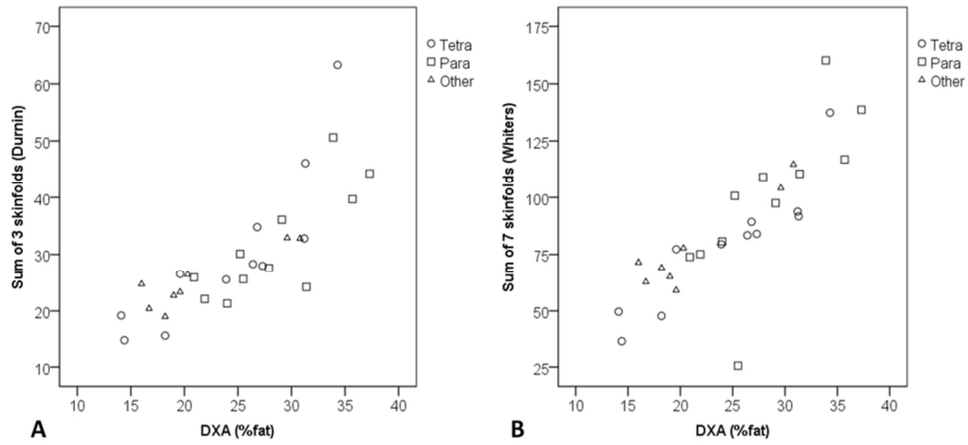


Fig. 2: Relationship between sum of 3 (A) or 7 (B) skinfolds and percentage fat measured by DXA 84x37mm (300 x 300 DPI)

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3 A ~~comparison~~Comparison of ~~methods~~Methods for the ~~estimation~~Estimation of ~~body~~
4 ~~Body composition~~Composition in ~~highly~~highly-trained ~~wheelchair~~Wheelchair ~~games~~
5 ~~Games~~pPlayers
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Introduction

The assessment of body composition within both Olympic and Paralympic athletes is commonly used as a tool to help define the impact that sports training and dietary interventions have on adipose tissue. That said, when working with Paralympic athletes this becomes a challenging topic, as the transferability of able-bodied athletes normative values are questionable due to the increased fat mass (FM) and decreased bone density and lean mass (fat-free mass (FFM)) [[123](#), [304](#), [356](#)]. Currently, the methods available to assess changes in adiposity in persons who participate in wheelchair sports (e.g. individuals with a spinal cord injury (SCI), polio, amputation or with a neurological disorder) have tended to include simple and relatively cheap field-based techniques, such as skinfold callipers and bioelectrical impedance (BIA). But for obvious reasons the suitability with respect to the physical impairment of the athlete must be carefully considered. For example, hand-to-foot BIA analysers cannot be used with double leg amputees; similarly, the number and location of skinfold sites measured may need to be reduced, depending on the physical impairment type. In spite of this, these techniques have reportedly been used in persons with these aforementioned physical impairments with some degree of satisfactory results [[1](#), [267](#), [278](#)]. However, previous studies are limited with small sample sizes (e.g. n=8 males [[267](#)]) or with heterogeneous impairment groups (e.g. wheelchair games players comprising of both amputees and persons with a low to mid-level SCI [[356](#)]). Moreover, practitioners are cautious when using skinfolds since FM is typically underestimated in individuals with a SCI when using skinfolds [[254](#), [356](#)] and the general conclusions have stated the need for larger sample sizes so that an appropriate skinfold prediction equation can be developed.

