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Longitudinal changes in adiposity following anterior cruciate ligament reconstruction and associations with knee symptoms and function

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ABSTRACT

Objective: To evaluate adiposity after anterior cruciate ligament reconstruction (ACLR): i) cross-sectionally (1-year post-ACLR) compared to uninjured controls; ii) longitudinally up to 5 years post-ACLR; and iii) associations with patient-reported symptoms and physical performance.

Methods: In 107 individuals post-ACLR and 19 controls, we assessed global (BMI), peripheral (subcutaneous adipose tissue thickness on the posteromedial side of knee MRI), and central (waist circumference in ACLR group) adiposity. Patient-reported symptoms (Knee injury and Osteoarthritis Outcome Score) and physical performance (hop for distance) were evaluated at 1 and 5 years post-ACLR. Linear regression models evaluated adiposity between groups. Paired t-tests evaluated changes in adiposity from 1- to 5 years post-ACLR. Linear regression models analyzed adiposity's associations with patient-reported symptoms and physical performance at 1-year post-ACLR, changes in symptoms and performance over 4 years post-ACLR, and longitudinal changes in adiposity and symptoms and performance, controlling for age, sex, and activity level.

Results: Individuals 1-year post-ACLR were associated with higher average global (3 kg/m^2) and peripheral adiposity (2.3 mm). From 1- to 5 years post-ACLR, higher average global (0.58 kg/m^2) and central (5 cm) adiposity, and lower average peripheral adiposity (1.3 mm) were observed. In general, adiposity at one-year post-ACLR was negatively associated with patient-reported symptoms and physical performance, and changes from 1 to 5 years post-ACLR. Increases in adiposity were negatively associated with changes in patient-reported symptoms and physical performance over four years post-ACLR.

Conclusion: Greater global and central adiposity is a feature of young adults following ACLR and influences current and future patient-reported symptoms and physical performance.

1. Introduction

Anterior cruciate ligament (ACL) rupture is a common traumatic knee injury in active adolescents and young adults [1–3]. Following ACL rupture and surgical reconstruction (ACLR), an initial decline in physical activity is inevitable [4]. However, diminished levels of physical activity can persist for many years [5–7]. For example, less moderate-to-vigorous intensity physical activity has been reported in individuals 2 years post-ACLR, and those 3–12 years following youth sport-related knee injury, compared to matched uninjured controls [5,8]. A potential consequence of diminished physical activity after a knee injury is weight gain [9–12]. This is particularly concerning given that excess adiposity is a strong risk factor for incident knee osteoarthritis (OA) and may exacerbate the already high risk of early-onset post-traumatic OA following ACLR [13–16].

Excessive or abnormal accumulation of body fat, also known as adiposity, can lead to significant health risks [17,18]. Body mass index (BMI) is an anthropometric estimate of global adiposity. Young female athletes reporting knee injuries exhibit greater increases in global adiposity than their uninjured peers [19]. Additionally, research

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indicates increases in global adiposity over time in adolescents following ACLR [12,20]. However, results are inconsistent in adults who have undergone ACLR [21,22]. Although BMI is easy to calculate, it does not differentiate between adipose tissue and lean muscle mass, which have opposite effects on health and well-being. For example, individuals with higher muscle mass, such as athletes, may be misclassified as obese based on BMI [23], while older individuals with increases in central adiposity, despite losing body mass, may be inaccurately classified within the normal BMI range [24]. Therefore, additional measures beyond BMI have been advocated to improve obesity estimates, such as measures of central adiposity (e.g., waist circumference, waist-to-height ratio) and peripheral adiposity (e.g., imaging methods or circumferences to measure adipose tissue at the hip, thigh, and knee) [25]. A better understanding of global, central, and peripheral adiposity in individuals following ACLR will help guide research and clinical efforts to minimize adiposity gains post-ACLR.

Studies have also shown that higher global adiposity is cross-sectionally associated with poor functional, patient-reported, and structural OA outcomes following ACLR [26–28]. However, little is known about longitudinal associations of adiposity with clinical outcomes in individuals post-ACLR. Additionally, to our knowledge, no studies have evaluated the cross-sectional and longitudinal associations of central and peripheral adiposity with patient-reported symptoms and physical performance. This knowledge could be useful, as interventions that target excess adiposity may help improve clinical outcomes in people who have undergone ACLR.

