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# Anterior cruciate ligament deficiency reduces walking economy in "copers" and "non-copers"

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**Abstract**

*Purpose* Patients with ACL injury requiring surgical treatment (non-copers) demonstrate altered neuromuscular control and gait pattern compared with those returning to their pre-injury activities without surgery (copers). Pathological gait pattern may increase the energy cost of walking. We compared the energy cost of flat, uphill, and downhill walking between ACL-deficient and healthy individuals and between "copers" and "non-copers".

*Methods* Nineteen young males with unilateral ACL injury were allocated into "copers" and "non-copers" according to their ability to return to pre-injury activity without ACL reconstruction. Lysholm and IKDC scales were recorded, and a control group ($n = 10$) matched for physical characteristics and activity levels was included. All participants performed 8-min walking tasks at 0, +10, and −10 % gradients. Energy cost was assessed by measurement of oxygen consumption ($VO_2$). HR and ventilation (VE), respiratory exchange ratio (RER), and $VE/VO_2$ were also measured.

*Results* $VO_2$ and HR were higher in ACL-deficient patients than in controls during walking at 0, +10, and −10 % gradients ($p < 0.01$–$0.05$). There were no differences between "copers" and "non-copers" in $VO_2$ and HR for any gradient. No differences were observed in VE, RER, and $VE/VO_2$ among the three groups.

*Conclusions* The walking economy of level, uphill, and downhill walking is reduced in ACL-deficient patients. Despite the improved functional and clinical outcome of "copers", their walking economy appears similar to that of "non-copers" but impaired compared with healthy individuals. The higher energy demand and effort during locomotion in "copers" and "non-copers" has clinical implications for designing safer rehabilitation programmes. The increased energy cost in "copers" may be another parameter to consider when deciding on the most appropriate therapeutic intervention (operative and non-operative), particularly for athletes.

*Level of evidence* II.

**Keywords** Energy cost · Energy expenditure · Oxygen consumption · ACL reconstruction · ACL · ACL-deficient

## Introduction

Anterior cruciate ligament (ACL) rupture is a very common injury, especially during sporting activity. Over 120,000 ACL reconstructions are performed in the USA each year, with an increasing tendency, as more people are engaging in exercise and sports [28]. Currently, two treatment options are available for patients with ACL deficiency. The one is a non-operative treatment, where the

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patient follows a specific physiotherapy protocol. The other option includes a surgical procedure directed towards the reconstruction of the ACL. Those individuals who manage to return to their pre-injury activities without ACL reconstruction following a non-operative treatment are defined as "copers," whereas those who are not able to resume their pre-injury activities and require surgical intervention are defined as "non-copers" [13, 22, 27].

ACL deficiency is linked to altered gait pattern [5, 14, 46]. Kinetic and kinematic studies have demonstrated differences in neuromuscular control and quadriceps morphology between "copers" and "non-copers" [32]. In fact, these two groups of patients adopt different gait patterns leading to altered loading on the knee joint [2]. Previous findings in patients with lower-limb musculoskeletal abnormalities, such as degenerative osteoarthritis of the knee, ACL deficiency, and reduced range of motion of the knee and knee flexion contraction over 20°, have shown that a pathological gait pattern may increase the energy cost of walking (i.e. reduce exercise economy) [8, 22, 34, 37]. Thus, based on the kinetic and kinematic differences between "copers" and "non-copers" during walking, it is conceivable that the energy cost of ambulatory activities may differ between these groups. To the best of our knowledge, the metabolic cost of walking between "copers" and "non-copers" is yet to be examined; this is despite the high incidence of ACL injury and the different treatment options used.

Taking into account that pathological gait patterns may increase energy cost, patients who have an ACL injury should have decreased gait economy [45]. Surprisingly, only one study has investigated the metabolic cost of locomotion in ACL-deficient patients. The study reported an increased energy cost in ACL-deficient patients compared with healthy controls only during jogging and not during walking [35]. McHugh et al., however, implemented the walking condition only at a 0 % gradient. It is not known whether more demanding walking tasks for the quadriceps muscle and the knee joint stability, such as uphill or downhill walking, may further affect the energy cost of walking in ACL-deficient individuals.