With respect to other techniques, ~~then~~ to the authors' knowledge only one study has described the ability of air displacement plethysmography (ADP) to accurately assess body composition in persons with a SCI [[56](#)]. Their results suggested that ADP is a valid method

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3 for the calculation of total body volume and density in persons with a SCI below T3. That
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5 said, there may be problems with the measurement of thoracic gas volume of persons above a
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7 lesion of T6 which would result in the use of predicted values taken from the able-bodied
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9 norms [56]. Additionally, the theoretical problem with the use of ADP, is the assumption of a
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11 fixed density of FFM, implying that proportions of minerals, water and proteins remain
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13 constant and are not affected by sex, body mass, age, or body composition. However, the
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15 mass of bone mineral and skeletal muscle may be substantially reduced in wheelchair athletes,
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17 hence invalidating this assumption. The use of two compartmental models that make
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19 assumptions about FM and FFM may therefore not be suitable for the use in individuals who
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21 have significant deviations from the norms, such as individuals with a physical impairment.
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23 As a result three or more compartmental models are the preferred methods of assessment of
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25 body composition for accuracy and reliability, whilst methods that are not dependent upon
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27 body density, such as dual-energy X-ray absorptiometry (DXA), may offer greater accuracy.
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29 Despite the noted difficulties with the positioning of an individual with a physical impairment
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31 on the DXA couch, Keil et al. [189] recently found DXA to be a highly reproducible
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33 technique in the estimation of total and regional body composition of elite wheelchair
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35 basketball athletes.
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42 It is clear that many comparative studies exist, that have assessed the accuracy of a
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44 given body composition technique to a reference method such as DXA, in a number of
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46 different cohorts, including healthy individuals [34, 201, 245], young children [101, 2930];
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48 and athletes [23]. In contrast, to help inform the selection of methodology of athletes with a
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50 physical impairment then there is very little published data available [267, 356]. Therefore,
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52 the main purpose of this study was to assess the agreement in body composition
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54 measurements of trained wheelchair athletes using skinfolds, BIA and ADP with the reference
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56 method of DXA. This was done for the total group as well as for those participants with a SCI
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3 (e.g., tetraplegia vs. paraplegia) on the agreement. Furthermore, the second purpose was to
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5 develop new skinfold prediction equations to estimate percentage fat in wheelchair athletes
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7 with a SCI.
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10 11 **Methods**