This study aimed to: (i) compare global and peripheral adiposity in individuals one-year post-ACLR and uninjured controls; (ii) investigate changes in global, peripheral, and central adiposity from one to five years post-ACLR; (iii) investigate the associations of global, peripheral, and central adiposity at one-year post-ACLR with patient-reported symptoms and physical performance, at one-year post-ACLR (i.e., cross-sectional association) and with changes in patient-reported symptoms and physical performance from one to five years post-ACLR (i.e., longitudinal association); and (iv) investigate the longitudinal (1–5 years post-ACLR) associations between changes in adiposity and changes in patient-reported symptoms and physical performance from one to five years post-ACLR.

2. Methods

2.1. Participants

This study used data from an established prospective cohort of patients who had undergone ACLR [15,29,30] and uninjured controls. Individuals following ACLR were recruited from one of two orthopedic surgeons in Melbourne, Australia. Inclusion criteria were aged 18–50 years and had primary single-bundle hamstring-tendon autograft ACLR approximately one year previously [15]. Exclusion criteria included previous injury/surgery to the index knee before ACL rupture and subsequent injury to (or follow-up surgery on) the index knee. Any patient with a condition other than ACLR that currently affected their function in daily living or reported a contraindication to MRI was also excluded. Uninjured control participants were included if they were aged 18–50 years and had no lower-limb injury/surgery history. The control group was recruited via word-of-mouth to match the mean age, sex, and level of pivoting sport participation of those following ACLR [15]. The level of participation in pivoting sports was defined from level I (sports with frequent jumping, cutting, and pivoting) to level IV (sedentary) [31]. Ethical approval was obtained from The University of Melbourne (HREC 1136167), The University of Queensland (HREC 2012000567 and 20133001448), and La Trobe University (HEC 15-100) Human Research Ethics Committees. All participants provided written informed consent. Participants in the ACLR group underwent assessments at one- and five-years post-surgery, while uninjured controls were evaluated once.

2.2. Global adiposity

Global adiposity was assessed with body mass index (body mass in kilograms ÷ height^2 in meters) in participants following ACLR at one and five years post-ACLR and in uninjured controls at one time point. Body mass was measured to the nearest 100 grams with digital scales and recorded in kilograms. Height was measured to the nearest centimeter with a wall-mounted stadiometer.

2.3. Central adiposity

Central adiposity was assessed using waist circumference, measured (in cm) at the umbilicus with a tape measure (Model W606PM, Lufkin, Apex Tool Group, USA) at one- and five-years post-ACLR. Central adiposity was not recorded in uninjured controls.

2.4. Peripheral adiposity

Peripheral adiposity was evaluated by measuring the thickness of subcutaneous adipose tissue located on the posteromedial aspect of the distal femur using knee magnetic resonance imaging (MRI). Peripheral adiposity was measured from knee MRI acquired using a single 3.0 T system (Philips Achieva) at one and five years post-ACLR and at one time point in uninjured controls [15,30]. Two investigators (AM, CK) who remained aware of the group and study visits, independently measured subcutaneous adipose tissue thickness using axial proton density-weighted turbo spin-echo sequences (slice thickness: 2.5 mm, slice gap: 2.0 mm, repetition time/echo time: 3,850msec/34msec and field of view:140 mm^2). The investigators used the ruler function to measure 5.5 cm above the medial distal femur articular surface on the central coronal slice (Fig. 1) (3D Slicer Version 4.13.0, Surgical Planning Laboratory at Brigham and Women's Hospital and the MIT Artificial Intelligence Laboratory, Massachusetts). Subsequently, an axial slice corresponding to this measurement was identified. The thickest portion of the subcutaneous adipose tissue was measured by placing a horizontal line using the ruler function on the posteromedial side of the selected axial slice. This approach has been used previously to measure subcutaneous adipose tissue thickness around the distal femur (7–7.5 cm above the lateral joint line) using knee MRIs from a database of patients with atraumatic/non-traumatic knee pain [32]. In the previous study, an axial slice corresponding to around 7–7.5 cm above the lateral joint line was used. We used an axial slice corresponding to 5.5 cm above the medial distal femur articular surface, as this axial slice was available for all participants. After establishing the measurement technique, two investigators independently measured subcutaneous adipose thickness in 10 randomly selected MRIs, and the reliability of the measurement technique between the two investigators was established. The interrater reliability of peripheral adiposity was excellent (ICC [95% Confidence Interval, CI]: 0.99 [0.95 to 1.00]). The mean values of adipose thickness from these 10 measurements were 18.60 mm (±9.00) and 18.50 mm (±8.76) for raters.

