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REVIEW ARTICLE

Alterations of energy expenditure after anterior cruciate ligament tear and reconstruction. A systematic review

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Abstract

Background: The ever-increasing sport level makes every single detail of the athlete's cardiorespiratory profile count, and therefore, it is deemed crucial to clarify how the anterior cruciate ligament (ACL) reconstruction (ACLR) affects the energy economy of an athlete compared to the ACL-deficient and healthy subjects. The purpose of this review was to systematically analyze the studies investigating the correlation between the energy-oxygen cost in patients following ACLR in unreconstructed and intact ACLs.

Methods: We conducted this systematic review according to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines. PubMed, Cochrane, and Google Scholar databases were searched, and eight articles describing miscellaneous methods for the assessment of oxygen consumption in patients with ACL deficiency or ACL reconstructed knees were included.

Results: In total, 285 subjects were recorded with a mean age of 29.61 years. The type of exercise the patients were subjected to varied among the studies, including one-leg cycling, exercise in the closed kinetic chain, walking, jogging, or running at various speeds, and treadmill inclinations. The energy expenditure of an ACL-deficient patient is considerably higher than a healthy subject. Additionally, chronicity of the ACL tear is not correlated with energy expenditure. ACL deficiency leads to higher energy consumption, not only during walking but during jogging as well. ACLR could improve the efficiency of walking by lowering the energy demands. After ACLR, professional soccer players' aerobic capacity (VO_2max) is improved significantly.

Conclusions: ACL insufficiency affects substantially the metabolic energy costs, resulting in increased energy expenditure. According to current literature, ACLR can help to partially reverse this condition, as significant improvements and a more efficient, energy-wise, locomotion are expected. However, further research is necessary to clarify if ACLR can completely normalize energy expenditure again. HIPPOKRATIA 2023, 27 (4):119-125.

Keywords: anterior cruciate ligament reconstruction, anterior cruciate ligament deficiency, oxygen consumption, energy expenditure, energy cost, walking economy, cardioventilatory fitness, aerobic capacity, VO_2max

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Introduction

Sports participation is increasing steadily, subsequently leading to more sports-related injuries[1]. The incidence of anterior cruciate ligament (ACL) injuries exceeds 250,000 cases per year in the United States, while ACL reconstruction (ACLR) surgeries are performed in 125,000-175,000 knees annually[2]. It is the most common ligamentous injury, with football players being the most vulnerable group (53 % of total tears), followed by skiers and gymnasts, who are at high risk too[3]. Females sustain ACL injuries more frequently than males, which could be attributed to the fact that they have larger valgus knee angles and valgus torque, as well as low hamstring-quadriceps muscle activation ratio[4]. The surgical techniques of ACLR have been improved over time, resulting in better surgical outcomes and greater chance for athletes to return to sport (RTS). Some criteria for RTS with low re-injury risk include the time post-ACLR, knee stability, hop tests, isokinetic strength tests, and self-reported questionnaires[5]. However, 20-25 % of professional players are unfit to RTS after ACLR at the same level as before the injury, and young athletes who RTS have a 30 % chance to sustain a secondary injury within two years[6]. After ACLR, patients are required to abstain from physical activities for a specific timeframe, which may worsen the patient's physical status[7]. ACL deficiencies can cause gait pattern alterations, and consequently the energy cost of walking changes as well. This is estimated by measuring the oxygen expenditure (dividing the oxygen consumption/kg for a particular walking time by the speed of walking), which is higher in the injured limb compared to the healthy one[8]. Furthermore, a reconstructed ACL with impaired aerobic fitness is shown to have a greater risk for re-injury, so clinicians have utilized the single-leg cycling model to evaluate the aerobic fitness [maximum oxygen uptake (VO_2max), ventilatory threshold (VT)] of the injured and uninjured limb[4]. VO_2max can be characterized as the highest rate that the human body can use oxygen during intensive exercise, and it is a recommended measure to assess the cardiorespiratory fitness of an athlete[5].

The purpose of this review was to systematically analyze the studies investigating the correlation between the energy-oxygen cost in patients following ACLR in unreconstructed and intact ACLs.

Materials and methods

The systematic review was carried out in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines[9]. The search parameters used for the PICO framework were as follows: population (P) defined as athletes with ACL deficiency or ACL reconstructed knees; intervention (I), defined as miscellaneous methods for assessing energy-oxygen cost; comparison (C), defined as ACL-deficient knees versus ACL reconstructed knees versus intact ACL knees, and outcomes (O) defined as energy-oxygen cost/expenditure.