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14 *Participants:* The study was approved by University Research Ethics Committee and the
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16 National Research Ethics Service and participants provided written informed consent prior to
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18 data collection. Participants included thirty male trained wheelchair games players from the
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20 sports of wheelchair basketball (n=19; 29 ±7yrs with a body mass of 72.1 ±13.1kg) and
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22 wheelchair rugby (n=11; 32 ±5yrs with a body mass of 68.2 ±10.7kg). Diagnoses were spinal
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24 cord injury from the lumbar to cervical region (n=22), [diastrophic dysplasia](#) ~~dystrophie~~
25
26 [dysphasia](#)-(n=3), hip damage (n=1) and lower limb damage (amputation (n=4)), indicative of
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28 physical disabilities that meet the eligibility criteria to participate in wheelchair basketball and
29
30 wheelchair rugby. All participants were considered trained having competed at a national
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32 level on a regular basis. As body composition estimates may differ between individuals with a
33
34 high and low SCI, subgroups comprising of persons with paraplegia (n=11) and tetraplegia
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36 (n=11) were formed. This study has been performed in accordance with the ethical standards
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38 of the International Journal of Sports Medicine [[145](#)].
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46 *Experimental Design:* Each individual attended a single session in a euhydrated state having
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48 refrained from exercise and consuming alcohol and caffeine for 12 hours, and eating or
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50 drinking at least 2 hours before each testing session to minimise variation in gastrointestinal
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52 contents and hydration status. Urine osmolality was assessed using an Osmocheck (Vitech
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54 Scientific Ltd, West Sussex, UK) to determine hydration status. Every participant underwent
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56 a whole-body DXA scan and participated in an anthropometry session. Additional
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3 measurements using the techniques of air displacement plethysmography (ADP, also known
4 by the commercial term BODPOD) and bioelectrical impedance analysis (BIA) were also
5 undertaken for those participants where standard electrode placement sites were accessible
6 and electrode placement was possible.
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14 *Dual-energy X-ray absorptiometry (DXA)*: Body composition was assessed using a Lunar
15 Prodigy Advance DXA scanner (GE Lunar, Madison, WI, USA) running version 12.20
16 enCORE 2006 software. Standard quality assurance and stability monitoring of the DXA
17 scanner was performed with daily measurement of the GE-Lunar calibration block and
18 aluminium/water bath spine phantom prior to the use of the machine to detect and correct for
19 any drift. The same trained operator performed all scans and analyses. Short-term precision
20 for DXA measurements were determined in a previous study [189], using the same scanner,
21 operators and in the same cohort as participants for the present study. CV values for all whole
22 body measurements were <2.0%, and, with the exception of arm FM (kg) (CV = 7.8%),
23 ranged between 0.1-3.7% for all segmental measures of bone mass, FM, and lean tissue mass
24 (LTM). Participants wore loose fitting, light-weight clothing with no metal or reflective
25 material, and all jewellery and prostheses were removed where possible. Participants were
26 asked to identify any metal fixtures (e.g. surgical pins) prior to the scans being performed and
27 such fixtures were flagged as artefact on analysis. Each individual was aligned supine on the
28 bed and appropriately positioned as closely as possible to the standard protocols. Positions
29 that may have produced spasms or other movement and any discomfort were minimized and
30 enough time allowed for any spasm generated on positioning to subside before scanning.
31 Velcro restraints were applied around participants' knees and ankles to minimise movement
32 during the scan, unless this was not possible because of the disability. Afterwards, the
33 participants were positioned on the DXA-bed in a supine position as close as possible to
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3 standard positioning protocol, with Velcro straps used to help keep the legs still during
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5 measurement. The analyses of all scans were performed by the same operator to avoid any
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7 inter-observer variability. The total body scan was used to gain the outcome measures which
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9 were: total body FM, total body fat percentage (% fat), total LTM and bone mineral content
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11 (BMC). To allow for comparison with other methods FFM was calculated as LTM +BMC.
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16 *Anthropometry:* For participants unable to assume a standing position, body height was
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18 measured from the heel to the crown of the head in the supine position to the nearest 0.1 cm
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20 with a Luftkin measuring tape (Cooper Tools, Apex, USA). For participants who had a double
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22 amputation, height was measured using the same methodology, but to the point of amputation.
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24 For participants who were unable to lie straight or who had chronic contractures, body height
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26 was calculated from the sum of body segments.
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32 *Skinfolds:* Eight skinfold sites were obtained from all participants, unless access to specific
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34 skinfold sites was inhibited due to disability or absence of limbs, in which case, as many
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36 measurements were taken as possible. All measurements were made in accordance with the
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38 guidelines stated by International Society for Advancement of Kinanthropometry (ISAK)
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40 using Lohman et al. [212] for site locations, by the same trained investigator, using a set of
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42 Harpenden Skinfold Callipers (Baty International, West Sussex, UK). The eight sites included
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44 the following sites: biceps, triceps, subscapular, iliac crest, supraspinale, abdominal, [anterior](#)
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46 [front](#) thigh and medial calf. For non-wheelchair bound individuals, skinfold measurements
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48 were taken in the anatomical reference position (standing up). For wheelchair-bound athletes,
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50 skinfold measurements were taken in the seated position in a standardised seat without arm
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52 rests to allow for better access to the iliac crest and supraspinale. Each measurement was
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54 taken in duplicate and an average of the two measurements was recorded. Body density was
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3 calculated using the equations from Katch and McArdle [178], Withers et al. [37], the three
4 and four skinfold equations of Durnin and Womersley [940] and Sloan and Weir [334]. Body
5 fat percentage was then estimated using the Siri equation [323]: % fat = (4.95/density – 4.50)
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14 *Bioelectrical impedance:* Body composition was assessed using the Multiple Frequency
15 Bioimpedance Meter (Bodystat 1500, Isle of Man, UK). Participants were asked to remove
16 socks and jewellery before lying down in the supine position on a non-conductive surface for
17 ten minutes, for standardisation purposes. Two electrodes were placed on the posterior surface
18 of the right hand, at the distal end of the third metacarpal and between the styloid processes of
19 the radius and ulna. Where possible, two electrodes were placed on the anterior surface of the
20 right foot, at the end of the second metatarsal and between the medial and lateral malleoli of
21 the ankle. For single leg amputees missing their right foot, the left foot was used instead and
22 for double leg amputees, this technique was not used. Body composition was determined by
23 the measurements of resistance made at 50kHz, using the previously validated prediction
24 equations of Lukaski et al. [223].
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41 *Air displacement plethysmography:* Body composition was assessed using a commercially
42 accessed BODPOD (BODPOD, Life Measurements, Concord, CA). Participants were asked
43 to wear ~~tight-tight~~-fitting swim-wear or in the absence of such attire, small shorts were worn,
44 all prostheses and items of jewellery were removed and participants were provided with a
45 tight fitting nylon cap to cover their hair. -A two-point calibration was conducted, using an
46 empty chamber prior to each individual assessment. Participants who were able to stand were
47 weighed using the BODPOD system's electronic scales. For those who could not stand, body
48 weight was matched using free weights (to the nearest 0.25kg) and loaded onto the scales to
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3 give a reading. On instruction, each participant entered the chamber and was asked to remain
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5 still throughout the assessment. A single ADP procedure consisted of two measurements of
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7 body volume, unless they differed by more than 150ml, in which case, the system required a
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9 third measurement. Body volume was determined by the volume of air displaced, when the
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11 participant is secured in the chamber. The measured body volume was adjusted for thoracic
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13 gas volume, which was estimated according to the methods described by Dempster and
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15 Aitkens [78]. The corrected body volume was used in combination with body mass and height
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17 to determine body density, from which percentage FM was estimated. All estimations were
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19 calculated using prediction equations integral to the system's software. Data pertaining to fat
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21 and muscle mass in kilograms and percentages were displayed on the system's monitor and
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23 were recorded.
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30 **Statistical analysis**

