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ORIGINAL ARTICLE

The association between regional body composition and metabolic outcomes in athletes with spinal cord injury

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Study design: Cross-sectional study comparing athletes with spinal cord injury (SCI) and age and body mass index matched able-bodied controls (AB).
Objective: To examine the impact of exercise training on the relation between whole body, regional and intermuscular adipose tissue (IMAT) and glucose tolerance, insulin action and lipid profile.
Setting: University Research Laboratory, USA.
Methods: Fourteen college-aged athletes with SCI (seven men; duration of injury 16.5 ± 5.7 years, level of injury T5-L5) and 17 sedentary AB (eight men) were assessed for body composition via dual-energy X-ray absorptiometry (DXA) and magnetic resonance imaging. Insulin sensitivity index (ISI) was determined via 2-h oral glucose challenge; standard lipid profile was determined from fasting blood samples.
Results: Although ISI was 30% higher in SCI, there were no significant differences between groups in glucose and insulin responses or in lipid measures. Adjusting for absolute and relative thigh IMAT area, fasting insulin (13.8 ± 5.3 μIU, 16.3 ± 5.6 μIU; $P < 0.05$; SCI vs AB respectively) and ISI (4.0 ± 1.4, 3.1 ± 1.3; $P < 0.05$) were significantly better among SCI athletes compared to AB. Measures of adiposity did not correlate with glucose response or most lipid measures. Within SCI and AB, respectively, ISI correlated strongly (all $P < 0.05$) with absolute ($r = -0.70$, -0.54) and relative IMAT ($r = -0.54$, -0.50), than with trunk ($r = -0.62$, -0.64) and whole body fat mass ($r = -0.61$, -0.64).
Conclusion: Habitual physical activity can maintain insulin sensitivity in SCI compared to sedentary AB controls. Total body fat mass, central adiposity and thigh IMAT appear to impact risk for metabolic disease in SCI individuals with IMAT playing a larger role in SCI than AB.
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Keywords: spinal cord injury; physical activity; intermuscular adipose tissue; insulin sensitivity; HDL cholesterol

Introduction

Similar to other populations, the favorable impact of exercise training on body composition,[1–6] glucose and insulin levels[7] and the lipid profile[1–5,8] has been investigated in the spinal cord injury (SCI) population. Beyond whole body measures, novel adipose tissue depots measured by magnetic resonance imaging (MRI) allows for the measurement of subcutaneous adipose tissue and intermuscular adipose tissue (IMAT).[9] Greater adipose infiltration of the muscle in obese[10] and elderly,[11] and abdominal obesity are associated with glucose intolerance,[12] insulin resistance[13] and cardiovascular disease[14] and IMAT has been associated with type II diabetes[15] and metabolic syndrome.[16] To date, no studies have utilized MRI to assess the impact of physical activity on the relation between adipose depots and risk for metabolic disease in the SCI population.

In this context, the aim of this study was to assess the effect of habitual physical activity on the association between body composition and glucose tolerance, insulin sensitivity and the lipid profile of individuals with SCI compared to sedentary able-bodied (AB) individuals. A major focus of this investigation was to examine the relation of metabolic indices with thigh and arm muscle and fat in paraplegics, with special focus on IMAT. For this study, IMAT is defined as adipose tissue located beneath the fascia lata and between muscles.[9,10]

Methods

Subjects

Fourteen highly active athletes with SCI (seven men, seven women; duration of injury 16.5 ± 5.7 years, level of injury

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T5-L5) were recruited from university varsity athletic teams and compared to 17 age- and body mass index (BMI)-matched sedentary AB reference controls (eight men, nine women). The SCI athletes participated in the varsity athletic program between 1 and 5 years, which involved 12 h of sport-specific and 3 h of resistance training per week, while the AB sedentary subjects participated in less than 60 min of purposeful physical activity per week throughout the past 6 months. All subjects signed a consent form approved by the university's Institutional Review Board upon enrollment in the study.