Inclusion/Exclusion criteria

The systematic review contains studies describing miscellaneous methods for assessing oxygen consumption in patients with ACL deficiency or ACL reconstructed knees. We considered eligible and included in the review i) case series, prospective comparative or non-comparative studies, retrospective comparative or non-comparative studies, and randomized-controlled trials (RCTs), ii) written in the English language, regarding iii) adult patients, iv) active in sports with ACL deficiency or ACLR assessed with means on the consumption of oxygen. We excluded from the review i) case reports, editorials, letters to the editor, reviews, experimental trials, and animal studies, ii) articles written in languages other than English, ii) without full-text availability, iii) regarding pediatric patients (<18 years of age).

Search strategies and data source

On October 24, 2022, two authors (A.K and KG.M) conducted a comprehensive systematic literature search, encompassing articles from three databases: PubMed, Cochrane, and Google Scholar. We investigated only the first 200 articles from the Google Scholar search. We employed the following search strategy to identify relevant articles: (ACL reconstruction OR ACL deficiency) AND (oxygen consumption OR energy expenditure OR energy cost OR walking economy OR VO2max). A third author (A.V) addressed any disagreement among the authors regarding selecting retrieved studies.

Outcomes of interest

Three authors (A.K, KG.M, and E.I), working independently, reviewed the included articles and gathered demographic information, along with data related to injuries and surgeries: year of article publication, study design, patients' number, age, gender, body weight, height, body mass index (BMI), time of injury, type of sport involvement, type of exercise during measurements, type of ACL graft, and respiratory outcome measurements. Specifically, peak power output (W_{peak}) (W), first ventilatory threshold (VT_1), second ventilator threshold (VT_2), VO_2max (ml/min/kg), peak minute ventilation (VE_{peak}) (L/min), peak heart rate (HR_{peak}) (beats/min).

Methodological quality assessment

Two authors (A.K and KG.M), working independently, conducted the quality assessment, and a third author (E.I) resolved any discrepancies between them. The level of evidence for the included studies was determined using the criteria established by Wright et al[10]. The non-comparative and comparative studies were evaluated using the 12-point methodological index for non-randomized studies (MINORS) criteria[11]. Cochrane Collaboration's risk of bias tool was used for the appraisal of the risk of biases in the RCTs[12].

Results

Study selection

The process of selecting and excluding studies was carried out independently by two authors (A.K and KG.M). The comprehensive flow diagram is demonstrated in Figure 1 - the preliminary search generated 253 results. Mendeley reference manager was utilized to perform duplicate removal. Thus, 203 remained for further screening. Subsequently, the titles and abstracts of the articles were screened, leading to the exclusion of 192 articles. Consequently, there were 11 full-text articles remaining for eligibility assessment, and three of them were excluded for specified reasons. Finally, our systematic review comprised eight articles (Figure 1).

Methodological quality assessment

According to the level of evidence assessment tool by Wright et al[10], this systematic review incorporated two level I[7,13], and six-level II studies[4,5,8,14-16].

In accordance with the MINORS checklist[11], comparative studies demonstrated a mean score of 20.4 (ranging from 19 to 22) out of 24 points, while non-comparative studies achieved a mean score of 12 out of 16 points. The assessment of two RCTs followed our Cochrane Collaboration's risk of bias tool[12] that evaluated seven parameters, including random sequence generation, allocation concealment, blinding of participants and personnel, analysis intention (blinding of outcome assessment), incomplete outcome data, selective reporting (selection of the reported results), and other types of bias not considered previously (e.g., contamination bias, design bias) (Table 1).