The increased energy cost during activity may reduce the tolerance to daily tasks and to exercise and impair quality of life. In particular, higher energy demands during locomotion reduce the physiological reserves of the body, increasing physical effort and fatigue when performing activities of daily living. Thus, the knowledge about differences in the energy cost of locomotion between "copers" and "non-copers" or between ACL-deficient patients and healthy controls during uphill and downhill walking may assist in designing more suitable and safer rehabilitation programs for these individuals, that is, avoiding the undesirable conditions associated with exaggerated physiological effort and fatigue. Also, understanding the changes in energy cost of locomotion in "copers" and in "non-copers", while considering the energy needs of the patient, may aid the practitioner in deciding for the type of treatment (operative and non-operative treatment). With these in mind, the aims of this study were to compare the energy cost of walking at various surface gradients (flat, uphill, and downhill) between "copers" and "non-copers" and between ACL-deficient patients and healthy controls.

## Materials and methods

Nineteen male patients diagnosed with isolated unilateral ACL injury were included in the study. Table 1 summarizes the physical characteristics and the number of "copers", "non-copers", and controls relative to their sporting activity. There were no significant differences in age, height, weight, and BMI between the ACL-deficient (copers and non-copers) and control groups; the groups were also matched for the physical activity pattern at the initiation of the study. The participants with ACL injury were recruited from the sports injury outpatient clinic of our hospital. Patients with

**Table 1** Physical characteristics (means ± SD) and the *number* of participants relative to their physical activity pattern for copers, non-copers, and controls

| Variable | ACL-deficient ($n = 19$) | Non-copers ($n = 9$) | Copers ($n = 10$) | Controls ($n = 10$) |
|---|---|---|---|---|
| Age (years) | 25.0 ± 5.6 | 25.2 ± 5.3 | 24.8 ± 6.1 | 25.6 ± 6.4 |
| Height (cm) | 178.8 ± 7.7 | 178.5 ± 3.8 | 179.1 ± 10.3 | 181.2 ± 10.2 |
| Weight (kg) | 82.4 ± 19.6 | 85.6 ± 18.6 | 79.5 ± 21.0 | 89.7 ± 9.8 |
| BMI (kg/m$^2$) | 25.5 ± 4.7 | 26.8 ± 5.4 | 24.4 ± 3.9 | 25.3 ± 1.9 |
| Soccer | 12 | 6 | 6 | 6 |
| Basketball | 2 | 1 | 1 | 1 |
| Martial arts | 2 | 1 | 1 | 1 |
| Gymnastics | 2 | 1 | 1 | 1 |
| Downhill skiing | 1 | 0 | 1 | 1 |

more complex knee joint injuries, such as meniscus tears, medial and lateral ligament tears, and posterior cruciate ligament rupture, were excluded from the study. Patients with cardiovascular, pulmonary, and other orthopaedic, systemic, and metabolic diseases were also excluded from the study. All patients were regularly taking part in sporting activities (from three to six times per week) before the injury, and their injury was sports related. All the patients attended a rehabilitation programme three times a week for 8 weeks. The programme consisted of physiotherapy sessions, muscle strengthening exercises of the lower limb, cardiovascular training, and sport-specific agility drills. At the end of this programme, the patients were allocated into two groups: "copers" ($n = 10$) and "non-copers" ($n = 9$). The participants were placed into "copers" group if they had returned to all of their pre-injury activity and had no episodes of their knee giving-way during jumping, cutting, and lateral movements. Those who did not pass these criteria after the rehabilitation programme were classified as "non-copers" [16, 17, 22]. A control group ($n = 10$) matched for gender, age, physical characteristics, and physical activity pattern was included in the study (Table 1). All participants performed, in a crossover balanced randomized order, generated by a computer-based program, flat (0 % gradient), uphill (+10 % gradient), and downhill (−10 % gradient) walking on a treadmill for 8 min. All tests were performed in a quiet room, at the same time of the day (±1 h), and in similar atmospheric conditions (temperature, 22–23 °C; relative humidity, 40–50 %). The energy cost was assessed continuously with direct measurement of oxygen consumption throughout the tasks. The participants were instructed to abstain from caffeinated drinks and tobacco products 12 h prior to testing, from alcohol consumption for at least 24 h before testing, and from any exercise activity for 48 h prior to testing.

