Journal of Cleaner Production 535 (2025) 147136

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Environmental life cycle assessment of surgical versus conservative care pathways for an anterior cruciate ligament injury

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HIGHLIGHTS

- Surgical ACL care is at least 8.5 times more burdensome than conservative care.
- ACL-injured patients should be carefully allocated between these two care pathways.
- Surgery burden hotspots include single-use products, transportation and HVAC.
- Physiotherapy burden hotspots include transportation, laundry and space heating.

ARTICLE INFO

Keywords:
Life cycle assessment
Anterior cruciate ligament
Surgery
Physiotherapy

ABSTRACT

Environmental degradation is a major global health threat, and the healthcare sector functions as both its victim and perpetrator. To effectively inform mitigation strategies it is essential to quantify the environmental burden originating from healthcare activities and then favour environmentally preferable treatment options.

This Switzerland-based study evaluated and compared the environmental impacts from surgical and conservative care pathways after an anterior cruciate ligament injury using Life Cycle Assessment; it also identified the environmental hotspots stemming from the surgery itself, as well as from physiotherapy. Environmental impacts were quantified across 18 ReCiPe midpoint impact categories.

Results indicated that, on average, after an anterior cruciate ligament injury, the surgical pathway imposes at least an 8.5-fold greater relative environmental burden than the conservative pathway. Regarding the anterior cruciate ligament surgery alone, the hotspots of environmental impacts were identified as the manufacturing of single-use products, transportation of patient and staff, and the use of heating-ventilation-air-conditioning and electricity. Regarding physiotherapy, results indicated that a large share of environmental impacts can be attributed to transportation of patient and staff, laundry, and space heating.

This difference in environmental impacts emphasises the importance of a careful patient allocation between these two care pathways. Recommendations to reduce the environmental impacts from surgery should prioritise investing in reusable equipment, streamlining surgical instrument trays, and opting for occupancy-based heating-ventilation-air-conditioning. To reduce the environmental impacts originating from physiotherapy, recommendations should encourage soft mobility, patient's self-management, and the physiotherapist's following of evidence-based guidelines. Reducing laundry frequency can be relevant as well.

1. Introduction

Climate change is considered to be the biggest global health threat of

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https://doi.org/10.1016/j.jclepro.2025.147136
Received 4 May 2025; Received in revised form 10 October 2025; Accepted 16 November 2025
Available online 24 November 2025

Glossary

ACL	Anterior Cruciate Ligament
ALO	Agricultural land occupation
CGP	Clinical Practice Guidelines
CC	Climate change
CP	Conservative Pathway
EU	European
FD	Fossil depletion
FWEc	Freshwater ecotoxicity
FWEu	Freshwater eutrophication
GHG	Green House Gas
GWP	Global Warming Potential
HDPE	High-Density Polyethylene
HT	Human toxicity
HUG	University Hospitals of Geneva
HVAC	Heating, Ventilation and Air-Conditioning
IPCC	Intergovernmental Panel on Climate Change
IR	Ionising radiation
ISO	International Organisation for Standardization
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LDPE	Low-Density Polyethylene
MEc	Marine ecotoxicity
MEu	Marine eutrophication
MD	Metal depletion
NLT	Natural land transformation
OD	Ozone depletion
PET	Polyethylene Terephthalate
PMF	Particulate matter formation
POF	Photochemical oxidant formation
PP	Polypropylene
PVC	Polyvinyl Chloride
RCT	Randomized Controlled Trial
SD	Standard Deviation
SP	Surgical Pathway
TA	Terrestrial acidification
TEc	Terrestrial ecotoxicity
ULO	Urban land occupation
WD	Water depletion
WHO	World Health Organization

the 21st century (Costello et al., 2009). Human activities are causing some unprecedented changes to the environment which exacerbate climate-sensitive health risks such as heat-related illnesses and deaths, air pollution-related health effects, and infectious diseases (IPCC, 2021a). In the coming decades, it is expected that the effects of climate change on health will increasingly put the lives and wellbeing of billions of people at risk, especially in the absence of strong, rapid, and sustained implementation of greenhouse gases (GHGs) emissions reduction strategies (IPCC, 2021b). These strategies will require contribution and collaboration from all sectors of government, economy and civil society, including the health sector, that currently functions as both perpetrator and victim of environmental pollution (Lenzen et al., 2020). Switzerland, for example, has been recently classified amongst the top ten healthcare polluters with 1.02 tCO2e per capita emitted annually and 6.7 % of national emissions attributable to the healthcare sector (ASSM, 2022). Moreover, the annual carbon footprint of healthcare specific to the canton of Geneva has recently been estimated to account for 0.84 tCO2eq per capita (Mermillod et al., 2024).

Beside GHGs, healthcare services are responsible for unsustainable resource use and other forms of environmental degradation, including the emissions of particulate matter, sulphur and nitrogen oxides, persistent organic pollutants, and toxic metals, which also represent significant burdens for public health (Eckelman and Sherman, 2016). Therefore, this sector has an important role to play in resolving the issues it is contributing to and should be an essential target for environmental pollution and resource use reduction. It is expected that the efforts to reduce the environmental impacts of healthcare will not only help the sector to align itself with the ambitions of the Sustainable Development Goals but will also have important health co-benefits by reducing the burden on public health and improving healthcare quality and safety (Wise, 2021).

To effectively inform mitigation strategies it is essential to thoroughly quantify the environmental burden originating from healthcare activities, but data is often scarce or lacking (Alshqaqeeq et al., 2020). Efforts to evaluate the environmental impacts of medical sectors, devices, supplies, procedures and waste are underway and some first recommendations and strategies towards more sustainable practices have been formulated (Alshqaqeeq et al., 2020; Kumar et al., 2023; McGain and Naylor, 2014; Sherman et al., 2020; Taylor and Mackie, 2017). Broadly speaking, researchers working in the field of sustainable healthcare seem to agree that it is time for best clinical practices to evolve beyond the logic of sole cost-effectiveness and start including notions of resource efficiency and pollution prevention as well (Atkinson et al., 2010; Bhopal and Norheim, 2021; Duane et al., 2014; Mortimer et al., 2018; Naylor and Appleby, 2012; Sherman et al., 2020; Twomey and Overcash, 2020).