Anthropometry
Body weight was measured on a calibrated digital scale (Tanita, Model BWB-627A), with SCI subjects transferring onto a tare-weighted stool. Height was determined with all subjects in the supine position using a Gulick II retractable measuring tape (Country Technologies Inc., Gay Mills, WI, USA) from the top of the head to the bottom of the heel. SCI individuals that could not extend all joints were segmented by joint and measured accordingly. BMI was computed as weight in kg divided by height in m^2 (kg/m^2). Waist circumference measures were taken in the supine position at the level of the umbilicus.

Dual-energy X-ray absorptiometry
Whole body and regional composition was measured using dual-energy X-ray absorptiometry (DXA) (Hologic QDR 4500A, software version 11.1:3, Waltham, MA, USA). Precision for DXA measurements of interest is between 1 and 1.5% in our laboratory.

Magnetic resonance imaging
Images of the right thigh and right upper arm were collected on a 1.5 T magnet (GE Signa Echospeed, Milwaukee, WI, USA; repetition time, 100 ms; echo time, 4.2 ms; field of view, 40 cm; matrix 256×256). T_1-weighted transaxial images, 0.5 cm thick and 0.25 cm apart, were taken from the upper arm and thigh using a whole body coil. Images used for analysis were centered at the midpoint of the limb of interest and included the mid-slice and one proximal and one distal slice with values averaged for data analysis. Midpoint of the upper arm was determined as half way between the acromion and olecranon processes. Midpoint of the thigh was determined as half way between the inguinal crease and proximal border of the patella. Analyses of the images were performed using Winvessel 2.011 software (Ron Meyer, PhD at Michigan State University). Images were automatically segmented into fat, skeletal muscle and background bone regions as described previously.[16–18]

To correct for differences in muscle area and limb size, IMAT areas of a given limb were divided by the muscle area of that limb, providing the relative IMAT for the limb. Similarly, the muscle areas and subcutaneous fat areas of a given limb were divided by the whole area of the respective limb, resulting in the relative muscle and subcutaneous fat areas for the limb. Two individuals analyzed the slices. Inter-rater reliability was excellent with correlation coefficients and absolute error (cm^2) being 1.0, 0.30 ± 0.36 (whole area), 1.0, 0.41 ± 0.41 (muscle area), 0.99, 0.18 ± 0.20 (IMAT area), and 1.0, 0.52 ± 0.52 (subcutaneous fat area).

Oral glucose tolerance test
A 75-g, 2-h oral glucose tolerance test (OGTT) was conducted following a 12–14 h fast, at least 24 h following the last bout of exercise for SCI, whereas AB participated in no physical activity the day before the OGTT. Blood samples were drawn from an antecubital vein in the fasted state and 30, 60, 90 and 120 min after ingestion of the glucose beverage. Blood not immediately analyzed was stored at $-80^{\circ}C$. Plasma glucose concentrations were measured by the glucose oxidase method using an automated glucose analyzer (YSI 2300, Yellow Springs, OH, USA) and plasma insulin concentrations were measured by a double-antibody radioimmunoassay (ImmuChem, Belgium). The functional sensitivity of the assay was determined to be 4.2 μIU/ml. The total areas under the glucose and insulin curves (area under the curve (AUC)) were calculated using the trapezoidal rule. The insulin sensitivity index of Matsuda and DeFronzo was calculated as $(10\,000/\sqrt{}$ (fasting glucose $\times$ fasting insulin) $\times$ (mean OGTT glucose $\times$ mean OGTT insulin concentration). The Homeostasis Model Assessment of insulin resistance (HOMA) was calculated as ((fasting insulin $\times$ fasting glucose)/405).