2.5. Patient-reported symptoms

Participants at one and five years following ACLR completed the Knee injury and Osteoarthritis Outcome Score (KOOS) [33], which has been validated for use in patients post-ACLR [34]. The KOOS consists of five subscales: Pain, Symptoms, Function in Activities in Daily Living (ADL), Function in Sports and Recreation (Sport/Rec), and Quality of Life (QoL). A normalized score is calculated (0–100) for each subscale, where zero indicates maximum limitations.

2.6. Physical performance

Participants post-ACLR also completed three trials of single-leg forward hop for distance and the maximum horizontal distance (cm) hopped on the ACLR limb [35] at one and five years post-ACLR were evaluated.

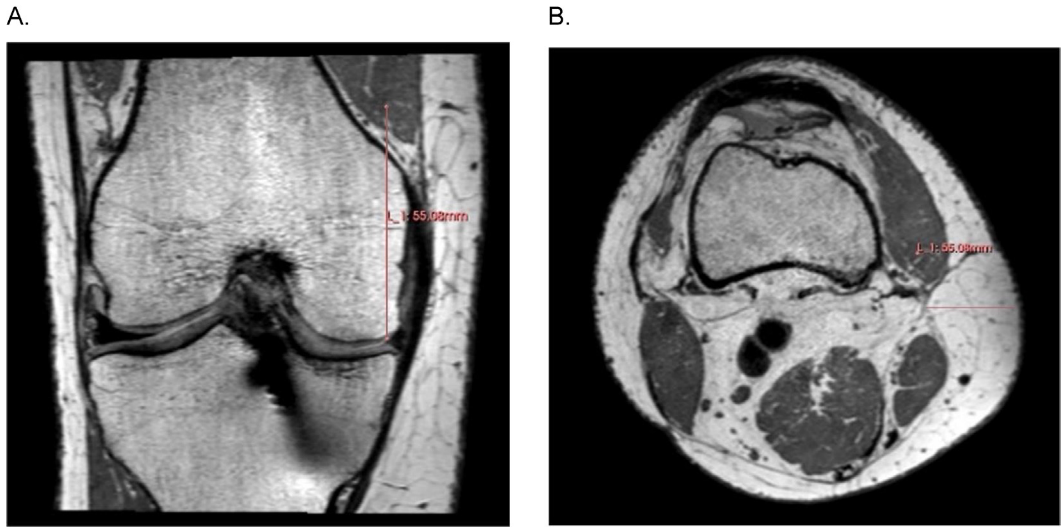

Fig. 1. The images obtained from the software depict: (A) Coronal protein density-weighted non-fat-suppressed MRI slice (midpoint in the anterior-posterior direction) illustrating 5.5 cm from the distal femur articular surface (highlighted by the red line and labeled with red text). (B) Axial protein-density non-fat-suppressed MRI slice (corresponding to 5.5 cm identified using the coronal plane MRI slice) illustrating the measurement of subcutaneous adipose tissue thickness (solid red line) on the posteromedial side. The red text denotes an example of the subcutaneous adipose thickness measured using the ruler tool.

2.7. Statistical analysis

Participant characteristics are presented as means with standard deviation, or percentages, as appropriate. Linear regression models evaluated the associations between groups (uninjured controls and one-year post ACLR) and global and peripheral adiposity measures. The coefficients represent the differences in the average adiposity between the control and ACLR groups. Unadjusted analyses and analyses adjusted for age, and sex, and analyses adjusted for age, sex, and activity level were conducted. Activity level was assessed with the Tegner Activity Scale, a score of 10 represents knee-demanding elite (inter)national sports and zero represents disability because of knee problems [36]. Changes in global, peripheral, and central adiposity from one to five years post-ACLR were evaluated using paired t-tests.