In that sense, one of the recommendations that is proposed, by some authors, due to its considerable mitigation potential is the favouring of environmentally preferable treatment options and pathways, especially whenever a clinical equipoise exist (Ferchichi et al., 2021; Sherman et al., 2020; Twomey and Overcash, 2020). Clinical equipoise can be defined as the genuine uncertainty within the scientific and medical communities as to which interventions are clinically superior (Freedman, 1987). Alshqaqeeq et al. (2020), reviewed studies evaluating environmental impacts from different patient-care alternatives, but the gathered data is still insufficient to broadly and effectively guide clinical practice in the context of the current environmental crisis. Additional critical comparisons of the impacts of care pathways that have similar patient outcomes are very much needed.

In the field of orthopaedics, such clinical equipoises exist also, like in the management of anterior cruciate ligament (ACL) rupture, degenerative meniscal tears, subacromial impingement syndrome, spinal canal stenosis or degenerative disc disease (Blom et al., 2021). The orthopaedic surgical procedures commonly performed in these cases can therefore make good candidates for a comparative study on the environmental impacts of surgical and conservative care pathways. Since there seems to be an agreement that the surgical department represents a high yielding mitigation opportunity within healthcare, being a particularly demanding subsector with significant fractions of energy use and consumable throughput (Alshqaqeeq et al., 2020; Drew et al., 2021; MacNeill et al., 2017; Rizan et al., 2020), and that environmental evaluations of orthopaedic settings are still scarce (Engler et al., 2022; McAleese et al., 2024; Phoon et al., 2022), this field can be especially relevant for an environmental evaluation of care pathways.

Additionally, the field of physiotherapy has also been proposing to favour conservative treatments over surgical care for certain musculoskeletal conditions, emphasising that conservative care can be as good a therapeutic option and assuming that physiotherapy rehabilitation is less problematic for the environment (Bruyneel, 2020; Ferchichi et al., 2021; Maric and Nicholls, 2019; Palstam et al., 2022). Being a low tech approach, physiotherapy could indeed be an environmentally friendly practice and a potential key player in the healthcare's ecological

transition (Palstam et al., 2022), but it seems there hasn't been any assessments of its environmental impacts so far (Li et al., 2024). Such studies of the environmental footprint would be essential to make an evidence-based claim that conservative care is less polluting than surgical care.

Among the options proposed by Blom et al. (2021), the management of an anterior cruciate ligament (ACL) injury appears to be a suitable choice: the surgery is a relatively short procedure that does not require any particularly distinctive equipment. Also, the ACL is a frequently injured structure, particularly during sporting activities, with around 3′000 persons with ACL injuries in Switzerland per year (Coppens et al., 2018). Both the incidence of the injury and the surgical reconstruction are currently on the rise (Coppens et al., 2018). Clinical recommendations cite both surgical and conservative treatments as acceptable options for an ACL injury (Diermeier et al., 2021), and several systematic reviews and meta-analyses have noted that it is unclear whether ACL surgery is overall superior to physiotherapy alone for restoring an ACL-deficient knee function (Blom et al., 2021; Lien-Iversen et al., 2020; Smith et al., 2014).

Recent American and French studies provided the first environmental evaluations on an ACL surgery in their respective geographical contexts (Karam et al., 2024; Silva de Souza Lima Cano et al., 2025), but these studies did not look into comprehensive care pathways that are typically followed after an ACL injury.

In the context of this existing clinical equipoise and the absence of environmental data comparing comprehensive care pathways in the orthopaedic setting, the aim of this study was to evaluate and compare the environmental impacts stemming from surgical and conservative care after an ACL injury. For methodological reasons, it was therefore assumed that both options are similar from a clinical perspective. A secondary objective was to gain insight into which activities contribute the most to environmental impacts associated with the ACL surgery alone, as well as into those associated with physiotherapy alone, in the Swiss and European contexts.

This work intends to make a timely contribution to the growing field of sustainable healthcare by generating new evidence on the environmental impacts of comparable care pathways rather than isolated procedures. The study is intended to provide valuable input to healthcare-related environmental research and to address the increasing demand for data that can guide environmentally responsible clinical decision-making. By advancing methodological approaches and highlighting the potential environmental trade-offs of treatment options, this work aspires to contribute to the emerging field of sustainable healthcare and to support the development of more ecologically responsible models of care delivery.

2. Methods

This evaluation was performed using Life Cycle Assessment (LCA), which is the recommended method for environmental footprinting in the health sector (McGinnis et al., 2021). LCA is a standardised decision making tool that quantifies the environmental impacts of a product or a service across its entire life cycle, from raw materials acquisition through manufacture, transportation, use and disposal, and is commonly referred to as "cradle-to-grave" analysis (Saadé and Jollier, 2024). Since the results are related to the function of a product or service, they allow comparisons between alternatives (Saadé and Jollier, 2024), which is essential for conducting research about sustainable care pathways (Twomey and Overcash, 2020). In addition to deepening the understanding about which pathway has a lower environmental impact, and by how much, LCA can also display the most polluting steps of any alternative, allowing for different kinds of mitigation priority settings (Twomey and Overcash, 2020).

Therefore, an attributional approach was applied to the functional unit of "one knee rehabilitation". Two separate care pathways were examined and compared. The first one was the Surgical Pathway (SP) after an ACL injury, which included pre-operative physiotherapy, ACL surgery, and post-operative physiotherapy. The second one was the Conservative Pathway (CP) after an ACL injury, which included conservative physiotherapy only (Fig. 1).

The inputs needed for an ACL surgery were gathered based on the technique used at Geneva University Hospitals (hitherto referred to as HUG, Hôpitaux Universitaires des Genève), which is described by Menetrey et al. (2016) as being a single-bundle autologous reconstruction, using a graft from the middle-third quadriceps tendon harvested on the same side as the injured ACL (Menetrey et al., 2016). System boundaries encompassed processes needed to perform the surgery from the moment the patient enters the operating room, to the moment the patient leaves, with the additional consideration of the transportation needs of the hospital staff and the patient. System expansion was performed to account for avoided heat and electricity production in the waste incineration plant. Recycling processes were excluded due to a cut-off approach to waste management (Fig. 2). Main data was collected in HUG's operating rooms in May and June 2023 and additional information was provided by the hospital staff or taken from academic literature and various online sources and reports. Extensive details about the data collection process for surgery, assumptions made, and the full modelling approach are provided in Appendix A.