Lipid profile
Fasting total cholesterol, high-density lipoprotein cholesterol (HDL-C) and triacylglycerol were determined by enzymatic assays (Infinity, Thermo Electron, Pittsburgh, PA, USA) as was non-esterified fatty acid (NEFA) (Wako Diagnostics, Richmond, VA, USA). Very low-density lipoprotein and low-density lipoprotein cholesterol (LDL-C) were calculated using the Friedewald equation.[19] All intra- and inter-assay %CV were below 6.3 and 8.1%, respectively.

Statistical analyses
The statistical analyses were performed with SPSS 14.0.0. Data were assessed for normality, and absolute and relative arm and thigh IMAT, insulin, insulin AUC, HOMA, total cholesterol, LDL-C and NEFA were normalized by log transformation. Two-way analysis of variance (ANOVA; gender by group) and analysis of covariance (ANCOVA) and partial correlational analyses, controlling for various measures of adiposity, sex (because of sex differences in body composition) and duration of injury (SCI only) were used to explore differences between the groups. Statistical significance was accepted at P-value < 0.05.

Results

The groups were matched on age and BMI and did not differ in percentage body fat (Table 1). The AB controls had higher fat mass, trunk fat mass, greater thigh muscle area and thigh muscle area relative to whole thigh area, and smaller thigh IMAT and thigh IMAT relative to muscle area (all $P < 0.01$)

than the SCI athletes. Alternatively, SCI athletes had greater arm muscle area and arm muscle area relative to whole arm area, and smaller arm IMAT relative to arm muscle area (all $P<0.05$) than the AB controls. Groups did not differ in arm IMAT area.

Although SCI athletes had lower insulin values, there were no significant differences between the groups in responses to the glucose challenge (Table 2) except in plasma glucose at 60 min during the OGTT (Figure 1). Using ANCOVA to control for total fat mass or central adiposity group differences did not become significant; however, controlling for either absolute or relative thigh IMAT area, all insulin sensitivity measures were significantly better among the SCI athletes compared to the AB controls (Figure 2). Adjusting for relative thigh muscle area had similar effects on insulin sensitivity; however, adjusting for absolute thigh muscle area or absolute or relative arm IMAT or muscle areas did not impact the group differences. Regarding lipids, no group differences existed except adjusting for relative thigh muscle area resulted in lower LDL-C among SCI athletes. Adjusting for total body fat mass, trunk fat mass, or waist circumference had little effects on lipids; only HDL-C levels became significantly higher among SCI athletes ($P<0.01$; data not shown).

The relative importance of whole body and regional fatness and ectopic adiposity on metabolic outcomes by group status was further explored by partial correlational analyses (Table 3). After adjusting for gender and duration of injury, whole body lean soft tissue was not correlated with metabolic outcomes in either group ($P>0.05$, data not shown). Subcutaneous thigh fat was a strong predictor of insulin response in both groups ($r=0.53$–0.71); however, after adjusting for whole body fat mass the relation diminished. No measures of adiposity were related to fasting or glucose AUC in either group. In AB controls, measures of

Table 1 Subject characteristics

Variable	*SCI athletes (n = 14)*	*AB controls (n = 17)*
Age (years)	22.5±3.7	22.5±3.8
Duration of injury (years)[a]	16.5±5.7	NA
Weight (kg)	57.6±11.0	70.5±12.5[b]
Height (cm)	161.6±11.1	172.1±11.4[b]
BMI (kg/m^2)	22.2±3.6	24.3±2.7
Waist circumference (cm)	75.4±9.5	83.3±7.4[b]
DXA measures		
Fat mass (kg)	14.3±4.0	19.1±5.0[b]
Lean soft tissue (kg)	41.7±10.0	51.9±12.8[b]
Body fat (%)	25.1±7.0	26.5±7.2
Trunk fat mass (kg)	5.7±1.6	7.9±2.1[b]
MRI measures		
Thigh muscle area (cm^2)	64.6±38.3	132.0±32.5[b]
Thigh muscle/whole (%)	49.0±21.6	65.3±12.4[b]
Thigh IMAT area (cm^2)	4.7±5.1	0.9±1.1[b]
Thigh IMAT/muscle (%)	13.3±17.7	0.7±1.1[b]
Arm muscle area (cm^2)	54.6±13.3	37.0±13.4[b]
Arm muscle/whole (%)	70.9±9.9	57.1±11.9[b]
Arm IMAT area (cm^2)	0.2±0.2	0.2±0.1
Arm IMAT/muscle (%)	0.4±0.3	0.6±0.3[b]