Study characteristics and outcomes

Out of the eight studies included in this systematic re-

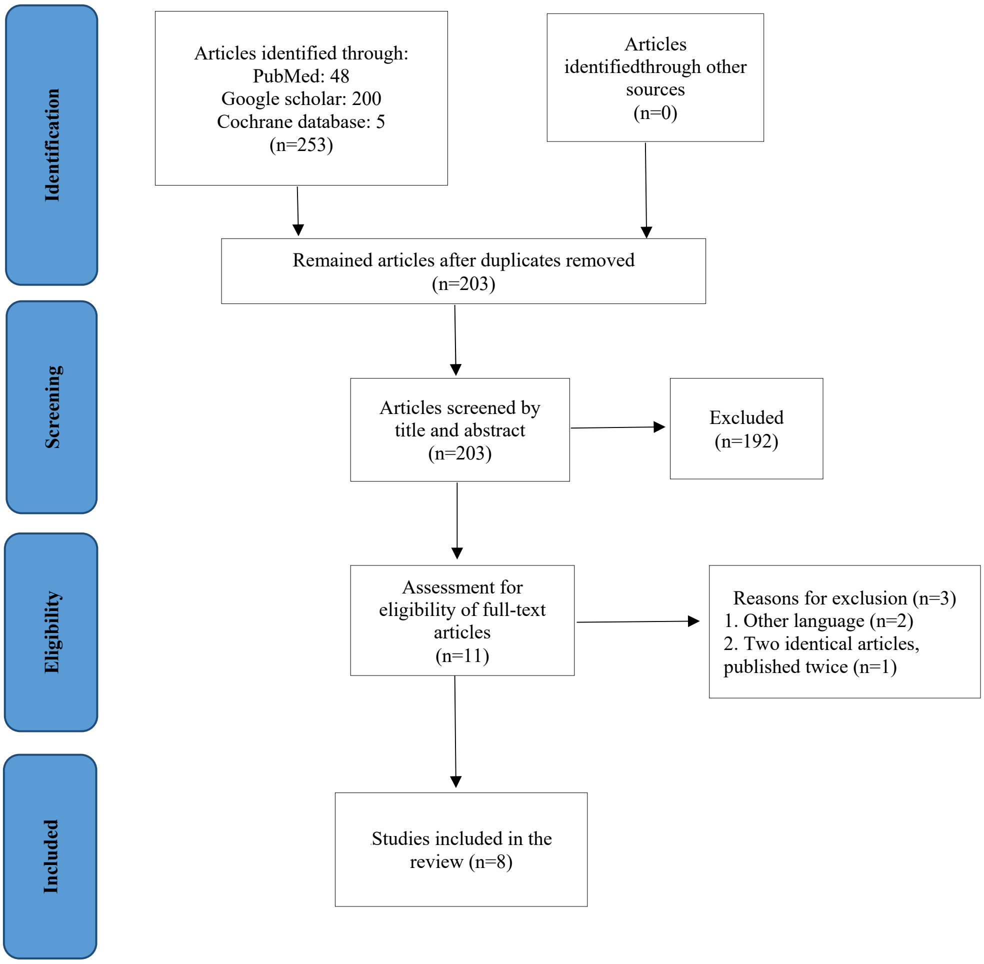

Figure 1: Flow chart demonstrating the process of the systematic literature search that included eight studies after initially identification of 253 studies, duplicate removal, and excluding following screening, and assessment for eligibility of 11 full-text studies.

Table 1: Risk of bias summary based on the review author's judgments about each risk of bias item for the included randomized controlled trials.

	Random sequence generation	Allocation concealment	Blinding of participants and personnel	Blinding of outcome assessment	Incomplete outcome data	Selective reporting	Other bias
Iliopoulos 2017[13]	+	+	+	+	+	+	?
Olivier 2010[7]	+	-	-	-	+	+	?

view, two were RCTs[7,13]; five were prospective comparative studies[4,5,14–16], and one prospective cohort study[8]. In total, 285 subjects active in sports participated, 235 males and 50 females, with a mean age of 29.61, mean height of 1.76 m, mean body mass of 75.62 kg, and mean BMI of 24.8 kg/m^2. The mean time of injury since the ACLR was 5.33 months. The type of exercise the patients were subjected to varied among the studies, including one-leg cycling, exercise in the closed kinetic chain, walking, jogging, or running at various speeds, and treadmill inclinations. The graft type in the group of ACLR was bone patellar tendon bone (BPTB) autograft in 53 patients, hamstrings tendons in 43, and cadaveric allograft in one. Details about the characteristics of each study are presented in Table 2 and Table 3.

The energy expenditure of an ACL-deficient patient is considerably higher than a healthy subject. Additionally, chronicity of the ACL tear is not correlated with energy expenditure. ACL deficiency leads to higher energy consumption, not only during walking but during jogging as well. ACLR could improve the efficiency of walking by lowering the energy demands. After ACLR, professional soccer players' aerobic capacity (VO$_2$max) is improved significantly. However, further research is necessary to clarify if ACLR can completely normalize energy expenditure again.

Discussion

The premise of this systematic review is that the metabolic cost and the energy consumption in various

Table 2: Characteristics of studies and patient demographics for the eight eligible studies included in the systematic review.