Physiotherapy contents were based on information collected in December 2022 and January 2023 by conducting semi-structured interviews and follow-up discussions with two experienced sport physiotherapists based in Geneva (Switzerland), that indicated following available Clinical Practice Guidelines in their daily practice (Jenkins et al., 2022). System boundaries also comprised inputs needed to perform the rehabilitative sessions, from the moment the patient enters the physiotherapy clinic, to the moment the patient leaves, with the additional inclusion of patient's and physiotherapist's transportation.

The SP and CP differed in the number of physiotherapy sessions needed for a knee rehabilitation, but not in the nature of inputs needed to perform this rehabilitative service, which were assumed to be equivalent (Fig. 3). Based on the interviews, it was assumed that the CP would consist of 23 physiotherapy sessions, and the SP would require a total of 79 sessions, 9 of which to be performed before the surgery. Therefore, modelling of physiotherapy in the SP was based on a multiplication of all the input processes from the conservative physiotherapy model by 3.43 ($79/23 \approx 3.43$). A sensitivity analysis was performed varying the number of physiotherapy sessions: a short rehabilitation scenario (with a total of 18 sessions in the CP and 45 sessions in the SP), as well as a long rehabilitation scenario (with 27 sessions in the CP and 113 sessions in the SP) were defined, based on the minimum and maximum values given by the interviewed physiotherapists. Extensive details about the data collection process for physiotherapy, assumptions made, and the full modelling approach are provided in Appendix B.

Due to the unavailability of data specific to modal choices of health professionals and patients, a sensitivity analysis was performed to test the influence of transportation means (car, bus, bicycle and walking) on environmental impacts. However, the limited clinical feasibility of cycling and the context-dependent feasibility of walking should be noted.

An additional sensitivity analysis was performed using European (EU) electricity mix, so that the results could be extrapolated to the European context. This change in electricity mix affected processes related to heating, ventilation, and air-conditioning (HVAC), lighting, use of electrical equipment, laundry, sterilisation, as well as the credit calculated for the avoided electricity production in the waste incineration plant when applying the system expansion approach.

After the comparison of pathways, additional analyses were performed to look into the activities that contribute the most the environmental impacts associated with the ACL surgery alone, as well as physiotherapy alone. Sensitivity analyses with the same modal choice variations and electricity mix variation were also conducted in both cases. Additional sensitivity analyses were performed for physiotherapy,

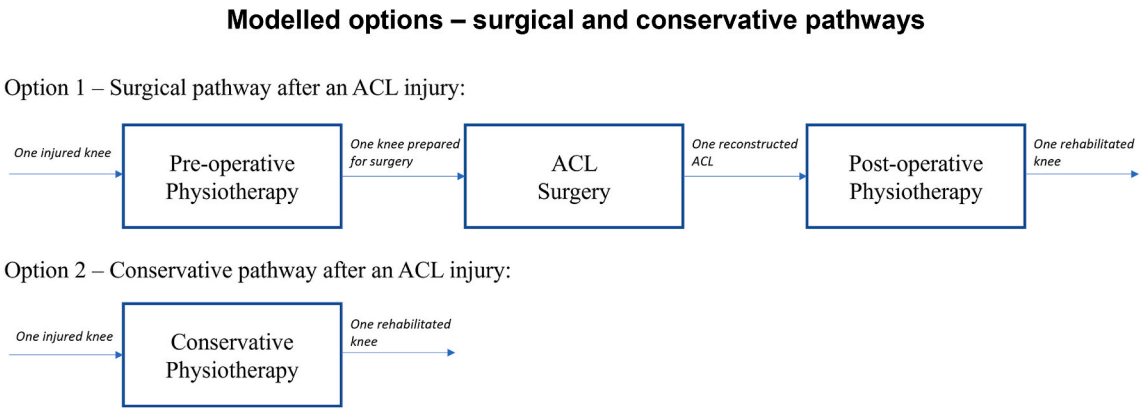

Fig. 1. Modelled options; ACL = anterior cruciate ligament.