## Patients' evaluation

The inclusion of the participants in the study was performed following their clinical and radiological evaluation. More specifically, the outcomes of the Lachman's test, the lateral pivot shift test, and anterior drawer test were recorded. Clinical tests were performed by an experienced blinded examiner. The Lysholm Knee Scoring Scale [42] and the International Knee Documentation Committee (IKDC) subjective knee evaluation form [21] were used to obtain the integrated clinical rating of the cohort. Table 2 presents the clinical evaluation of the ACL-deficient patients and the outcomes for the Lysholm and the IKDC scales. An MRI of the injured knee was performed on all patients to confirm the ACL tear and exclude other orthopaedic injuries.

**Table 2** Clinical evaluation of the ACL-deficient patients and the scores for the Lysholm and the IKDC scales

| Variable | 1+ | 2+ | 3+ |
|---|---|---|---|
| Lachman's test (no. of patients) | 6 | 10 | 3 |
| Anterior Drawer test (no. of patients) | 7 | 10 | 2 |
| Pivot shift test (no. of patients) | 11 | 8 | 0 |

| Variable | Mean | SD |
|---|---|---|
| Lysholm Scale | 72.7 | 17.3 |
| IKDC Score | 61.9 | 17.6 |

## Exercise protocol

All walking tests took place at the Exercise Physiology Laboratory of the Hospital. Upon arrival at the laboratory, height and body mass were measured using a stadiometer and a weighing scale to the nearest 0.1 kg and 0.1 cm, respectively (Seca, Hamburg, Germany). The participants executed three 8-min walking tasks on a motorized treadmill (Leisure Works, Maurice Pincoffs, Ontario, Canada) with a 10-min rest interval. The three walking tasks were performed in a randomized order at 5 km/h, at 0, +10 (uphill), and −10 % (downhill) gradients. This walking speed was selected because for most adults it is within the functional range of walking speeds [44] and is associated with the lowest walking metabolic cost of healthy young men [9, 26]. Respiratory gas exchange was measured breath-by-breath during the walking tests using a portable metabolic system ($K4b^2$, Cosmed, Rome, Italy). This system has been widely used in the last 25 years in sport and clinical settings for the assessment of cardiopulmonary indices. The measurement accuracy of flow meter and $O_2$ and $CO_2$ analysers of this device is ±2, ±0.02, and ±0.01 %, respectively. The system has been tested and validated as an accurate and reliable device for the measurement of energy expenditure during resting, walking, and running [11, 41]. The test–retest reliability of this device for $VO_2$ measurement during submaximal exercise has been reported as high over a wide range of exercise intensities (ICC = 0.85 up to 0.96) [11, 12, 36, 41, 43]. Furthermore, changes in $VO_2$ exceeding 1.0 ml/kg/min can be considered as true change during walking [11]. The $O_2$ and $CO_2$ analysers were calibrated prior to and after each test using ambient air and a gas of known composition (16 and 5.0 %, respectively). Also, a gas delay calibration and a turbine calibration were performed before each test using a 2-l syringe. Heart rate was continuously recorded using chest belt telemetry (Polar Electro, Kempele, Finland). The respiratory data from each task were averaged over the last 3 min (steady state metabolic condition) and analysed for oxygen consumption ($VO_2$, ml/kg/min), ventilation (VE, l/min), oxygen respiratory equivalent ($VE/VO_2$), respiratory exchange ratio (RER), and heart rate (HR, b/min).

The study conformed to the standards set out in the Declaration of Helsinki (2000) and was approved by The Institutional Ethical Committee of Aristotle University of Thessaloniki, Greece (ID No: 65/18.02.2014). All participants provided written informed consent prior to the study and completed a health history questionnaire.