	STUDY TYPE	LEVEL OF EVIDENCE	GROUPS	NUMBER	GENDER	AGE (Y) (mean ± sd)	HEIGHT (m) (mean ± sd)	BODY WEIGHT (kg) (mean ± sd)	BMI (kg/m2) (mean ± sd)	TIME OF INJURY (m) (mean ± sd)	TYPE OF EXERCISE	SPORT LEVEL	GRAFT TYPE
Olivier 2010 [7]	Randomized clinical trial	I	G1: RH without aerobic training G2: RH with aerobic training	G1: 12 G2: 12	24 M	G1: 23.31 ± 3.12 G2: 25.11 ± 3.41	G1: 1.81 ± 0.09 G2: 1.79 ± 0.08	G1: 78.12 ± 10.21 G2: 76.31 ± 8.21	N/A	2 ± 0.2	one-leg cycling with the untreated knee (OLC) A1: before RH program A2: after RH program	regional-level soccer players (4.7 ± 0.3 h/w)	21 BPTB 3 HT
Almeida 2018 [5]	Prospective comparative study	II	G1: before ACLR G2: 6 months after ACLR G3: control healthy group	G1,G2: 20 G3: 20	G1,G2: 20 M G3: 20 M	G1,G2: 21 (18-28) (median, range) G3: 20.5 (18-34)	G1,G2: 1.82 ± 0.08 G3: 1.79 ± 0.07	G1: 79.2 ± 10.1 G2: 79.3 ± 8.9 G3: 74.8 ± 6.2	G1: 23.7 ± 2.0 G2: 24.0 ± 2.0 G3: 23.4 ± 1.8	3 (1-12) (mean, range)	running to a treadmill	professional soccer player	20 HT
Andrade 2014 [14]	Prospective comparative study	II	G1: involved knee G2: uninvolved knee	18	18 M	33 ± 12	1.77 ± 0.05	79 ± 9	N/A	N/A	exercise in closed kinetic chain A1: moderate exercise A2: anaerobic threshhold A3: peak effort	physically active athletes (2.7 ± 0.7 h/w)	18 BPTB
Bagley 2020 [4]	Prospective comparative study	II	G1: leg with ACLR G2: the healthy leg of same subject	8	5 M 3 F	23 ± 3.5	1.697 ± 0.094	72.3 ± 17.3	N/A	N/A	single-leg cycling on both legs	6/8 competitive athletes	4 BPTB 2 HT 1 allograft
Colak 2011 [8]	Prospective cohort study	II	ACLR patients	8	8 M	31 (20-44) (mean, range)	1.73 (1.70-1.77) (mean, range)	76 (67-93) (mean, range)	25 (22-31) (mean, range)	27 (5-22) (mean, range)	G1: walking 50 m/min G2: walking 70 m/min G3: walking 90 m/min	N/A	8 HT
McHugh 1994 [16]	Prospective comparative study	II	G1: ACL deficiency G2: healthy control	G1: 30 G2: 98	G1: 21M, 9F G2: 60M, 38F	G1: 30.1 ± 1.1 G2: 33 ± 9.7	G2: 1.718 ± 0.012 G2: 1.719 ± 0.093	G1: 74.8 ± 1.8 G2: 69.6 ± 12.4	N/A	N/A	Walking and jogging A1: 53.6 m/min A2: 80.5 m/min A3: 107.2 m/min A4: 134.1 m/min A5: 160.9 m/min	N/A	-
Iliopoulos 2017 [15]	Prospective comparative study	II	G1: ACL rupture without ACLR G1a: copers G1b: non-copers G2: control group	G1: 19 G1a:10 G1b:9 G2: 10	G1: 19 M G2: 10 M	G1: 25.0 ± 5.6 G1a: 24.8 ± 6.1 G1b: 25.2 ± 5.3 G2: 25.6 ± 6.4	G1: 1.788 ± 0.077 G1a: 1.791 ± 0.0103 G1b: 1.785 ± 0.038 G2: 1.812 ± 0.0102	G1: 82.4 ± 19.6 G1a: 79.5 ± 21.0 G1b: 85.6 ± 18.6 G2: 89.7 ± 9.8	G1: 25.5 ± 4.7 G1a: 24.4 ± 3.9 G1b: 26.8 ± 5.4 G2: 25.3 ± 1.9	N/A	A1: flat treadmill A2: uphill treadmill A3: downhill treadmill	sport activities (3-6 t/w)	-
Iliopoulos 2017 [13]	Randomized clinical trial	I	G1: ACLR with BPTB G2: ACTR with HT G3: control group	G1: 10 G2: 10 G3: 10	G1: 10 M G2: 10 M G3: 10 M	G1: 24.8 ± 5.0 G2: 26.7 ± 7.2 G3: 26.5 ± 4.6	G1: 1.816 ± 0.038 G2: 1.752 ± 0.056 G3: 1.794 ± 0.083	G1: 88.7 ± 19.2 G2: 77.7 ± 19.0 G3: 81.9 ± 13.7	G1: 26.7 ± 5.6 G2: 24.6 ± 4.3 G3: 26.1 ± 2.2	N/A	A1: flat treadmill A2: uphill treadmill A3: downhill treadmill	sport activities (3-6 t/w)	10 HT 10BPTB