Linear regression models were built to evaluate the: (i) associations of global, peripheral, and central adiposity with patient-reported knee symptoms and physical performance at one-year post-ACLR; (ii) associations of global, peripheral, and central adiposity at one-year post-ACLR with changes in patient-reported symptoms and physical performance from one to five years post-ACLR; and (iii) associations of changes in global, peripheral, and central adiposity with changes in patient-reported symptoms and physical performance from one to five years post-ACLR. Unadjusted analyses and analyses adjusted for age, sex, and activity level were conducted. Additionally, associations between adiposity and body height normalized single-leg hop for distance were conducted. After testing the assumptions for linear regression model, linear regression models with robust standard errors were used for mild violation of underlying assumptions. Unstandardized estimates with 95% CI are presented. Data were analyzed using Stata Version 17.

3. Results

3.1. Participants characteristics

In the present study, we included 107 participants 13 ± 1 months following ACLR (65% men, age 30 ± 8 years, mass 81 ± 16 kg, height 1.76 ± 0.09 m) and 19 uninjured controls (63% men, age 30 ± 7 years, mass 70 ± 11 kg, height 1.75 ± 0.09 m) [15]. Global adiposity was assessed in all participants, and central adiposity, patient-reported symptoms, and physical performance data were available in 107 participants one-year post-ACLR. Peripheral adiposity was assessed in 106 participants one-year following ACLR and 18 injured controls due to MRI scan quality. Of the 77 participants who completed the five-year follow-up, 75 individuals (62% men, age 30±9 years, mass 81 ± 16 kg, height 1.77 ± 0.09 m) were included in this study. Global and central adiposity and performance-based function data were available in 73 participants, and peripheral adiposity and patient-reported symptoms were available in 75. Baseline characteristics of participants following ACLR who did not contribute to the 5-year follow-up data is included as a supplementary file (Supplementary Table 1).

3.2. Adiposity in ACLR and uninjured controls and longitudinal changes in adiposity in individuals post-ACLR

When controlling for the influence of age, sex, and activity level, the ACLR group had a 2.9 kg/m^2 higher average global adiposity (95% CI, 1.9 to 3.9) and a 2.4 mm higher average peripheral adiposity (95% CI, −0.37 to 5.1) compared to the control group (Table 1). The results of unadjusted analyses and analyses adjusted for age and sex are included as a supplementary file (Supplementary Table 2).

A 0.58 kg/m^2 higher average global adiposity (95% CI, 0.19 to 0.97), a 5 cm higher average central adiposity (95% CI, 4 to 7), and a 1.3 mm lower average peripheral adiposity (95% CI, −0.5 to 2.0) were observed from one to five years post-ACLR (Table 1).

3.3. Associations of adiposity with patient-reported symptoms and physical performance at one-year post-ACLR

There were cross-sectional associations between adiposity and patient-reported knee symptoms and physical performance at one-year post-ACLR — with every one-unit higher adiposity associated with differences in KOOS subscale scores ranged from −0.62 to 0.79 points. Similarly, the associations between adiposity and the distance hopped during a single-leg forward hop for distance ranged from 0.85 cm to 2.32 cm (Table 2) when adjusting for age, sex, and activity levels. The results of unadjusted models, and unadjusted and adjusted height-normalized physical performance models are included as supplementary files (Supplementary Tables 3 and 4).

Table 1
Adiposity and patient-reported symptoms and physical performance for individuals post-ACLR and uninjured controls.

	Between-Group		Longitudinal Changes Post-ACLR	
	One-year post ACLR (n = 107)	Control (n = 19)	One year (n = 75)	Five years (n = 75)
Adiposity				
Global adiposity (kg/m^2)	26.1 ± 3.9	22.7 ± 1.8	25.8 ± 3.8	26.2 ± 3.6
Peripheral adiposity (mm)	18.1 ± 6.2	16.7 ± 8.1	18.5 ± 5.5	17.2 ± 5.6
Central adiposity (cm)	–	–	84.8 ± 11.1	89.6 ± 10.8
Patient-reported symptoms and physical performance				
KOOS Pain (0-100)	–	–	91.0 ± 9.3	93.3 ± 8.8
KOOS Symptom (0-100)	–	–	84.8 ± 12.0	84.6 ± 14.6
KOOS ADL (0-100)	–	–	96.7 ± 6.7	96.4 ± 7.9
KOOS Sport/Rec (0-100)	–	–	81.3 ± 16.8	81.5 ± 16.4
KOOS QoL (0-100)	–	–	69.2 ± 18.0	78.0 ± 16.9
Single-leg forward hop for distance (cm)	–	–	106.2 ± 28.4	109 ± 28.2