Abbreviations: AB, able-bodied individuals; BMI, body mass index; DXA, dual energy X-ray absorptiometry; IMAT, intermuscular adipose tissue; MRI, magnetic resonance imaging; SCI, individuals with spinal cord injury.
[a]Only values for the SCI athletes (seven women, seven men).
[b]$P<0.05$ for group.

Table 2 Group differences in blood metabolic outcomes

Variable	*SCI athletes (n = 14)*	*AB controls (n = 17)*
Fasting glucose (mg/dl)	87.1±5.0	89.1±6.2[a]
Fasting insulin (μIU/ml)	13.8±5.3	16.3±5.6[a,b,c]
Glucose AUC (mg/dl/min)	104.9±21.7	118.2±22.2
Insulin AUC (μIU/ml/min)	64.0±27.1	86.8.1±39.8[a,b]
ISI	4.0±1.4	3.1±1.3[a,b,c]
HOMA	3.0±1.2	3.6±1.3[a,b,c]
Total cholesterol (mg/dl)	150.7±51.2	158.6±41.8
Triacylglycerol (mg/dl)	56.9±29.8	40.9±18.1
HDL (mg/dl)	53.1±15.7	46.2±11.0
vLDL (mg/dl)	11.4±6.0	8.2±3.6
LDL (mg/dl)	86.2±44.3	104.2±35.7[c]
NEFA (mEq/l)	0.4±0.1	0.4±0.2

Abbreviations: AUC, area under the curve; HDL, high-density lipoprotein; HOMA, homeostasis model assessment; ISI, insulin sensitivity index; LDL, low-density lipoprotein; NEFA, non-esterified fatty acids; vLDL, very low-density lipoprotein.
[a]$P<0.05$ for group when corrected for thigh IMAT.
[b]$P<0.05$ for group when corrected for thigh IMAT/muscle.
[c]$P<0.05$ when corrected for thigh muscle/whole area.