RH: rehabilitation, ACLR: anterior cruciate ligament reconstruction, ACL: anterior cruciate ligament, BPTB: bone patellar tendon bone, HT: hamstring tendons, M: males, F: females, N/A: not applicable, h/w: hours/ week, t/w: times/ week.

sports activities are higher in subjects with ACL deficiency[15], but is this also observed in athletes after ACLR? Undoubtedly, a native ACL constitutes a valuable knee stabilizer and energy sparer. As a result, the current point of interest is focused on the energy consumption of an athlete with ACL deficiency or after ACLR. The ever-increasing sport level, especially in sports requiring frequent cutting maneuvers like football, makes every single detail of the athlete's cardiorespiratory profile count. Therefore, it's deemed crucial to clarify how the ACLR affects the energy economy of an athlete compared to the ACL-deficient and healthy subjects.

According to the existing literature listed below, the energy expenditure of an ACL-deficient patient is considerably higher than a healthy subject. The first study comparing the latter was conducted by McHugh et al[16] in 1994, including 30 ACL-deficient patients and 98 healthy controls. The steady-state oxygen consumption during jogging on a level treadmill at a speed of 160.9 m/min was found to be significantly higher in the ACL-deficient group ($p < 0.05$). Additionally, it was proved that chronicity of the ACL tear was not correlated with energy expenditure. Similar results highlighting the superiority of energy sparing of the control group were deduced by Iliopoulos et al[13]. They found that steady-state oxygen consumption, HR_{peak}, and VE_{peak} during walking at 0, +10, and -10 % gradients were significantly increased in 20 patients with ACL rupture compared to ten control subjects. In a different study by the same author's team[15] and the same protocol, 19 patients with ACL tears were divided into two groups, "non-copers" and "copers", according to their ability to return to their pre-injury activities with or without ACLR, respectively. It was found that although the clinical and functional scores of the "copers" were better, the walking economy at flat, downhill, and uphill walking was similar, but when compared with healthy individuals, it was impaired. Finally, Almeida et al[5] conducted the first study regarding the metabolic cost of male professional football players. Twenty of them with ACL deficiency were metabolically measured and examined pre- and post-operatively and compared to 20 healthy ones. The VO_2max of the injured athletes before surgery was 45.2 ± 4.3 ml/kg/min, remarkably decreased compared to the healthy group of 56.9 ± 4.2 ml/kg/min. VO_2max accounts for the highest rate at which oxygen can be utilized during demanding exercise. Moreover, the first and the second ventilatory thresholds were significantly lower pre-operatively compared to the healthy group. In conclusion, they highlighted that the cardiorespiratory fitness of the ACL-deficient group was noticeably lower compared to healthy professional football players.

After high-energy knee trauma including ACL rupture, the recovery and rehabilitation timeline may alter the cardiorespiratory status of a patient with ACL deficiency. A well-documented rehabilitation program, including aerobic exercise, is deemed crucial for avoiding physical deconditioning. Based on this fact, Olivier et al[7] conducted an RCT with 24 conservatively treated "copers". Twelve of them were managed during their rehabilitation program, including aerobic training, while the other 12 did not. According to their results, one leg cycling of the uninjured knee in the group of aerobic exercise led to an increase of VO_2max, W_{peak}, and VE_{peak} when compared to both the pre-rehabilitation status of the same group and the post-rehabilitation status of the other group without aerobic exercise.

Prompted by these initial reports, it was suspected that ACL deficiency leads to higher energy consumption, not only during walking but during jogging as well[5,13,15,16]. This finding can be attributed to altered gait kinematics usually developed in ACL-deficient patients, primarily to "quadriceps avoidance" pattern, meaning a sustained knee flexor moment during mid-stance[17]. More importantly, further research showed that gait patterns tend to return to normal after ACLR[18,19], raising a valid question: Can the normalization of gait biomechanics post-ACLR also be translated into a normal energy expenditure?