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32 The assumption of normality was checked for the body composition outcome measures by a
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34 Shapiro-Wilk test and visual inspection of the q-q plot and the box plot of the data. A One-
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36 Way ANOVA and a Tukey post-hoc test were performed on height, body mass, calf
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38 circumference and the DXA outcomes to check for differences between athletes with a
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40 tetraplegia, paraplegia and other disability. A paired samples t-test was performed to test for
41
42 systematic bias between the DXA outcomes and the other body composition outcomes (BIA,
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44 ADP, skinfolds). Intra-class correlations coefficients (ICC, two-way random, absolute
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46 agreement) were computed to test the relative reliability between the DXA outcomes and the
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48 outcomes of the other body composition measurement techniques. ICC's were considered
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50 sufficient when >0.8, moderate when 0.7 to 0.8, and insufficient when <0.7 [362]. Systematic
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52 bias and relative reliability were checked for the total group as well as for the groups with a
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54 paraplegia and tetraplegia separately. Bland-Altman plots with 95% limits of agreement were
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3 made to determine absolute reliability, i.e. underlying trends and within-subject differences in
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5 the results [45].
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8 Lastly, new equations for wheelchair games players to predict percentage body fat
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10 were developed using univariate regression analyses with percentage body fat measured by
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12 DXA as dependent variable and as independent variable one of the following variables: % fat
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14 measured by BIA, sum of three or four skinfolds used by Durnin and Womersley [940] or the
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16 sum of seven skinfolds as used by Withers et al. [37]. Different regression models were tested
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18 (e.g. linear, log, quadratic) and the models with the highest explained variance were finally
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20 chosen. In a secondary analysis, age or calf circumference (chosen as a measure indicative of
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22 muscle atrophy) were added to these models to check whether it improved the explained
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24 variance of the regression model. Level of significance was set at $p < 0.05$.
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29 30 Results