### Statistical analyses

A prospective power analysis was performed for our main variable of interest ($VO_2$). The calculation of the sample size was based on an expected 20 % increase in $VO_2$ (reduction in walking efficiency) with an α of 0.05, β of 0.20, and a standard deviation of 15 %. The calculations indicated that a sample of nine participants per group would be necessary to identify statistically significant differences in $VO_2$. All data are presented as means ± SD and were analysed using SPSS version 17.0 (SPSS Inc., Chicago, IL, USA). Shapiro–Wilk tests were used to examine whether the data were normally distributed. Independent samples t-tests and one-way ANOVAs for independent groups were used to compare the physical characteristics, the energy cost of walking, and the respiratory gas exchange data. Significant effects were followed by Tukey's post hoc tests to locate the significantly different means. The level of significance was set at a $p$ value of 0.05. The effect sizes (ES) were calculated using omega squared [$\omega^2 = (SS_{between} - df_{between} \times MS_{within}) \div (SS_{total} + MS_{within})$] for ANOVAs and Cohen's $d$ ($d$ = difference between means ÷ *pooled* SD) for $t$ tests. Small, medium, and large effects would be reflected for $\omega^2$ in values greater than 0.010, 0.059, and 0.138, respectively [29, 31], and for Cohen's $d$ in values greater than 0.20, 0.60, 1.20, and 2.0, for small, moderate, large, and very large, respectively [23, 24]. The 95 % confidence intervals ($CI_{95\,\%}$) for the differences between means for all $t$ tests and Tukey's pairwise comparisons were calculated.

## Results

### ACL-deficient patients versus controls

Figure 1 presents the $VO_2$ (1a) and HR (1b) mean values for ACL-deficient and control groups. $VO_2$ (ml $kg^{-1}$ $min^{-1}$) was significantly higher in ACL-deficient patients compared with controls during 0 % gradient walking (16.6 ± 2.0 vs. 13.9 ± 1.8; $p < 0.01$; $d = 1.38$, large ES; $CI_{95\%}$ 1.1–4.2), during +10 % gradient walking (20.2 ± 3.7 vs. 16.2 ± 1.2; $p < 0.001$; $d = 1.26$, large ES; $CI_{95\%}$ 1.4–0.4), and during the −10 % gradient walking (14.2 ± 2.1 vs. 11.4 ± 1.5; $p < 0.01$; $d = 1.39$, large ES; $CI_{95\%}$ 1.1–0.3). Similarly, heart rate (HR, b $min^{-1}$) was significantly higher in ACL-deficient patients versus controls for all walking tasks: 120.8 ± 14.8 versus 103.0 ± 8.5 at 0 % gradient ($p < 0.01$; $d = 1.42$, large ES; $CI_{95\%}$ 7.8–28.6), 131.2 ± 17.1 versus 105.4 ± 8.6 at +10 % gradient ($p < 0.001$; $d = 1.74$, large ES; $CI_{95\%}$ 13.9–37.8), and 114.6 ± 12.1 versus 99.3 ± 9.0 at −10 % gradient ($p < 0.01$; $d = 1.35$, large ES; $CI_{95\%}$; 6.2–24.2). Of note, the $CI_{95\%}$ for the differences between means for all statistically significant ($p < 0.05$) comparisons ($VO_2$ and HR) did not include the zero value, supporting that the means were different. Table 3 summarizes the results for VE, RER, and $VE/VO_2$ in ACL-deficient patients and controls for the three walking tasks. Mean values for