Table 3: Measurements about cardioventilatory profile as presented in the eight eligible studies included in the systematic review.

	GROUPS	TYPE OF EXERCISE	Wpeak (W) (mean ± sd)	VO₂peak (mL/min/kg) (mean ± sd)	VEpeak (L/min) (mean ± sd)	HRpeak (Beats/min) (mean ± sd)	VT1 (mean ± sd)	VT2 (mean ± sd)
Olivier 2010 [7]	G1: RH without aerobic training G2: RH with aerobic training	one-leg cycling with the untreated knee (OLC) A1: before RH program A2: after RH program	G1A1: 133 ± 11 G2A1: 132 ± 9 G1A2:120 ± 10 G2A2:152 ± 9	G1A1: 29 ± 4 G2A1: 28 ± 4 G1A2: 26 ± 4 G2A2: 30 ± 5	G1A1: 86 ± 21 G2A1: 83 ± 17 G1A2: 76 ± 16 G2A2: 92 ± 20	G1A1: 184 ± 7 G2A1: 188 ± 9 G1A2: 185 ± 5 G2A2: 191 ± 8	G1A1: 69 ± 5 (W) G2A1: 63 ± 7 G1A2: 71 ± 5 G2A2: 73 ± 8	(W) G2A1: 86 ± 9 G1A2: 80 ± 8 G2A2: 97 ± 8
Almeida 2018 [5]	G1: before ACLR G2: 6 months after ACLR G3: control healthy group	running to a treadmill	N/A	G1: 45.2 ± 4.3 G2: 48.9 ± 3.8 G3: 56.9 ± 4.2	N/A	N/A	G1: 30.3 ± 5.1 (ml/kg/min) G2: 34.3 ± 3.5 G3: 37.2 ± 3.7	G1: 38.3 ± 4.1 (ml/kg/min) G2: 41.4 ± 4.5 G3: 49.1 ± 3.6
Andrade 2014 [14]	G1: involved knee G2: uninvolved knee	exercise in closed kinetic chain A1: moderate exercise A2: anaerobic threshhold A3: peak effort	N/A	(L/min) G1A2:0.96 ± 0.22 G1A3: 1.81 ± 0.47 G2A1: 0.58 ± 0.25 G2A2: 0.98 ± 0.34 G2A3: 1.75 ± 0.45	G1A1: 18.4 ± 5.1 G1A2: 25.6 ± 5.1 G1A3: 62.1 ± 17.9 G2A1: 18.9 ± 5.4 G2A2: 26.4 ± 5.5 G2A3: 63.6 ± 19.6	G1A1: 88 ± 12 G1A2: 104 ± 14 G1A3: 137 ± 21 G2A1: 90 ± 14 G2A2: 105 ± 16 G2A3: 141 ± 21	N/A	N/A
Bagley 2020 [4]	G1: leg with ACLR G2: the healthy leg of same subject	single-leg cycling on both legs	G1: 127 ± 29 G2: 127 ± 29	G1: 30.55 ± 8.55 G2: 31.22 ± 7.24	N/A	G1: 169 ± 27 G2: 169 ± 12	G1: 21.09 ± 7.97 (ml/kg/m) G2: 20.65 ± 3.04	N/A
Colak 2011 [8]	ACLR patients	G1: walking 50 m/min G2: walking 70 m/min G3: walking 90 m/min	N/A	N/A	N/A	N/A	N/A	N/A
McHugh 1994 [16]	G1: ACL deficiency G2: healthy control	Walking and jogging A1: 53.6 m/min A2: 80.5 m/min A3: 107.2 m/min A4: 134.1 m/min A5: 160.9 m/min	N/A	(Steady state VO2 consumption) G1A1: 9.9 ± 0.2 G1A2: 12.8 ± 0.2 G1A3: 18.5 ±0.3 G1A4: 29.9 ± 0.4 G1A5: 36.5 ± 0.6 G2A1: 10.4 ± 0.2 G2A2: 12.6 ± 0.2 G2A3: 18 ± 0.3 G2A4: 28.6 ± 0.3 G2A5: 33.7 ± 0.3	N/A	N/A	N/A	N/A