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32 Height ($p=0.31$) and body mass ($p=0.31$) were not significantly different between among the
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34 groups with a tetraplegia, paraplegia and other disability. The calf circumference of athletes
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36 with another disability was significantly different compared to the SCI groups ($p=0.01$). Post-
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38 hoc test results showed that athletes with another disability showed a larger calf
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40 circumference compared to athletes with a tetraplegia. All participants ($n=30$) underwent a
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42 DXA scan, yet due to the array of physical impairments not all participants were able to be
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44 measured via all the body composition field-based methods due to the limitations described
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46 previously and problems accounted with access to the BODPOD by the athletes with
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48 tetraplegia. This resulted in 28 participants being measured via the methods of BIA, 18 via the
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50 methods of ADP and up to 27 participants were able to have all the skinfold sites taken.
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52 Importantly, all participants were noted as being euhydrated as determined via the osmolality
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54 of the waking urine sample that was analysed on arrival to the laboratory prior undertaking
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3 the BIA measurement. The DXA assessment showed a total body fat percentage for the total
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5 group of wheelchair games players as $25.0 \pm 6.6\%$. No significant differences were found in
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7 DXA outcomes between athletes with a tetraplegia and paraplegia or between tetraplegia and
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9 the group with another disability. However, athletes with paraplegia had a significantly higher
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11 %fat and significantly lower FFM (kg) compared to the group with another disability.
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16 *Systematic bias:* Table 1 shows the mean and standard deviations of all body composition
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18 outcome measures and the results of the systematic bias testing. Compared to the DXA, the
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20 BIA and ADP techniques systematically overestimated FFM while they systematically
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22 underestimated FM and percentage FM. The predictions of % fat of all skinfold measurement
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24 formulas also systematically underestimated the percentage FM as measured by the DXA.
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26 These results were similar for the total group as well as for those with tetra- and paraplegia.
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31 *Agreement:* Table 1 shows the results for relative agreement between DXA outcomes and the
32
33 other body composition measurement techniques. All ICC values, except for the measurement
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35 of FFM (kg) by BIA and ADP (~~resp.~~ ICC=0.824 and 0.877 respectively) and fat (kg) by ADP
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37 (ICC=0.702), were below 0.7, indicating that the relative agreement of FM measured by BIA,
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39 % fat measured by BIA and ADP and skinfold body composition outcomes with the reference
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41 DXA measurement was insufficient. Similar results were found for people with ~~a~~-tetra- and
42
43 paraplegia. Figures 1A-F show the absolute agreement between % fat measured by the DXA
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45 measurement and measured by the BIA, ADP or skinfolds formulas. The Bland-Altman plots
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47 clearly show that the % fat measured by the DXA is systematically higher for almost all
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49 participants with all body composition measuring technique. The smallest mean difference
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51 with the DXA was found for the ADP and three skinfolds formula of Durnin and Womersley
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[910] (both a mean difference of 6.1%) but with high 95% confidence intervals of the difference: -3.4 to 15.5 and -2.2 to 14.4, respectively.

New equations: [The relationship between skinfold thicknesses and % fat by DXA seemed curvilinear \(Figure 2\)](#), and ~~The~~ quadratic regression equations showed the best explained variances. Table 2 shows the regression models to predict the % fat as measured by DXA by the sum of three, four or seven skinfolds or the % fat measured by BIA in wheelchair games players. Furthermore, the effect of adding age or calf circumference to the models is shown. The best model, with the highest R^2 , to predict % fat is the one with the 7 skinfolds and calf circumference ($R^2=0.84$), [see formula 1 below](#).

[Formula 1: %Body fat = -3.04 + 0.41 · \$\sum\$ SF7 - 0.001 · \$\sum\$ SF7² + 0.03 · Calf circumference](#)

The models using the sum of three skinfolds showed also a quite high explained variance ($R^2=0.74-0.75$), [see formula 2 below](#), and were better compared to the models using four skinfolds ($R^2=0.62-0.70$) or the % fat measured by BIA as independent variable ($R^2=0.46-0.51$).

[Formula 2: %Body fat = -5.04 + 1.46 · \$\sum\$ SF3 - 0.001 · \$\sum\$ SF3²](#)

Discussion

This study contributes to the search for a valid field-based body composition technique in ~~highly-highly~~ trained male wheelchair games players and extends previous studies to include the methods of ADP and identifies the suitability of methods with respect to SCI lesion level. In the present study we employed DXA as the criterion method and the mean % fat of $25 \pm 7\%$ is similar to those values reported for other USA and Japanese male wheelchair athletes [[156](#), [256](#), [267](#)] and male athletes from other British cohorts [[112](#)].