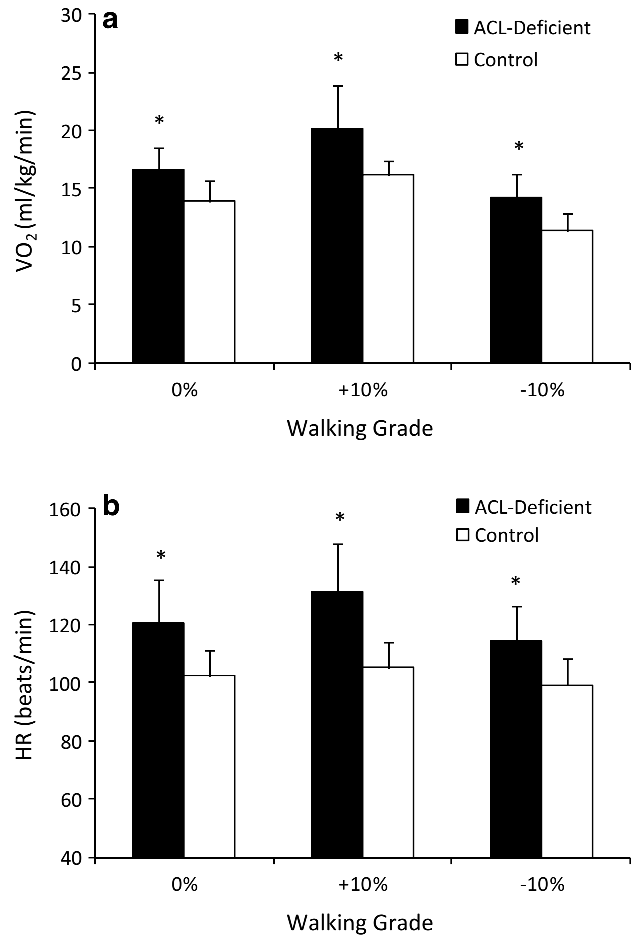


**Fig. 1** $VO_2$ (**a**) and HR (**b**) values for ACL deficient and controls. Data are means ± SD. *$p < 0.05$ versus respective control. All comparisons between ACL deficient and controls showed a large effect size ($d$ = 1.26–1.74). The $CI_{95\%}$ for the differences between means for all comparisons between ACL deficient and controls did not include the zero value, suggesting that the means are different

**Table 3** Pulmonary ventilation (VE), respiratory exchange ratio (RER), and oxygen ventilatory equivalent ($VE/VO_2$) for ACL deficient and controls during walking at 0, +10, and −10 % gradients (values are means ± SD)

| Walking gradient | Variable | ACL deficient ($n = 19$) | Control ($n = 10$) | $p$ value | CI (95 %) | Effect size ($d$) |
|---|---|---|---|---|---|---|
| 0 % gradient | VE (l/min) | 30.4 ± 4.9 | 28.6 ± 3.8 | n.s. | −1.9–5.5 | 0.39 |
| | RER | 0.75 ± 0.04 | 0.74 ± 0.03 | n.s. | −0.02–0.04 | 0.27 |
| | $VE/VO_2$ | 23.2 ± 2.6 | 23.2 ± 4.0 | n.s. | −2.5–2.5 | 0.00 |
| +10 % gradient | VE (l/min) | 36.4 ± 7.7 | 33.0 ± 5.0 | n.s. | −2.1–8.9 | 0.49 |
| | RER | 0.76 ± 0.04 | 0.75 ± 0.03 | n.s. | −0.02–0.04 | 0.27 |
| | $VE/VO_2$ | 23.2 ± 2.5 | 22.1 ± 4.0 | n.s. | −1.4–3.6 | 0.35 |
| −10 % gradient | VE (l/min) | 26.1 ± 4.5 | 23.8 ± 2.3 | n.s. | −0.8–5.4 | 0.58 |
| | RER | 0.74 ± 0.04 | 0.73 ± 0.02 | n.s. | −0.02–0.04 | 0.29 |
| | $VE/VO_2$ | 23.6 ± 2.2 | 23.8 ± 3.9 | n.s. | −2.5–2.1 | 0.07 |

*n.s.* not significant *p* value

VE, RER, and $VE/VO_2$ were not statistically significantly different between the two groups ($p$ value not significant; $d = 0$–$0.49$, trivial to small ES). The endpoints of the $CI_{95\%}$ for the differences between means for the above respiratory variables had opposite signs, including the null value.

### Non-copers versus copers versus controls

Figure 2 presents the $VO_2$ (2A) and HR (2B) mean values for non-copers, copers, and control groups during flat, uphill, and downhill walking. ANOVAs indicated a significant group effect on $VO_2$ ($p < 0.01$; $\omega^2 = 0.226$–$0.276$; large ES; Fig. 2a) and on HR ($p < 0.01$–$0.001$; $\omega^2 = 0.254$–$0.398$, large ES; Fig. 2b) within all three walking gradients. $VO_2$ was significantly higher in non-copers and copers versus controls at 0 % gradient walking (16.4 ± 1.8 and 16.8 ± 2.2 vs. 13.9 ± 1.8; $p < 0.01$–$0.05$), at +10 % gradient walking (20.0 ± 5.0 and 20.3 ± 2.3 versus 16.2 ± 1.2; $p < 0.05$), and at –10 % gradient walking (13.9 ± 2.5 and 14.3 ± 1.8 versus 11.4 ± 1.5; $p < 0.05$). There were no differences in $VO_2$ between the ACL-deficient groups within all walking tasks. HR was also significantly higher in copers and non-copers compared with controls, with no differences between non-copers and copers (Fig. 2b). For $VO_2$ and HR, the null value for differences between means lay outside the $CI_{95\%}$ for all statistically significant ($p < 0.05$) pairwise comparisons (copers and non-copers vs. controls), suggesting that the magnitude of the observed effect is greater than zero, while the $CI_{95\%}$ for all non-significant pairwise comparisons (copers vs. non-copers) included the null value. VE, RER, and $VE/VO_2$ mean values for all three walking tasks were not statistically different among the three groups and showed small "group" effect size ($p$ value not significant; $\omega^2 = 0.009$–$0.049$, small ES; Table 4). The $CI_{95\%}$ for differences between means for all pairwise