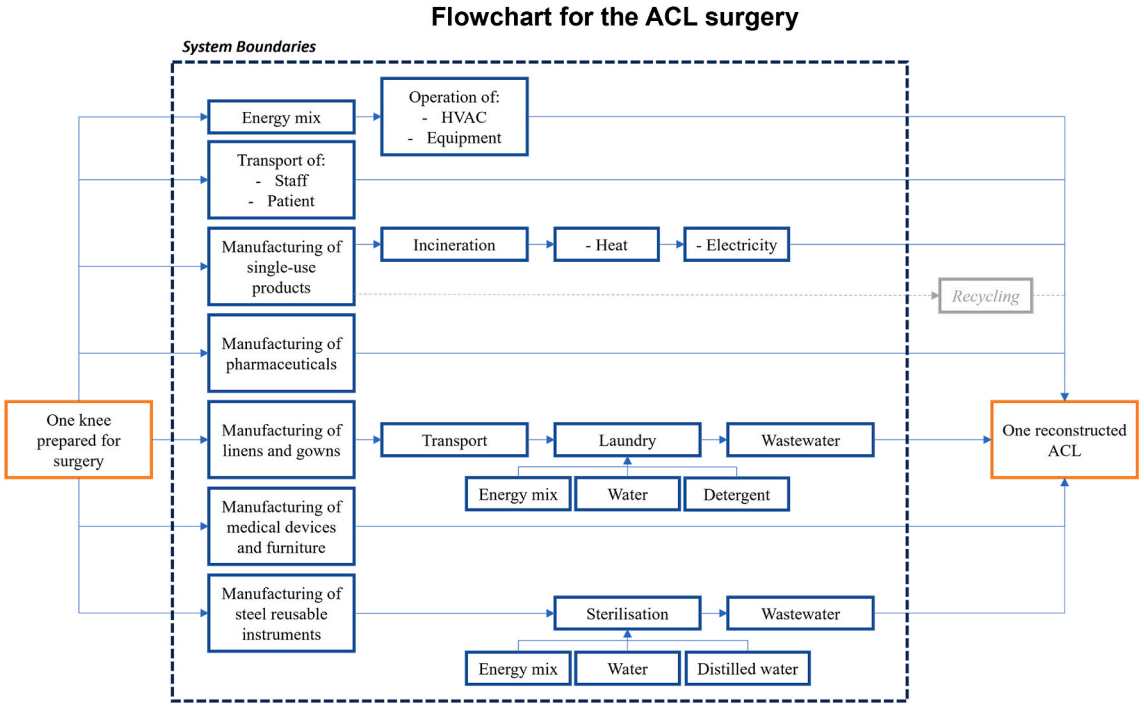

Fig. 2. Flowchart for the anterior cruciate ligament (ACL) surgery; HVAC = heating, ventilation and air-conditioning.

to account for uncertainties regarding equipment durability (a scenario with halved lifetime of the equipment was modelled) as well as laundry frequency (a scenario with towel washing after each session instead a personal towel washed after 9 sessions was modelled).

In both cases, the scenario with the modal choice set to car, being the most common mean of transportation in Switzerland (OFS, 2021), and the Swiss electricity mix will be referred to as the "reference" scenario.

Life Cycle Inventories were created using the ecoinvent version 3.5 cut-off database and the OpenLCA software. The Impact Assessment method was ReCiPe midpoint (hierarchist), v1.11. All 18 impact categories were taken into consideration.

3. Results

3.1. Whole pathways comparison

The Life Cycle Impact Assessment (LCIA) revealed that, on average, the reference scenario of the SP was associated with an 8.5-fold greater relative environmental burden than the CP (mean ratio ± standard deviation: 8.5 ± 6) (Table 1). The smallest difference was observed in the Urban Land Occupation (ULO) impact category, where the SP was 4.3 times more problematic, whereas the highest difference was observed in the Water Depletion (WD) impact category, where the SP was 24.5 times more problematic. Relative amounts are visualised in Fig. 4. Moreover, physiotherapy sessions account for more than half of the environmental impact in 12 out of 18 impact categories. The distribution of environmental impacts between the surgery itself and physiotherapy sessions within the SP reference scenario can be found in appendix C, table C1.

For the short rehabilitation scenario, the SP imposed a relative environmental burden 9 (±7.7 SD) times greater than the CP on average. For the long rehabilitation scenario, the SP imposed a relative environmental burden approximately 8.5 (±5.1 SD) times greater on average (see appendix C, tables C2 and C3).

When the mode choice was changed to bus, bicycle and walking, the average relative difference between the surgical and conservative pathways shifted to 16.4 (±13.8 SD), 22.6 (±14.5 SD) and 32.4 (±19.5 SD) respectively; with the European electricity mix, the difference

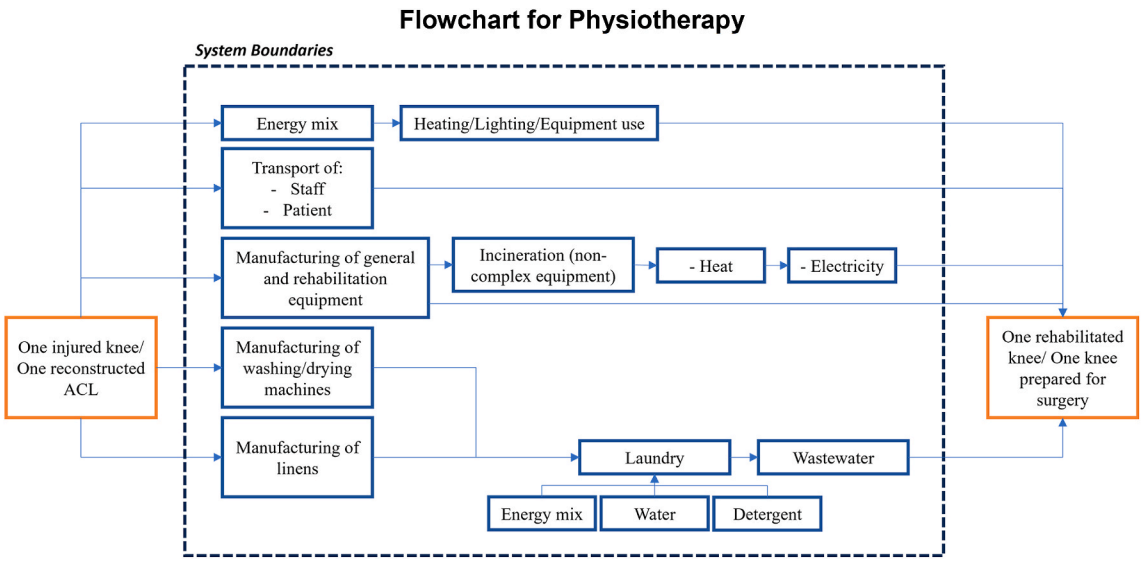

Fig. 3. Flowchart for physiotherapy (same inputs for pre-operative, post-operative and conservative physiotherapy); ACL = anterior cruciate ligament.

Table 1
Results for all 18 ReCiPe impact categories for the reference scenarios of surgical and conservative pathways.