Data are presented as mean ± standard deviation. KOOS = Knee injury and Osteoarthritis Outcome Score (0–100 score, 100 = no problems). ADL = Function in Activities of Daily Living, Sport/Rec = Function in Sports and Recreation, QoL = Quality of life. '—' indicates data not available.

Table 2
Associations of adiposity with patient-reported symptoms and physical performance in individuals post anterior cruciate ligament reconstruction when adjusting for age, sex, and activity level.

	Global adiposity (kg/m^2)		Peripheral adiposity (mm)		Central adiposity (cm)	
	R^2	β [95% CI]	R^2	β [95% CI]	R^2	β [95% CI]
Cross-sectional analysis: Adiposity and patient-reported symptoms and physical performance at one-year post-ACLR						
KOOS Pain (0-100)	0.079	0.02 [−0.38 to 0.41]	0.081	−0.13 [−0.43 to 0.17]	0.080	−0.03 [−0.18 to 0.12]
KOOS Symptoms (0-100)	0.085	0.20 [−0.40 to 0.81]	0.078	0.014 [−0.44 to 0.47]	0.082	0.01 [−0.24 to 0.26]
KOOS Sport/Rec (0-100)	0.179	−0.62 [−1.36 to 0.13]	0.185	−0.55 [−1.11 to 0.02]	0.199	−0.34 [−0.62 to −0.06]
KOOS ADL (0-100)	0.045	−0.02 [−0.25 to 0.21]	0.055	−0.13 [−0.34 to 0.09]	0.046	−0.02 [−0.09 to 0.05]
KOOS QoL (0-100)	0.209	0.79 [−0.05 to 1.63]	0.191	0.21 [−0.50 to 0.93]	0.190	0.13 [−0.22 to 0.47]
Hop for distance (cm)	0.490	−2.32 [−3.41 to −1.22]	0.499	−1.67 [−2.41 to −0.92]	0.489	−0.85 [−1.24 to −0.47]
Longitudinal analysis: Adiposity at one-year post-ACLR and changes in patient-reported symptoms and physical performance from one to five years post-ACLR						
KOOS Pain (0-100)	0.066	−0.49 [−1.08 to 0.09]	0.056	−0.29 [−0.67 to 0.09]	0.058	−0.17 [−0.43 to 0.10]
KOOS Symptoms (0-100)	0.074	−0.43 [−1.27 to 0.40]	0.066	−0.10 [−0.59 to 0.40]	0.069	−0.12 [−0.43 to 0.20]
KOOS Sport/Rec (0-100)	0.081	−0.59 [−2.12 to 0.95]	0.072	−0.22 [−1.06 to 0.62]	0.071	−0.10 [−0.68 to 0.47]
KOOS ADL (0-100)	0.086	−0.43 [−0.97 to 0.10]	0.093	−0.32 [−0.67 to 0.04]	0.097	−0.18 [−0.47 to 0.11]
KOOS QoL (0-100)	0.150	−0.80 [−2.01 to 0.41]	0.129	0.14 [−0.88 to 0.61]	0.129	−0.07 [−0.53 to 0.39]
Hop for distance (cm)	0.114	−0.39 [−1.62 to 0.84]	0.110	−0.04 [−0.83 to 0.74]	0.110	−0.01 [−0.39 to 0.37]
Longitudinal analysis: Changes in adiposity and changes in patient-reported symptoms and physical performance from one to five years post-ACLR						
KOOS Pain (0-100)	0.044	−0.36 [−1.05 to 0.33]	0.037	−0.22 [−0.94 to 0.49]	0.045	−0.09 [−0.27 to 0.09]
KOOS Symptoms (0-100)	0.118	0.35 [−0.97 to 1.66]	0.079	0.05 [−1.38 to 1.48]	0.119	0.09 [−0.25 to 0.44]
KOOS Sport/Rec (0-100)	0.130	−1.99 [−4.03 to 0.05]	0.078	0.09 [−1.33 to 1.50]	0.110	−0.31 [−0.76 to 0.15]
KOOS ADL (0-100)	0.068	−0.35 [−0.98 to 0.27]	0.074	−0.40 [−1.00 to 0.21]	0.066	−0.07 [−0.20 to 0.06]
KOOS QoL (0-100)	0.128	−1.14 [−3.14 to 0.86]	0.108	0.34 [−1.08 to 1.76]	0.139	−0.37 [−0.98 to 0.24]
Hop for distance (cm)	0.132	−1.82 [−3.68 to 0.04]	0.109	−0.03 [−1.21 to 1.15]	0.162	−0.64 [−1.37 to 0.09]