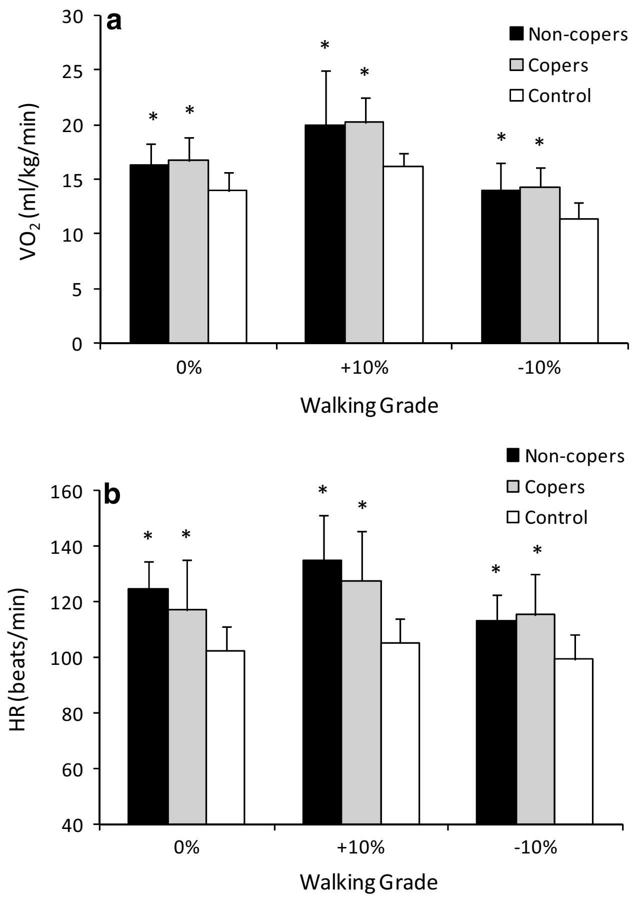


**Fig. 2** $VO_2$ (**a**) and HR (**b**) values for non-copers, copers, and controls. Data are means ± SD. *$p < 0.05$ versus respective control. For all statistically significant ($p < 0.05$) pairwise comparisons (copers or non-copers vs. controls), the null value for differences between means laid outside the $CI_{95\%}$, suggesting that the magnitude of the observed effect is greater than zero, whilst the $CI_{95\%}$ for all non-significant pairwise comparisons (copers vs. non-copers) included the null value

**Table 4** Pulmonary ventilation (VE), respiratory exchange ratio (RER), and oxygen ventilatory equivalent ($VE/VO_2$) for non-copers, copers, and controls during walking at 0, +10, and −10 % gradients (values are means ± SD)

| Walking gradient | Variables | Non-copers ($n = 9$) | Copers ($n = 10$) | Control ($n = 10$) | $p$ value (ANOVA) | Effect size ($\omega^2$) |
|---|---|---|---|---|---|---|
| 0 % gradient | VE (l/min) | 31.2 ± 4.8 | 29.7 ± 4.3 | 28.6 ± 3.7 | n.s. | 0.012 |
| | RER | 0.74 ± 0.05 | 0.75 ± 0.03 | 0.74 ± 0.03 | n.s. | 0.044 |
| | $VE/VO_2$ | 23.1 ± 2.4 | 23.4 ± 2.8 | 23.2 ± 4.0 | n.s. | 0.043 |
| +10 % gradient | VE (l/min) | 37.8 ± 10.0 | 35.1 ± 5.2 | 33.0 ± 5.0 | n.s. | 0.009 |
| | RER | 0.76 ± 0.04 | 0.76 ± 0.04 | 0.75 ± 0.03 | n.s. | 0.029 |
| | $VE/VO_2$ | 23.5 ± 2.3 | 22.8 ± 2.8 | 22.1 ± 4.0 | n.s. | 0.037 |
| −10 % gradient | VE (l/min) | 25.8 ± 5.0 | 26.3 ± 4.2 | 23.8 ± 2.3 | n.s. | 0.007 |
| | RER | 0.74 ± 0.05 | 0.74 ± 0.04 | 0.73 ± 0.02 | n.s. | 0.049 |
| | $VE/VO_2$ | 23.4 ± 1.9 | 23.8 ± 2.6 | 23.8 ± 3.9 | n.s. | 0.045 |