Impact Category	Unit	SP	CP	Ratio (SP/CP)
Agricultural land occupation (ALO)	m2*a	19.69	0.83	23.7
Climate change (CC)	kg CO2 eq	312.84	58.65	5.3
Fossil depletion (FD)	kg oil eq	103.54	19.71	5.3
Freshwater ecotoxicity (FWEc)	kg 1,4-DB eq	13.34	2.42	5.5
Freshwater eutrophication (FWEu)	kg P eq	0.08	0.01	6.5
Human toxicity (HT)	kg 1,4-DB eq	114.92	20.44	5.6
Ionising radiation (IR)	kg U235 eq	45.91	5.05	9.1
Marine ecotoxicity (MEc)	kg 1,4-DB eq	11.92	2.12	5.6
Marine eutrophication (MEu)	kg N eq	0.09	0.01	8.0
Metal depletion (MD)	kg Fe eq	26.82	5.95	4.5
Natural land transformation (NLT)	m2	0.09	0.02	4.5
Ozone depletion (OD)	kg CFC-11 eq	9.59E-05	9.40E-06	10.2
Particulate matter formation (PMF)	kg PM10 eq	0.49	0.09	5.6
Photochemical oxidant formation (POF)	kg NMVOC	0.98	0.19	5.1
Terrestrial acidification (TA)	kg SO2 eq	1.07	0.18	5.8
Terrestrial ecotoxicity (TEc)	kg 1,4-DB eq	0.45	0.03	14.0
Urban land occupation (ULO)	m2*a	6.33	1.47	4.3
Water depletion (WD)	m3	3071.73	125.42	24.5
Average relative ratio (SP/CP) ± standard deviation (SD) = 8.5 ± 6				

SP = surgical pathway, CP = conservative pathway.

between pathways changed to 8.2 (±4.7 SD), with a substantial SP/CP ratio modification in the WD impact category (see appendix C, tables C4 to C7).

3.2. ACL surgery

LCIA revealed that for the ACL surgery alone, most of the emissions and resource use in the reference scenario were related to the manufacturing of single-use products, with an average of 45.7 % of impacts across all environmental categories. Car transportation was the second most prevalent contributor with an average of 22.1 % of impacts, followed by HVAC, responsible for 18.2 % of impacts on average. Waste management, pharmaceuticals, laundry, sterilisation, and other equipment and devices were responsible for an average of 5.5 %, 4 %, 2.5 %, 1.3 % and 0.8 % of environmental impacts, respectively. The breakdown of contributors for each environmental impact category is illustrated in Fig. 5.

When changing the transportation mode from car to bus, bicycle and walking, environmental impacts from an ACL surgery decreased by an average of 14 %, 21 % and 22 % respectively; with the EU electricity mix, instead of the Swiss electricity mix, environmental impacts increased by 14 % on average (Fig. 6).

In the bus scenario, single-use products accounted for an increased average of 52.2 % of environmental impacts, with HVAC becoming the second hotspot of emissions and resource use (20.7 % of impacts on average) while transportation decreased its contribution to an average of 9.7 %. In this scenario, waste management, pharmaceuticals, laundry, sterilisation, and other equipment and devices were responsible for an average of 7.2 %, 4.8 %, 2.8 %, 1.5 % and 1.1 % of environmental impacts, respectively.

In the bicycle scenario, single-use products and HVAC accounted for an average of 57.7 % and 22.3 % of environmental impacts, respectively. Here, waste management became the third hotspot of emissions and resource use with 7.2 % of impacts on average. In this scenario, pharmaceuticals, laundry, transportation, sterilisation, and other equipment and devices were responsible for 5.4 %, 3 %, 1.6 %, 1.6 % and 1.1 % of environmental impacts on average, respectively.

In the walking scenario, single use products, HVAC and waste management accounted for an average of 58.7 %, 22.6 % and 7.4 % of environmental impacts, respectively. In this scenario, pharmaceuticals, laundry, sterilisation, and other equipment and devices were responsible for 5.5 %, 3.1 %, 1.4 % and 1.2 % of average impacts, respectively. No environmental impacts were attributed to transportation.

When the EU electric mix was applied to the reference scenario, single-use products' contribution decreased to an average of 40.6 % of environmental impacts, while HVAC became the second hotspot of emissions and resource use with 28.6 % of impacts, on average. Transportation by car became the third hotspot of environmental burden with a contribution of 19.2 % of environmental impacts on average. Pharmaceuticals, waste management, laundry, sterilisation, and other equipment and devices contributed for 3.4 %, 3.3 %, 2.4 %, 1.9 % and 0.9 % of average impacts. Additional graphs representing each ACL surgery scenario separately can be found in appendix C, figures C1 to C4.

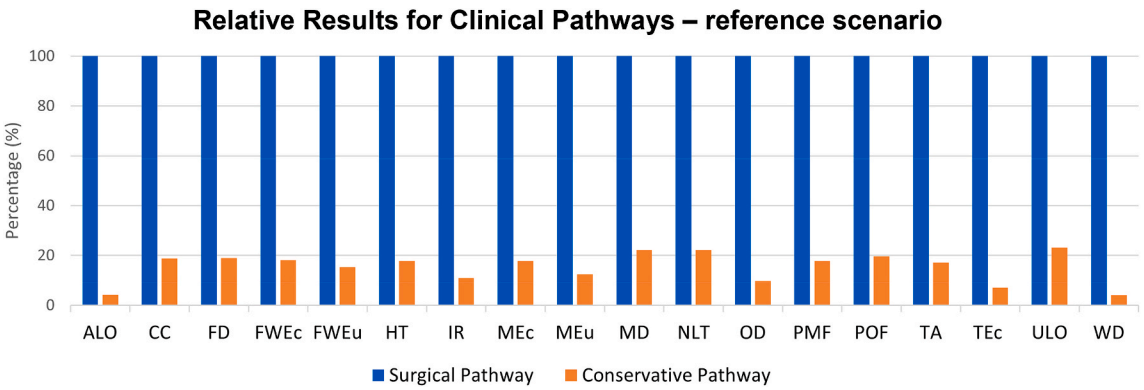

Fig. 4. Relative results with the reference scenario's surgical pathway set to 100 % and the reference scenario's conservative pathway displayed in relation to the surgical pathways' values; ALO = Agricultural land occupation, CC = Climate change, FD = Fossil depletion, FWEc = Freshwater ecotoxicity, FWEu = Freshwater eutrophication, HT = Human toxicity, IR = Ionising radiation, MEc = Marine ecotoxicity, MEu = Marine eutrophication, MD = Metal depletion, NLT = Natural land transformation, OD = Ozone depletion, PMF = Particulate matter formation, POF = Photochemical oxidant formation, TA = Terrestrial acidification, TEc = Terrestrial ecotoxicity, ULO = Urban land occupation, WD = Water depletion.