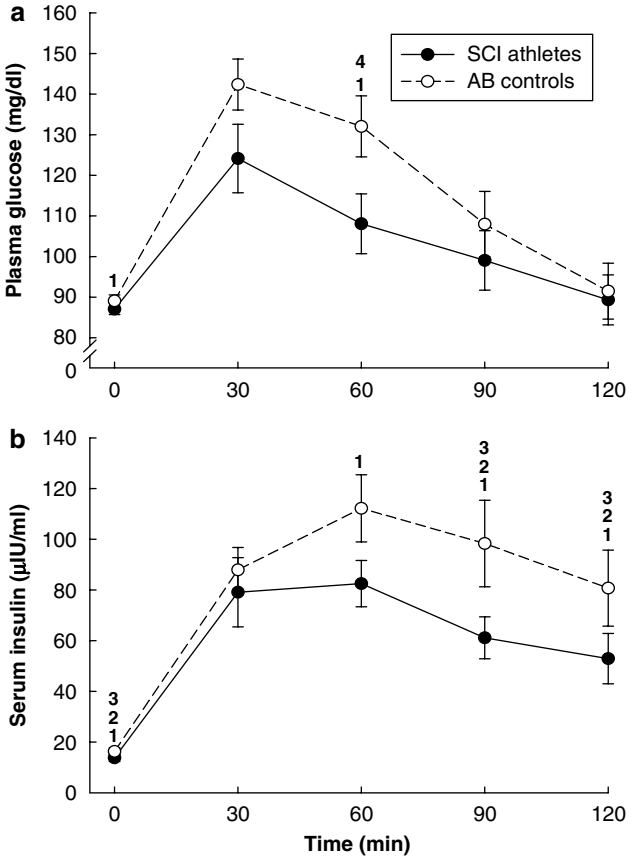

Figure 1 Glucose (**a**) and insulin (**b**) responses to the oral glucose tolerance test. SCI, individuals with spinal cord injury, AB, able-bodied individuals. [1]$P<0.05$ for group when corrected for thigh IMAT, [2]$P<0.05$ for group when corrected for thigh IMAT/muscle, [3]$P<0.05$ when corrected for thigh muscle/whole area, [4]$P<0.05$ for group unadjusted. Values are means and s.e.

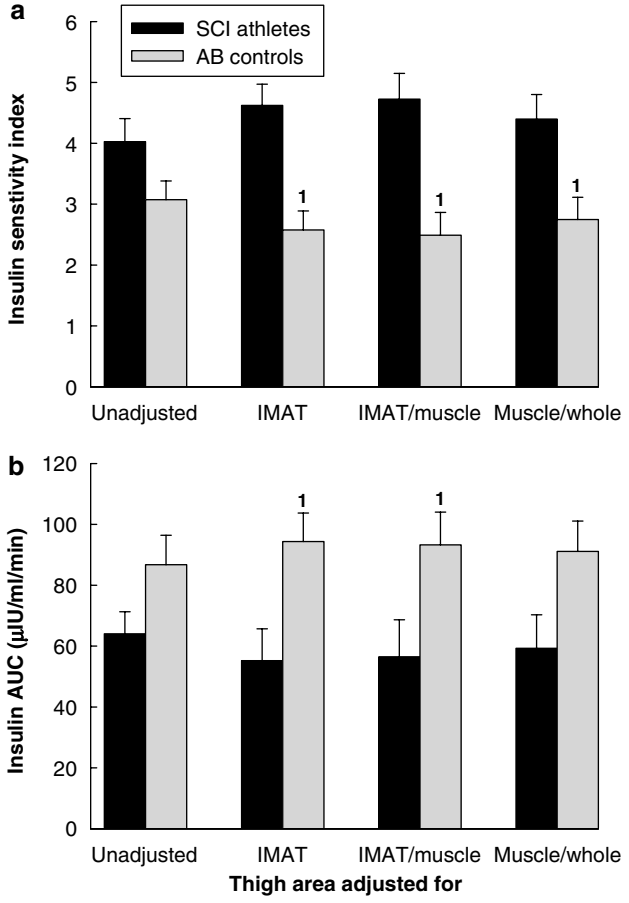

Figure 2 Insulin sensitivity as assessed by the insulin sensitivity index (**a**) and insulin area under the curve (**b**) after adjustment for thigh IMAT (absolute and relative) and thigh muscle (relative) areas. SCI, individuals with spinal cord injury, AB, able-bodied individuals, AUC, area under the curve, IMAT, intermuscular adipose tissue. [1]$P<0.05$ for group. Values are estimated adjusted means and s.e.

total body fat mass and central adiposity were more strongly related to all measures of insulin than absolute or relative IMAT. In SCI athletes, the total body fat mass, estimates of central adiposity and IMAT were similarly related to insulin measures.

Among the AB controls, no adiposity measures were significantly correlated with lipid measures. Among the SCI athletes, measures of central adiposity were positively related to total cholesterol, LDL-C, and HDL-C, the latter an effect that is difficult to explain. Relative and absolute IMAT did not correlate significantly with any of the blood lipid measures in either group.

Discussion

The primary finding of this study is that habitual high-level physical activity can maintain metabolic outcomes in individuals with SCI to the same level as sedentary AB individuals despite the greatly reduced muscle mass activation. This is encouraging as metabolic disease (that is, type II diabetes mellitus) appears decades earlier in SCI individuals due to greatly reduced activity levels and increased risk for obesity.[20] Moreover, indices of whole body and regional adiposity differ in their relation to insulin dynamics comparing young SCI athletes and AB controls. Our findings extend the recent literature regarding muscle fat and the interactive implications for adiposity, physical activity and metabolic disease risk.