The $CI_{95\%}$ for the differences between means for all pairwise comparisons (copers vs. control; non-copers vs. control; non-copers vs. copers) included the null value

*n.s.* not significant $p$ value

comparisons included the zero value for VE, RER, and $VE/VO_2$; thus, the possibility that the means of any two groups were not different was greater than 5 %.

## Discussion

The most important findings of the present study were that (1) the energy cost was significantly increased in ACL-deficient patients compared with healthy controls during flat, uphill, and downhill walking and (2) the energy cost of walking was not significantly different between "non-copers" and "copers", despite the "copers" superior functional and clinical outcomes. Thus, gait instability may not be the only factor contributing to increased energy cost in ACL-deficient patients. This study is the first to compare the energy cost of ACL-deficient patients during flat, uphill, and downhill walking and to investigate whether the energy cost is different between ACL patients that require surgical intervention to return to their pre-injury activities ("non-copers") and those not needing surgical treatment ("copers").

In the current study, energy cost was 18 and 23 % higher in ACL-deficient patients compared with healthy controls during flat and uphill/downhill walking, respectively. A previous report has also documented an 8 % increased energy cost in ACL-deficient patients; the reduced gait economy, however, was observed during jogging (9.7 km $h^{-1}$), but not during flat walking (3.2–6.4 km $h^{-1}$) [35]. The exact mechanisms explaining the effect of ACL deficiency on ambulatory economy have not been fully described. One of the possible mechanisms is that patients with an ACL injury modify their gait pattern during ambulatory activities in an effort to avoid anterolateral rotatory instability [25]. That is, the increased gait instability in these patients may increase the contractions of muscles, and thus, the energy expenditure required to stabilize walking [33]. This view is well supported by Colac et al. [8], who showed that the energy cost of flat walking was lower after the ACL reconstruction. The loss of strength in our ACL-deficient patients appears as another appealing explanation for their reduced walking economy; studies in athletes have shown that strength training is accompanied by increased strength of lower limbs and improved running economy [1, 20, 40]. However, a recent study in ACL-deficient patients failed to find differences in oxygen consumption when supine exercise was performed with affected or unaffected limb, despite the lower strength of the ACL-deficient leg [4]. The above findings suggest that the lower gait economy in ACL-deficient patients is rather explained by the higher effort required to overcome gait instability and not by the strength of lower limbs per se.

One of the main gait modifications that has been described in the literature in ACL-deficient patients is the reduction or even the avoidance of quadriceps contraction and/or greater activation of hamstring muscles [5, 30]. Patients with chronic ACL deficiency demonstrate a greater knee flexion angle and smaller internal rotation of the knee than healthy controls (pivot shift avoidance gait) [18]. Furthermore, ACL-deficient knees exhibit a significantly less extension during walking [19], a parameter (stride angle) that may also affect gait economy [39]. Gait alternations have been observed on both limbs in unilaterally deficient patients [5]. All of the above kinematic alternations in gait pattern may increase the energy cost. Indeed, there is a consensus that the walking economy of pathological gait patterns is lower compared with that of a healthy pattern [45]. It should be noted, however, that some studies failed to observe "quadriceps avoidance" gait pattern in patients with ACL deficiency [15, 38]. In fact, Ferber et al. [15] observed alterations in the hip joint mechanics in an effort to avoid anterior translation of the tibia.