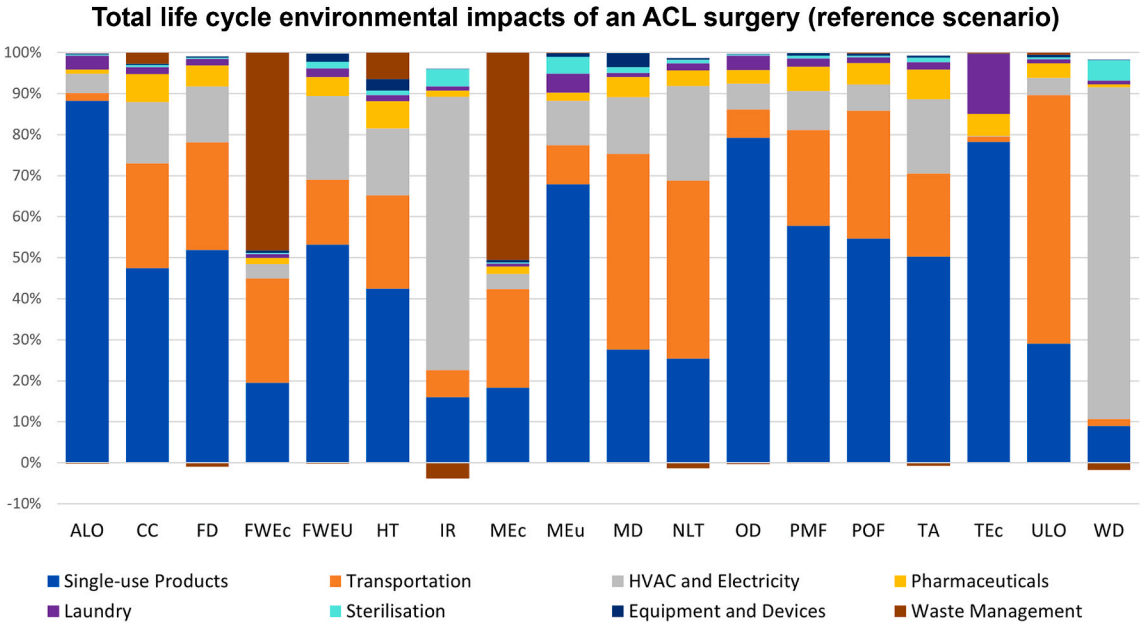

Fig. 5. Relative contributions of activities associated with an ACL surgery for each environmental impact category in the reference scenario. Negative amounts are due to the avoided heat and electricity production by the system expansion approach for incinerated waste. ALO = Agricultural land occupation, CC = Climate change, FD = Fossil depletion, FWEc = Freshwater ecotoxicity, FWEu = Freshwater eutrophication, HT = Human toxicity, IR = Ionising radiation, MEc = Marine ecotoxicity, MEu = Marine eutrophication, MD = Metal depletion, NLT = Natural land transformation, OD = Ozone depletion, PMF = Particulate matter formation, POF = Photochemical oxidant formation, TA = Terrestrial acidification, TEc = Terrestrial ecotoxicity, ULO = Urban land occupation, WD = Water depletion.

3.3. Physiotherapy

LCIA revealed that for physiotherapy alone, most of the emissions and resource use in the reference scenario were associated with transportation by car, with an average of 84.3 % of impacts across all environmental categories. Three quarters of those were attributable to the patient. Laundry, being particularly affected by the "Terrestrial Ecotoxicity" impact category, was the second most prevalent section with an average of 7.4 % of impacts, followed by heating and lighting, responsible for 4.7 % of impacts on average. General and rehabilitative equipment were responsible for an average of 2.5 % and 1.2 % of environmental impacts, respectively. The contribution of waste management was minimal (<0.01 % of impacts). The impacts distribution for each environmental category is illustrated in Fig. 7. When changing mode choice to bus, bicycle and walking, environmental impacts from physiotherapy were, on average, divided by four, seven and 15 times respectively (Fig. 8).

In the bus scenario, transportation remained the top hotspot of emissions and resource use, accounting for a decreased average of 61.5 % of environmental impacts. Laundry, heating and lighting, general equipment, as well as rehabilitative equipment were responsible for 13.2 %, 11.1 %, 9.5 % and 4.7 % of impacts, on average. The contribution of waste management remained minimal (<0.01 % of impacts).

In the bicycle scenario, transportation remained the top hotspot of environmental burden, accounting for a further decreased average of 31.8 % of impacts. Heating and lighting became the second hotspot of emissions and resource use (30 % of impacts on average, 98 % of which are attributable to space heating), whereas the relative contribution of laundry decreased to an average of 18.8 %. General and rehabilitative equipment respectively contributed to an average of 12.6 % and 6.8 % of impacts, while waste management still remained minimal (<0.01 % of impacts).