Data are presented as coefficients [95% confidence interval]. KOOS=Knee injury and Osteoarthritis Outcome Score (0-100 score, 0 = maximum symptoms/limitations), Sport/Rec = function in sport/rec, ADL = function in activities of daily living, QoL = quality of life, ACLR = anterior cruciate ligament reconstruction.

3.4. *Associations of adiposity at one-year post-ACLR with changes in patient-reported symptoms and physical performance from one to five years post-ACLR*

Adiposity at one-year post-ACLR was associated with changes in patient-reported symptoms and physical performance over four years post-ACLR (Table 2). Specifically, one-unit higher global, peripheral, and central adiposity at one-year post-ACLR was associated with differences in KOOS subscales from one to five years post-ACLR, ranging from −0.43 to 0.80 points, −0.32 to 0.14 points, and −0.07 to −0.18 points, respectively. The associations between one-unit higher adiposity at one-year post-ACLR and changes in distance hopped during single-leg forward hop for distance ranged from −0.01 cm to −0.39 cm (Table 2). The results of unadjusted models, and unadjusted and adjusted height-normalized physical performance models are included as supplementary files (Supplementary Tables 3 and 4).

3.5. *Associations of changes in adiposity and patient-reported symptoms and physical performance over four years post-ACLR*

Gains in adiposity over four years post-ACLR were associated with a negative change in various subscales scores, including pain, sport and recreation, activities of daily living, and quality of life (Table 2). A one-unit gain in global and central adiposity was associated with 0.36 to 1.99 points, and 0.07 to 0.37 points decline in KOOS subscales scores, respectively. A one-unit higher peripheral adiposity from one to five years post-ACLR was associated with differences ranging from −0.40 to 0.34 points in the KOOS subscales during the same period. Additionally, a change in adiposity was associated with a change in distance hopped over four years after ACLR. Specifically, one-unit gain in global and central adiposity from one to five years post-ACLR was associated with a 1.82 cm (95% CI, −3.68 to 0.04) and a 0.64 cm (95% CI, −1.37 to 0.09) decline in distance hopped, respectively. The results of unadjusted models, and unadjusted and adjusted height-normalized physical performance models are included as supplementary files (Supplementary Tables 3 and 4).

4. Discussion

4.1. *Summary of findings*

One year following ACLR, young adults had higher average global and peripheral adiposity compared to uninjured controls. Average global and central adiposity was higher at four years post-ACLR than at one-year post-ACLR, while peripheral adiposity was lower. In general, global, peripheral, and central adiposity at one-year post-ACLR was negatively associated with patient-reported symptoms and physical performance at one year, and changes in patient-reported symptoms and physical performance from one to five years post-ACLR. Furthermore, increases in global, peripheral, and central adiposity were also negatively associated with changes in patient-reported symptoms and physical performance over four years post-ACLR.

4.2. Adiposity post-ACLR

Despite overweight and obesity being one of the strongest risk factors for incident knee OA in the general population [37,38], the current study is one of the first to evaluate adiposity in a young adult population at high risk of early-onset OA. A previous study in pediatrics and adolescents reported an increased BMI percentile at three months post-ACLR that peaked at six months [20]. Further to this, despite BMI trending back towards baseline (time of surgery) BMI levels at nine months post-ACLR, it remained elevated at two years post-ACLR relative to baseline. Another study reported that young female athletes who reported knee injury had greater increases in BMI percentile by up to 5 units or more and an increase in body fat percentage by up to 1.5% within 1 year relative to their uninjured peers [19]. In overweight and obese older adults with, or at risk of, knee OA, increases in global adiposity by $\geq$ 10% have been associated with greater subcutaneous adipose thickness assessed at the knee joint than controls who had less than 3% change in global adiposity over four years [39]. The results of the present study also seem to indicate greater average global and peripheral adiposity in individuals one-year following ACLR when compared with uninjured controls.