Differences in the neuromuscular control and muscle hypotrophy of the affected limb have been demonstrated, even among ACL-deficient population [32], that is, between patients who require ACL reconstruction to return to their usual daily activities ("non-copers") and those not needing surgical intervention ("copers"). For example, the knee compression, knee extension, and shear forces during the stance phase of walking are significantly decreased in "non-copers" compared with what is observed in "copers" and healthy controls [2, 7]. A study by Alkjaer et al. has demonstrated that "copers" stabilize their knee joint using both hamstring and quadriceps muscles, whereas "non-copers" reduce the knee extensor moment in order to decrease the anterior displacement of the tibia [3]. Also, Boerboom et al. [7] have observed an atypical semitendinosus activity during the stance phase of the gait only in "copers". In agreement with these results, Courtney et al. [10] have also reported a unique hamstring muscle response in "copers" characterized by earlier and larger activation during fast walking. Taken together, these research groups suggested that the atypical hamstring muscle activity and the differences in loading patterns of the knee joint may be part of the compensatory mechanism adopted by the "copers" to stabilize the knee joint and perform at a relatively normal level. Furthermore, MRI findings demonstrate that the size of the anterior tibialis muscle in the affected limb is larger in "non-copers" than in "copers" [6]. The authors suggested that "non-copers" adapt a stabilizing technique for the knee either by stiffening of the ankle during heel strike or with an inversion of the foot, causing an external rotation of the tibia that may have resulted in the hypertrophy of the tibialis anterior muscle [6].

Despite the reports that "copers" and "non-copers" adopt different strategies to cope with to overcome anterolateral rotatory instability of the affected knee [7, 32] and the facts that "copers" remain more physically active, experiencing less loss of strength during walking [14], and show less instability incidence, no differences in energy cost were documented between the two ACL-deficient populations. Thus, even though "copers" manage to achieve higher activities without presenting symptoms, their strategy to accomplish that is insufficient, as evidenced by their increased energy requirements. The increased heart rate response in ACL-deficient patients compared with controls at all walking gradients may well explain their higher oxygen consumption and effort during locomotion. To the best of our knowledge, this is the first study to examine the energy cost of walking between "copers" and "non-copers"; thus, comparisons with other studies are not possible. Insights into the energy costs of ACL-deficient patients, and in particular of "copers" and "non-copers", are important for designing and guiding exercise rehabilitation programmes to optimize improvements in physical fitness and to reduce the risk of musculoskeletal injury, due to greater fatigue associated with increased energy cost of locomotion. Furthermore, these findings can be useful in the day-by-day clinical practice for sports injury specialists. It is important for the surgeon to know that ACL rupture may increase the energy demands of locomotion in both copers and non-copers. Thus, gait economy may be another parameter to consider at the time of the clinical decision for operative or non-operative treatment in either copers or non-copers, particularly for patients to whom the energy cost is of major importance, such as an athletic population.

The present study has some potential limitations. First, our findings are limited to physically fit males. It is possible that the unfit population and females may show different oxygen consumption responses because of differences in strength and gait (moving) economy. Second, a fairly small sample size was used. Although larger study groups could lead to more confidence in the results, the effect size and the confidence interval statistics in this study support the results obtained by the conventional null hypothesis testing. Third, the gait mechanics (kinetics/kinematics) and the electromyographic profiles have not been examined. Thus, our data do not provide a mechanistic rationale for the reduced walking economy in ACL deficiency and for the lack of differences in walking efficiency between copers and non-copers. Finally, it is not clear whether more demanding movement tasks, such as running, may unmask possible differences in gait economy between "copers" and "non-copers".

## Conclusion

In conclusion, the results of this study demonstrate that ACL-deficient patients have inferior economy during flat, uphill, and downhill walking compared with healthy controls. The present study extends the knowledge about the energy cost of walking in ACL-deficient patients, reporting that walking economy did not differ between "copers" and "non-copers". Thus, despite the copers' improved clinical and functional outcomes, such as an increased physical activity profile, their walking economy remains similar to that of "non-copers" and impaired compared with healthy individuals. This finding is of clinical importance for the implementation of safer rehabilitation programs, that is, avoiding the risk of musculoskeletal injury associated with greater fatigue induced by higher energy demands. The increased energy cost in copers, in particular, may be another parameter to consider when deciding between operative and non-operative treatment, especially for athletes.

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