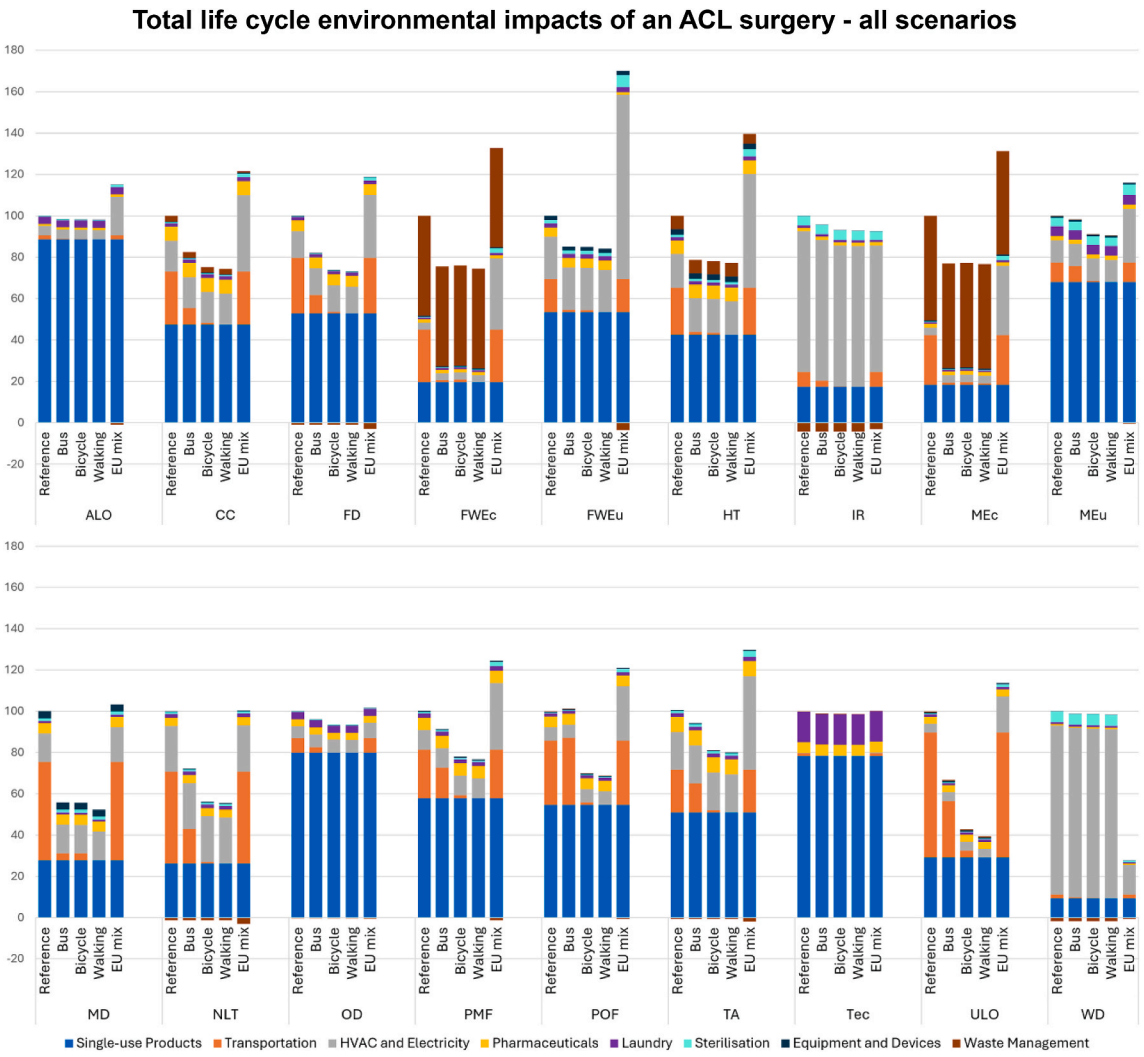

Fig. 6. Relative contributions of activities associated with an ACL surgery for each environmental impact category and each scenario (variations in modal choice and electricity mix). The total relative contributions of the surgical's reference scenario are set to 100 % and the other scenarios are displayed in relation to these values. Negative amounts are due to the avoided heat and electricity production by the system expansion approach for incinerated waste. ALO = Agricultural land occupation, CC = Climate change, FD = Fossil depletion, FWEc = Freshwater ecotoxicity, FWEu = Freshwater eutrophication, HT = Human toxicity, IR = Ionising radiation, MEc = Marine ecotoxicity, MEu = Marine eutrophication, MD = Metal depletion, NLT = Natural land transformation, OD = Ozone depletion, PMF = Particulate matter formation, POF = Photochemical oxidant formation, TA = Terrestrial acidification, TEc = Terrestrial ecotoxicity, ULO = Urban land occupation, WD = Water depletion.

In the walking scenario, heating and lighting became the first hotspot of environmental burden, accounting for an average of 47.7 % of impacts. Laundry decreased its relative contribution to an average of 24.5 %. General equipment, rehabilitative equipment and waste management were responsible for 21.5 %, 12.1 % and 0.2 %, respectively.

When increasing laundry frequency by washing towels after one use (instead of the default of 9 uses), environmental impacts increased by an average of 50 %. When decreasing the equipment's lifespan by half, environmental impacts increased by an average of 2 %. And when switching to EU electric mix, environmental impacts increased by 0.7 % on average (Fig. 9).

In the increased laundry's frequency scenario, transportation by car remained the first hotspot of emissions and resource use, with an average contribution decreased to 72.6 %. Laundry remained the second hotspot of environmental impacts, with an average contribution increased to 20.9 %. Heating and lighting, general equipment, rehabilitative equipment accounted for an average of 3.9 %, 1.7 % and 0.9 %, respectively. The contribution of waste management was minimal (<0.01 % of impacts).

In the decreased equipment's lifespan scenario, most of the environmental burden was embedded in the transportation by car, with an average of 82.2 % of impacts across all environmental categories. Laundry, and heating and lighting contributed to an average of 7.2 % and 4.6 %, respectively. Compared to the reference scenario, the contributions of general and rehabilitative equipment slightly increased to averages of 3.8 % and 2.2 % of all environmental impacts (from 2.5 % to 1.2 % in the reference scenario). The contribution of waste management remained minimal (<0.01 % of impacts).

When the EU electric mix was applied to the reference scenario, transportation by car remained the first hotspots of emissions and resource use, with a contribution that slightly decreased to an average of 83.8 % (from 84.3 % with the Swiss electricity mix). The contributions of laundry, heating and lighting, and general equipment slightly increased to an average of 7.7 %, 4.9 % and 2.6 % respectively. Rehabilitative equipment accounts for an average of 1.1 % of environmental impacts and the contribution of waste management remained minimal (<0.01 % of impacts). Additional graphs representing each physiotherapy scenario separately can be found in the appendix C5 to C8.