Iliopoulos 2017 [15]	G1: ACL rupture without ACLR G1a: copers G1b: non-copers G2: control group	A1: flat treadmill A2: uphill treadmill A3: downhill treadmill	N/A	(Steady state VO2 consumption) G1A1: 16.6 ± 2.0 G1aA1: 16.8 ± 2.2 G1bA1: 16.4 ± 1.8 G2A1: 13.9 ± 1.8 G1A2: 20.2 ± 3.7 G1aA2: 20.3 ± 2.3 G1bA2: 20.0 ± 5.0 G2A2: 16.2 ± 1.2 G1A3: 14.2 ± 2.1 G1aA3: 14.3 ± 1.8 G1bA3: 13.9 ± 2.5 G2A3: 11.4 ± 1.5	(Steady state VE) G1A1: 30.4 ± 4.9 G1aA1: 29.7 ± 4.3 G1bA1: 31.2 ± 4.8 G2A1: 28.6 ± 3.7 G1A2: 36.4 ± 7.7 G1aA2: 35.1 ± 5.2 G1bA2: 37.8 ± 10.0 G2A2: 33.0 ± 5.0 G1A3: 26.1 ± 4.5 G1aA3: 26.3 ± 4.2 G1bA3: 25.8 ± 5.0 G2A3: 23.8 ± 2.3	(Steady state HR) G1A1: 120.8 ± 14.8 G1aA1: N/A G1bA1: N/A G2A1: 103.0 ± 8.5 G1A2: 131.2 ± 17.1 G1aA2: N/A G1bA2: N/A G2A2: 105.4 ± 8.6 G1A3: 114.6 ± 12.1 G1aA3: N/A G1bA3: N/A G2A3: 99.3 ± 9.0	N/A	N/A
Iliopoulos 2017 [13]	G1: ACLR with BPTB G2: ACTR with HT G3: control group	A1: flat treadmill A2: uphill treadmill A3: downhill treadmill	N/A	(Steady state VO2 consumption) preG1A1: 16.5 ± 2.3 preG2A1: 16.6 ± 2.6 preG3A1: 13.9 ± 1.9 preG1A2: 20.3 ± 3.9 preG2A2: 21.3 ± 2.7 preG3A2: 16.7 ± 1.3 preG1A3: 13.7 ± 2.3 preG2A3: 14.7 ± 2.2 preG3A3: 11.5 ± 1.5 postG1A1: 14.9 ± 2.3 postG2A1: 15.1 ± 2.1 postG3A1: 14.2 ± 1.8 postG1A2: 18.0 ± 3.0 postG2A2: 18.7 ± 2.1 postG3A2: 16.3 ± 1.1 postG1A3: 12.7 ± 1.8 postG2A3: 12.9 ± 1.6 postG3A3: 11.7 ± 1.5	(Steady state VE) preG1A1: 30.6 ± 2.3 preG2A1: 30.1 ± 4.6 preG3A1: 27.4 ± 2.9 preG1A2: 37.7 ± 4.2 preG2A2: 37.0 ± 7.2 preG3A2: 33.6 ± 4.7 preG1A3: 26.0 ± 1.4 preG2A3: 25.9 ± 4.9 preG3A3: 23.5 ± 2.1 postG1A1: 28.2 ± 1.8 postG2A1: 26.4 ± 3.9 postG3A1: 27.6 ± 2.8 postG1A2: 35.0 ± 2.3 postG2A2: 31.8 ± 5.3 postG3A2: 33.7 ± 4.6 postG1A3: 24.1 ± 2.3 postG2A3: 22.0 ± 3.8 postG3A3: 23.7 ± 2.0	(Steady state HR) preG1A1: 121.1 ± 9.3 preG2A1: 119.3 ± 12.1 preG3A1: 105.4 ± 8.4 preG1A2: 135.6 ± 14.9 preG2A2: 129.7 ± 15.0 preG3A2: 116.1 ± 11.5 preG1A3: 112.3 ± 8.8 preG2A3: 110.9 ± 8.8 preG3A3: 98.7 ± 10.1 postG1A1: 108.1 ± 9.2 postG2A1: 107.1 ± 9.4 postG3A1: 103.8 ± 7.6 postG1A2: 117.0 ± 10.9 postG2A2: 117.2 ± 10.9 postG3A2: 113.8 ± 11.2 postG1A3: 98.7 ± 5.6 postG2A3: 101.3 ± 6.9 postG3A3: 98.1 ± 7.2	N/A	N/A