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3 Furthermore, this data demonstrates how high training loads have a positive influence on %
4 fat since the aforementioned value is substantially lower than the ~30% body fat that has been
5 reported in sedentary, disabled participants [[167](#),[234](#)]. However, % fat estimates in disabled
6 athletes may not be comparable with those in other populations. In wheelchair athletes, body
7 FM may be typical relative to sedentary controls [[356](#)]. However, muscle atrophy and the
8 related low FFM contribute to a lower body mass, and hence an artefactually high estimate of
9 % fat. As such % fat is probably a less appropriate measure of obesity in wheelchair athletes.
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No difference in body composition was found between players with tetraplegia and paraplegia while a difference was found between players with paraplegia and other disability. This difference could result partly from muscle atrophy and hence lower FFM in the paraplegic athletes, whilst athletes with other disability (e.g. amputation) are likely to exhibit much less muscle atrophy. A comparable % fat in those with tetraplegia and paraplegia was found ~~before~~ [previously](#) [[345](#)].

This study found each technique showed substantial systematic error and significantly underestimated FM (% and kg) and overestimated FFM (kg) relative to DXA. The mean bias for ADP, BIA and both Durmin skinfold formulae was 5.8-6.8%, whilst that for the other skinfold techniques was 9.9-11.6%. This systematic bias was observed in both people with a high and low lesion level, confirming previous literature [[267](#)]. The Bland Altman plots demonstrated a large variability at both the individual and the group level in estimating FM (%) in all techniques when compared to DXA. The limits of agreement for all techniques (e.g. from -2.2 to 14.4% for the Durmin & Womersley [[940](#)] 3 skinfolds formula but with comparable limits of agreement for the other techniques) were not particularly wide compared to other studies on able-bodied participants [[67](#)]. However, substantial underestimation in FM (% and kg) in comparison to DXA demonstrated that these methods cannot be used