Global and central adiposity appears to continue to increase between one and five years post-ACLR. The proportion of individuals outside of the healthy global adiposity range, i.e., 25 kg/m^2 or greater, and central adiposity, a waist circumference of at least 102 cm for men and at least 88 cm for women [40], increased by 8% and 13% over four years post-ACLR, respectively. Previous work has shown that physical activity levels are reduced by 50% at six months after knee injury compared with before injury [4], and individuals with a history of knee injury also engage in lower moderate-to-vigorous physical activity levels 3–12 years post-ACLR than uninjured controls [4]. Another study reported that around 86% of individuals 5–8 years after ACLR are classified as physically inactive based on the current physical activity guidelines [41]. While uninjured controls and individuals one-year post-ACLR in the present study were matched based on their mean levels of participation in pivoting sports; the current study did not consider the amount of physical activity, which could be a contributing factor to the increased adiposity. It is plausible that, despite the changes in activity patterns following ACLR, individuals may not be adjusting their energy intake, which could be contributing to increases in global and central adiposity. However, this is speculative as the amount of physical activity was not assessed. Therefore, further research is required to determine whether the amount of physical activity (or other factors) could be contributing to changes in adiposity over time in individuals who have undergone ACLR.

In the present study, while global and central adiposity appear to increase over four years post-ACLR, the opposite was observed for peripheral adiposity. As previously mentioned, increases in global adiposity over 4 years have been associated with greater peripheral adiposity in overweight and obese individuals [39]. Further to this, positive associations between joint-adjacent adjacent adipose tissue thickness at the knee and the severity of joint structural damage over time have been reported [42]. The average subcutaneous adipose thickness was 2.3 mm higher in individuals one-year post-ACLR than uninjured controls, and then decreased by 1.3 mm at five-years post-ACLR compared with one-year post-ACLR. This discrepancy prompts consideration of potential possible explanations for the decrease in average peripheral adiposity despite increases in average global and central adiposity. One such explanation could relate to alterations in muscle recruitment strategies post-ACLR which may contribute to localized changes in adiposity [43]. Additionally, factors such as changes in muscle mass and inflammation levels specific to this patient population could influence these paradoxical changes. However, it is important to note that there is a potential source of error associated with peripheral adiposity measurements, specifically the knee coil used. The dedicated knee coil used may have caused compression of the adipose tissue around the knee where peripheral adiposity was assessed, potentially impacting our results. Thus, the results of the present study need to be confirmed in an adequately powered sample. Further to this, research is needed to determine whether the difference is clinically relevant.

4.3. Adiposity and patient-reported symptoms and physical performance post-ACLR

Increasing global adiposity has been associated with a progressive reduction in physical function in overweight and obese adults [44,45]. Obesity, defined based on BMI, has also been associated with poorer patient-reported function outcomes in individuals six years after ACLR [46]. To our knowledge, this is the first study to investigate the associations of global, peripheral, and central adiposity measures with patient-reported knee symptoms and physical performance in individuals post-ACLR. In general, higher adiposity one-year after ACLR was associated with worse patient-reported knee symptoms and physical performance at one-year post-ACLR and further worsening patient-reported knee symptoms and physical performance from one to five years post-ACLR. Moreover, gains in global, peripheral, and central adiposity from one to five years post-ACLR were associated with declines in patient-reported knee symptoms and physical performance from one to five years post-ACLR. The regression coefficients in general seem to indicate negative correlations, ranging from −0.01 to −2.32, between adiposity and patient-reported knee symptoms and physical performance — indicating association between higher adiposity and worse patient-reported knee symptoms and physical performance. This preliminary information highlights the importance of further investigating adiposity and its impact on symptoms, function, and OA-related outcomes in a larger sample. Interventions aimed at limiting increases in adiposity post-ACLR could potentially limit the decline in patient-reported knee symptoms and physical performance over time [47].