RH: rehabilitation, ACLR: anterior cruciate ligament reconstruction, ACL: anterior cruciate ligament, BPTB: bone patellar tendon bone, HT: hamstring tendons, W: power output, N/A: not applicable, VO_2: O_2 uptake, VE: minute ventilation, HR: heart rate, VT_1; first ventilatory threshold, VT_2: second ventilatory threshold.

Three studies attempted to evaluate the changes in metabolic energy cost after ACLR. First, Colak et al[8] conducted a study on eight patients with chronic ACL deficiency who were subjected to ACLR. All participants walked on a treadmill at three different ordinary speeds, both pre- and post-operatively, and net oxygen cost was measured and compared. Net oxygen cost, which refers to the additional oxygen consumed while practicing, was found to be significantly reduced post-operatively. As a result, the authors concluded that ACLR could improve the efficiency of walking by lowering the demands for energy[8]. In concordance with those suggestions were also the results from a following study[13], where all energy cost parameters (VO_2max , heart rate, and ventilation) were statistically improved in 20 patients, nine months after having undergone ACLR, while walking on a treadmill in three different gradients; Therefore, ACLR led once more to less costly locomotion in terms of energy. Lastly, Almeida et al[5] attempted to evaluate the cardiorespiratory fitness of 20 professional football players six months after ACLR by measuring VO_2max. A VO_2max threshold of 60 ml/kg/min has been proposed as the minimum level of physical fitness for an elite football player[20]. This prospective study[5] showed that after ACLR, the aerobic capacity (VO_2max) of professional soccer players improved significantly, from 45 ±4.3 ml/kg/min to 48.9 ± 3.8 ml/kg/min.

The potential of ACLR to decrease metabolic costs during practice and enhance the cardiorespiratory fitness of individuals, especially athletes, could serve as an additional benefit to improved functional outcomes. Therefore, knowing how these results could be compared to those of the healthy population to determine the extent to which improvements are attainable is also equally important. However, the literature on this topic is scarce, and the outcomes are controversial. Two studies, previously mentioned, compared further the energy expenditure of ACL-reconstructed patients to that of controls (healthy individuals)[5,13]. Iliopoulos et al[13] found that even though the walking economy had improved by 9-12 % post-operatively, it was still worse when compared to controls, reaching nonetheless 90-95 % of normal values[13]. Moreover, despite significant improvements regarding cardiorespiratory fitness after ACLR in professional football players, VO_2max remained 20 % lower than the average values of controls (healthy professionals competing at the same level), as shown by Almeida et al[5]. On the other hand, no significant differences were observed regarding the cardiopulmonary response when ACL- reconstructed limbs of 18 active male patients were compared to the uninvolved limbs[14]. It is also worth mentioning that the cardiorespiratory performance was similar four months after ACLR, despite significantly reduced muscle strength of the operated limb[14]. The same results were yielded from another study, where the aerobic capacity of eight post-ACLR limbs was comparable to that of the uninvolved ones during single-leg cycling. However, in this study, the strength of both limbs was proven to be similar six months after ACLR[4]. Nevertheless, as long as the literature remains limited and controversial, it is hard to extract any safe conclusion. Therefore, further research is necessary in order to clarify if ACLR can completely normalize energy expenditure again.

Moreover, the type of ACL graft and its role on metabolic energy cost, is yet another field, where more research is required. To date, there is only one study, where 20 patients were randomly assigned to receive either a hamstring or a BPTB graft. In the end, both graft types were proven equal, without significant differences in respect of walking economy[13].

It is important to acknowledge the limitations and shortcomings in this systematic review. First of all, the heterogeneity among the studies is remarkable. The exercise type that the patients were subjected to varied, including one-leg cycling, exercise in the closed kinetic chain, and walking, jogging, or running in various tempos and treadmill inclinations. Thus, it was infeasible to summarize and calculate the mean values of the cardiorespiratory measurements, and as a result, a meta-analysis could not be held. Moreover, there was only one study in the literature with professional football players, while the others included amateur athletes. This fact may alter the rehabilitation results, as professional players due to financial motivation follow the program with increased dedication and compliance.

Conclusion

ACL insufficiency significantly impacts metabolic energy costs, resulting in increased energy expenditure during walking and exercise, but could also lead to poor cardiorespiratory fitness. According to current literature, ACLR can help reverse this condition, as significant improvements and a more efficient, energy-wise, locomotion are expected. This is definitely an additional benefit to improved functional outcomes after ACLR and should, therefore, be considered and brought up during consultation with patients who sustained an ACL tear. However, further high-quality research is warranted to delineate if ACLR can bring metabolic energy costs back to normal and if graft types could have any impact on the outcome.

Conflicts of interest

The authors declare no conflict of interest. This research received no external funding.

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