It is evident in the literature that SCI individuals have increased risk for metabolic disorders compared to the AB population including impaired glucose tolerance and insulin resistance.[21,22] Little research has investigated the effect of physical activity on glucose tolerance and insulin action in the SCI population. Electrical stimulation of the lower-body muscles in paraplegics has been shown to improve glucose uptake in the paralyzed muscle[23] as well as glucose tolerance[24] and insulin sensitivity.[23] However, the effect of

Table 3 Partial correlation coefficients[a] between blood metabolic outcomes and estimates of body fat

Variable	*Total body fat mass (kg)*		*Trunk fat mass (kg)*		*Waist circumference (cm)*		*Thigh IMAT (cm^2)*		*Thigh IMAT/muscle (%)*	
	SCI	*AB*	*SCI*	*AB*	*SCI*	*AB*	*SCI*	*AB*	*SCI*	*AB*
Fasting glucose (mg/dl)	0.19	0.24	0.16	0.37	−0.06	0.40	0.36	0.21	0.12	0.13
Fasting insulin (μIU/ml)	0.37	0.72[b]	0.32	0.71[b]	0.39	0.67[b]	0.62[b]	0.47	0.60[b]	0.46
Glucose AUC (mg/dl/min)	−0.08	0.30	0.03	0.29	−0.22	0.37	−0.09	0.22	−0.11	0.23
Insulin AUC (μIU/ml/min)	0.71[b]	0.47	0.72[b]	0.44	0.65[b]	0.50[b]	0.56	0.47	0.30	0.45
ISI	−0.61[b]	−0.64[b]	−0.62[b]	−0.64[b]	−0.48	−0.67[b]	−0.70[b]	−0.54[b]	−0.54[b]	−0.50[b]
HOMA	0.38	0.72[b]	0.33	0.73[b]	0.37	0.70[b]	0.65[b]	0.48	0.60[b]	0.46
Total cholesterol (mg/dl)	0.54	0.33	0.54	0.25	0.80[b]	0.31	0.23	−0.04	0.14	0.01
Triacylglycerol (mg/dl)	−0.07	−0.16	−0.13	−0.13	−0.18	−0.09	0.21	−0.09	0.30	−0.03
HDL (mg/dl)	0.68[b]	0.40	0.77[b]	0.33	0.70[b]	0.44	0.19	0.09	−0.04	0.07
vLDL (mg/dl)	−0.07	−0.16	−0.13	−0.13	−0.18	−0.09	0.21	−0.09	0.30	−0.03
LDL (mg/dl)	0.41	0.29	0.38	0.21	0.70[b]	0.25	0.16	−0.07	0.13	0.00
NEFA (mg/dl)	0.03	−0.26	0.15	−0.22	−0.06	−0.23	−0.14	0.15	0.00	0.14

Abbreviations: AB, able bodied controls ($n=17$); AUC, area under the curve; HDL, high-density lipoprotein; HOMA, homeostasis model assessment; IMAT, intermuscular adipose tissue; ISI, insulin sensitivity index; LDL, low-density lipoprotein; NEFA, non-esterified fatty acids; SCI, athletes with spinal cord injury ($n=14$); vLDL, very low density lipoprotein.
[a]corrected for gender and duration of injury for SCI athletes and gender for AB controls.
[b]significant correlation coefficient ($P<0.05$).

upper-body exercise is not as clear. Some studies indicate that physical activity is not associated with fasting glucose,[1,4] glucose response to OGTT,[1] fasting insulin[4] or insulin response to OGTT[4] in SCI individuals. Alternatively, high-intensity upper-body physical activity has been shown to improve insulin sensitivity.[7] However, none of these studies included an AB comparison group.[1,4,7] It is probable that the young age and high level of training of our subjects impacted our findings.