4.4. Clinical and research implications

The preliminary findings from this secondary analysis of an existing cohort indicate greater global and central adiposity may be a feature of young adults following ACLR, with peripheral adiposity warranting further investigation. Whilst not conclusive, the findings also indicate associations between adiposity and patient-reported knee symptoms and physical performance. Higher global and central adiposity have also been associated with an increased risk of knee OA [48]. Therefore, continuous monitoring of adiposity during various stages of recovery following an ACL injury will offer opportunities to intervene early and limit the increase in adiposity. For instance, exercise can have favorable effects on global and central adiposity in overweight and obese individuals [49]. Providing nutritional counseling to adjust energy intake, or emphasizing a low-inflammatory diet, which has been linked to better knee symptoms in patients with knee OA [50], could also help patients manage weight while still meeting the nutritional needs of recovery [51]. Notably, excess adiposity has been associated with a wide range of health outcomes [47, 52,53]. Therefore, achieving and maintaining a healthy weight could carry significant health benefits for individuals post-ACLR. The study sample of this existing cohort was not calculated specifically to evaluate adiposity and its associations with symptoms and function. Furthermore, a significant proportion of participants were not included in the follow-up due to reasons such as time constraints, inability to be reached, and engagement in other research studies. Although we were able to obtain preliminary information on adiposity, adequately powered studies are required to confirm the results. Furthermore, since there are sex-based differences in surrogate measures of adiposity [54] and physical activity levels following ACLR [55], future studies should conduct sex-based analyses in a larger sample [56,57].

4.5. Limitations

There are some limitations that should be acknowledged. First, the measures of global and central adiposity used in the study are surrogate measures and have their limitations. For example, BMI does not differentiate between lean muscle tissue and adipose tissue. Hence, an increase in BMI may indicate an increase in lean muscle tissue rather than adipose tissue. The results may need to be confirmed with more accurate techniques to quantify adiposity such as DEXA scans. Second, the data for central adiposity were not available in uninjured controls. Consequently, we lack direct comparisons between individuals following ACLR and uninjured controls in terms of central adiposity. Additionally, the comparatively smaller sample size of the uninjured control group in contrast to the ACLR group warrants consideration when interpreting the results. Third, we did not evaluate the associations of adiposity with general health outcomes. ACL injuries increase the risk of knee OA and comorbidities beyond the musculoskeletal system such as chronic cardiovascular diseases [58]. Thus, this should be considered in future studies. Fourth, subcutaneous adipose tissue thickness measurements were evaluated at one location due to the constraints of an MRI of the knee. Future studies could also evaluate subcutaneous adipose tissue thickness at multiple anatomical sites, such as thigh and hip, to gain a more comprehensive understanding of peripheral adiposity. Fifth, we evaluated changes in adiposity over time, future studies may consider evaluating trajectories of adiposity change following ACLR and their associations with knee symptoms and functional outcomes. Lastly, although we controlled for the influence of age, sex, and activity level in our analyses, factors, such as occupation, nutrition, the amount of physical activity, ethnicity, and comorbidities, could also impact adiposity.

5. Conclusion

Elevated levels of global and central adiposity are a feature of young adults following ACLR. Greater adiposity appears to be associated with current and future patient-reported knee symptoms and physical performance. Future research is required to elucidate the relationship between adiposity and markers of OA disease, including structural outcomes, in individuals following ACLR.

Author contributions

All authors have made substantial contributions to (1) the conception and design of the study, or acquisition of data, or analysis and interpretation of data, (2) drafting the article or revising it critically for important intellectual content, and (3) final approval of the version to be submitted.

- Conception and design (Culvenor, Hart).
- Analysis and interpretation of the data (Michaud, Koskoletos, Patterson, Crossley, Birmingham, Culvenor, Hart).
- Drafting of the article (Michaud, Koskoletos, Hart).
- Critical revision of the article for important intellectual content (Patterson, Crossley, Birmingham, Culvenor).
- Final approval of the article (Michaud, Koskoletos, Patterson, Crossley, Birmingham, Culvenor, Hart).

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Conflict of interest

None to declare.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocarto.2024.100473.

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