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3 interchangeably at the group level, and individual values should always be interpreted with
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5 caution.
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7 Explanations for the underestimation of % fat reported via the skinfold technique
8 relative to DXA may be attributable to both theoretical and technical issues. Assessment of
9 body fat from skinfold thicknesses assumes that the skinfold thicknesses at measured sites are
10 proportional to the total body fat content. However, subcutaneous fat levels are particularly
11 high around the waist in persons with a SCI, which could have affected the accuracy of the
12 measures [134]. It is not known whether the proportion of fat situated subcutaneously differs
13 between SCI and healthy controls. Moreover, assessment of some skinfold sites may not be
14 feasible in this group due to e.g. amputation, whilst landmarks used for locating
15 anthropometric sites may be altered. [The need to make measurements in the seated position in
16 wheelchair athletes may have affected some skinfold thicknesses \(e.g. iliac crest\).](#)
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29 Mojahedi et al. [278] stated that BIA may be a more reliable field measure than
30 skinfolds since it measures resistance to electrical current through the body. Our data showed
31 that BIA consistently underestimated FM (% and kg) and overestimated FFM (kg) when
32 compared to DXA which supports previous findings [278]. These findings are not surprising,
33 as the measurement is influenced by the geometric proportions of the body, which may be
34 altered in wheelchair athletes. Furthermore, it has previously been reported that BIA
35 measurements are affected by a variety of factors such as nutritional status, hydration and
36 electrolyte balance [89], body position [312] and disease [123]. In the present study, there was
37 an attempt to control for training, caffeine, alcohol, food and general fluids, prior to
38 assessments, to reduce the impact that such factors would have on the assessment of body
39 composition. Participants were all confirmed as being in a euhydrated state, nonetheless, it is
40 highly likely that variability in the data was predominantly due to the significant body
41 asymmetry in amputees, and muscle wastage and altered extracellular fluid distribution in the
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3 lower limbs of wheelchair-bound athletes [[1920](#), [234](#), [356](#)], making this technique potentially
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5 less accurate in this cohort.
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8 This is the first study to assess the validity of ADP, using the commercially available
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10 BODPOD in elite wheelchair athletes, as to the author's knowledge only one study has
11 compared ADP with DXA within a clinical SCI population (n=13 mixed gender). Mean body
12 fat estimates were substantially and significantly lower than those by DXA, whilst 95%
13 confidence limits were high, suggesting that this technique is not a valid measure of body
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15 composition in this athletic cohort. Ballard et al. [[23](#)] reported ADP to be an accurate
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17 technique in the estimation of body composition in female athletes. However, densitometric
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19 techniques such as ADP assume a constant density of the FM and FFM. In wheelchair
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21 athletes, particularly those with SCI, the substantial losses of skeletal muscle and bone will
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23 affect the FFM density in particular, hence affecting estimates of % fat. However, FFM
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25 density may have been expected to be lower in those with SCI, which would result in
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27 overestimation of fat content as opposed to the underestimation seen here. It is important to
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29 note that we used the commercially available BODPOD so were unable to input directly the
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31 measured thoracic gas volume and our calculations were reliant on predicted able-bodied
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33 normative data. That said, for persons above a T6 lesion it has been suggested that there may
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35 be problems with directly measuring V_{TG} and therefore normative values may be
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37 recommended [[56](#)]. This does open the debate to how transferable the normative thoracic gas
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39 volume values are for persons with a SCI – there may be consistent differences that would
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41 further affect the estimate of body fat content. Further research is needed in this area.
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50 We used DXA as the reference technique in this study, but the errors associated with
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52 DXA may also be greater in this population. The technique makes assumptions about the
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54 relative attenuation of X-ray by fat and LTM [[289](#)]; but the skeletal muscle atrophy in
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56 wheelchair athletes may make these assumptions less reliable. Furthermore, the technique can
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3 only resolve two components in each pixel. In pixels containing bone, fat and LTM²s cannot
4 be resolved and are estimated based upon the composition of surrounding pixels, weighted to
5 account for differences in distribution of fat and lean relative to the bone. In wheelchair
6 athletes, there may be a smaller proportion of non-bone pixels in regions affected by atrophy,
7 producing greater error in estimating soft tissue composition. Further, this atrophy will alter
8 the distribution of fat and lean which could also make soft tissue composition estimates less
9 reliable. As such, it is important to remember that the differences between techniques
10 observed in this study will arise from errors in DXA as well as those in the other methods,
11 and the errors in DXA estimates may also be larger in this population. It would thus be
12 particularly important to evaluate techniques against a multi-component model, which allows
13 measurements of more of the components that may vary in this population.
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28 This study has attempted to develop a skinfold model for trained wheelchair games
29 players. We determined that a model containing only the three upper body skinfold sites of
30 the biceps, triceps and subscapular is similar to that containing the additional four sites of the
31 supraspinale, abdominal, front thigh and medial calf. The former model showed an explained
32 variance of $R^2=0.75$ compared to $R^2=0.69$. [Theoretically, an equation including a broader](#)
33 [range of sites should be able to take more account of inter-individual variation in fat](#)
34 [distribution, although this advantage may be counteracted by practical limitations at some of](#)
35 [the lower body sites. This may explain why the 7 skinfold equation explained only a little](#)
36 [more of the variance in %fat.](#) However, when adding calf circumference to the model with the
37 seven skinfold sites, this model was the best ($R^2=0.84$). As a practitioner the additional
38 benefit of the model with three skinfold sites is convenience and less intrusiveness since
39 wheelchair athletes tend to wear training trousers rather than shorts due to muscle atrophy of
40 the lower limbs. Further validation of these predictive models is warranted.
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Conclusion

Based on the findings in this study, the agreement between the methods employed to estimate body composition at both the group and SCI impairment level, when compared to the reference method of DXA, is comparable to the agreement found in able-bodied populations. It is clear from the data presented that BIA, ADP and skinfolds should be used with caution in the estimation of body composition of elite wheelchair athletes with substantial body asymmetry, lower body muscular atrophy and upper body muscular development. Further studies need to validate the prediction equations that were derived from this study.

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