The use of MRI to measure body composition has been shown to be of particular relevance in assessing muscle quality and adipose tissue in the SCI population.[17] In the AB population, there is a positive relation between thigh IMAT and risk for type II diabetes[15] and metabolic syndrome[16] and a negative relation between subcutaneous thigh fat and glucose levels[25] and metabolic syndrome.[16] Recent evidence suggests that thigh IMAT and subcutaneous fat areas are increased in sedentary SCI individuals and that relative IMAT is a strong predictor of plasma glucose suggesting an increased risk for impaired glucose tolerance and insulin resistance.[18] Although thigh subcutaneous fat was a strong predictor of metabolic outcomes within group, this effect was largely due to the relation to whole body fat mass and notably the relation was in the positive direction (that is, not protective). Our findings regarding thigh IMAT suggest that insulin sensitivity is associated with thigh IMAT in SCI individuals and that high-volume upper-body physical activity can protect against the risk of insulin resistance resulting from thigh IMAT accumulation and loss of muscle in this population.

For prevention of metabolic disorders, an important question in the SCI population is whether an increase in adipose or loss of muscle tissue is the major contributor to metabolic disease risk. There are indications that both tissues play a role in metabolic disorders in the SCI population.[20] Recent body composition studies in the elderly, for which disabled populations are often used as a model, suggest that body fatness and particularly abdominal obesity are independent risk factors for cardiovascular disease[14] and insulin resistance.[13] In addition, it appears that abdominal fat, and not muscle, contributes to glucose intolerance.[12] The role of IMAT for metabolic disease risk is not completely characterized.[26] Current literature on body composition in the SCI population is not adequate enough to establish which tissue (reductions in lean vs increases in fat) contributes most to risk for metabolic disease. Nevertheless, although our findings suggest that abdominal obesity and thigh IMAT accumulation relate to an increased risk for metabolic disease in the SCI population, high level physical training protects against glucose intolerance and insulin resistance compared to AB controls.

Surprisingly, we found little group differences and very few associations between body composition measures and the lipid profile in our sample. The lack of association between blood lipids and body composition and lack of differences in blood lipids between SCI and AB may be partly explained by the relatively low adiposity and similar body fat percentage in both groups. In addition, our subjects were young healthy individuals.

HDL-C levels in this study were of particular interest, because physical activity is known to increase HDL-C levels in the general population,[27] and low HDL-C levels in SCI individuals are often attributed to physical inactivity.[28,29] Although there was no significant difference between the groups in our study, the mean HDL-C level in the SCI athletes was 53 compared to 46 mg/dl in the sedentary AB controls, and this is well above HDL-C levels ranging between 32 and 45 mg/dl reported previously in sedentary SCI individuals.[28,29] In the AB population exercise training has shown to increase HDL-C levels by 2–8 mg/dl,[27] which is approximately the difference in mean HDL-C we found and levels reported previously in the SCI population. Possibly, with a larger sample size we may have been able to show a significant difference between groups. Indeed, the effect size for HDL-C was moderate at ~ 0.60.

The main limitation in this study is the lack of a sedentary SCI comparison group; however, there are several published studies with this population to draw comparisons with, as we have aimed to do in this discussion. The SCI individuals in this study were trained athletes, which does not reflect the typical physical activity level of most individuals with SCI. Another limitation is the lack of a measure of visceral adiposity using MRI, which was prohibited due to major artifacts in MRI abdominal scans. The hypothetical error due to metal implants in the DXA trunk fat measurements is unknown but assumed negligible. Lastly, our sample size is relatively small impacting our statistical power.

In summary, although glucose tolerance and lipid profile did not differ significantly between SCI athletes and AB controls, data from this study suggest that upper-body physical activity can improve insulin sensitivity and HDL-C levels in the SCI population compared to sedentary AB individuals. Furthermore, whole body, abdominal adiposity and thigh IMAT all appear to impact risk for metabolic disease in SCI individuals.

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