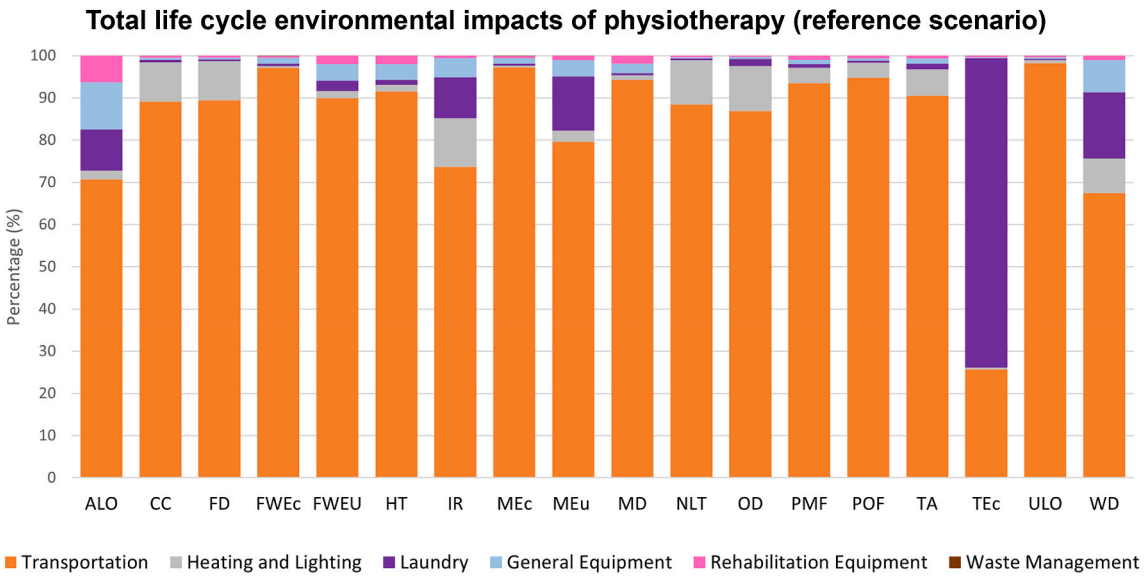

Fig. 7. Relative contributions of activities associated with physiotherapy for each environmental impact category in the reference scenario; ALO = Agricultural land occupation, CC = Climate change, FD = Fossil depletion, FWEc = Freshwater ecotoxicity, FWEu = Freshwater eutrophication, HT = Human toxicity, IR = Ionising radiation, MEc = Marine ecotoxicity, MEu = Marine eutrophication, MD = Metal depletion, NLT = Natural land transformation, OD = Ozone depletion, PMF = Particulate matter formation, POF = Photochemical oxidant formation, TA = Terrestrial acidification, TEc = Terrestrial ecotoxicity, ULO = Urban land occupation, WD = Water depletion.

4. Discussion

To our knowledge, this study is the first to compare 18 different types of environmental impacts of two clinical pathways after an ACL injury that may require an orthopaedic surgical procedure besides physiotherapy.

The results highlighted that, in the Swiss context, the conservative pathway is the environmentally preferable option, imposing, on average, a relative environmental burden 8.5 (±6 SD) times lower than that of the surgical pathway. It is important to note that this figure represents the mean of category-specific SP/CP ratios and is not a total environmental impact score. This difference widens considerably with more sustainable transportation, with the conservative pathway's environmental average relative burden becoming 16.4 (±13.8 SD), 22.6 (±14.5 SD) and 32.4 (±19.5 SD) times lower than that of the surgical pathway when all involved commute by bus, cycling or walking, respectively. These comparisons are not intended to represent typical clinical practice, particularly in the early stages of ACL rehabilitation, when patients are unlikely to be able to cycle and may only walk short distances with assistive devices. Instead, they serve to illustrate the strong influence of transportation modes on environmental outcomes. When assuming the European electricity mix instead of the Swiss local one, results show that the conservative pathway remains the environmentally preferable option, imposing an environmental burden at least 8.2 (±4.7 SD) times lower than the surgical pathway.

The difference found between surgical versus conservative care for the studied case could support the inclusion of environmental considerations when allocating patients to either the surgical or conservative pathways. The clinical criteria currently used are patient's age, gender, extent of knee instability, associated lesions, role in professional sports and the desired level of activity after recovery (Diermeier et al., 2021; Jenkins et al., 2022). These results also provide an essential argument for the importance of a careful, evidence-based patient selection for an ACL surgery, aligning with general recommendations such as avoiding the procedure for patients for whom it may offer limited clinical benefits, and prioritizing conservative treatment pathways whenever possible, as emphasized by numerous authors. (Blom et al., 2021; Drew et al., 2021; Lee and Mears, 2012; Pradere et al., 2022; Rizan et al., 2020; Smith et al., 2014). Allocating a patient to undergo a potentially unnecessary surgical ACL surgery might not only alter healthcare cost-effectiveness (Deviandri et al., 2023), but also negatively affect global public health, since numerous evaluated impact categories have links to morbidity, mortality and disease incidence, like climate change, human toxicity, ionising radiation, ozone depletion, as well as particular matter and photochemical oxidant formations (RIVM, 2016).

With this being said, it is however important to remember that this study has been conducted with the fundamental assumption that the evaluated pathways are comparable from a clinical perspective, based on the conclusions of available systematic reviews and meta-analyses (Lien-Iversen et al., 2020; Smith et al., 2014). These two review papers however agree that their findings are based on low-level evidence: only one high quality randomized controlled trial (RCT) has been performed for ACL tears (Frobell et al., 2010), with a five year follow-up (Frobell et al., 2013). Moreover, the included sample population might not be very well representative of all ACL injuries due to the usage of numerous exclusion criteria (Frobell et al., 2013), which makes its results potentially unapplicable to a significant number of patients that can be encountered in clinical settings. Additionally, it must be noted that more than half of participants in this RCT still chose to get the ligament reconstruction later on, with some needing a secondary partial meniscectomy as well. On the other hand, other included studies have mostly been of observational nature, which can suffer from selection bias, since patients with associated ligament, cartilage and/or meniscal injuries are generally initially treated with surgery (Lien-Iversen et al., 2020). Against this background, it must be kept in mind that the understanding of the clinical comparability between the two pathways might still evolve if additional RCTs are conducted.

Regarding ACL surgery alone, results indicate that the primary hotspots of environmental burden are first associated with the manufacturing of single-use products, with cotton-containing single-use items particularly affecting impact categories like agricultural land occupation, ozone depletion and terrestrial ecotoxicity. Then, if everyone involved commutes by car, transportation emerges as the second hotspot of emissions and resource use. However, as commuting becomes more sustainable, HVAC and electricity quickly replace transportation as the second-largest hotspot of environmental burden, mainly because of fossil fuels use, as well as Switzerland's reliance on hydro and nuclear power use which drives other impact categories like water

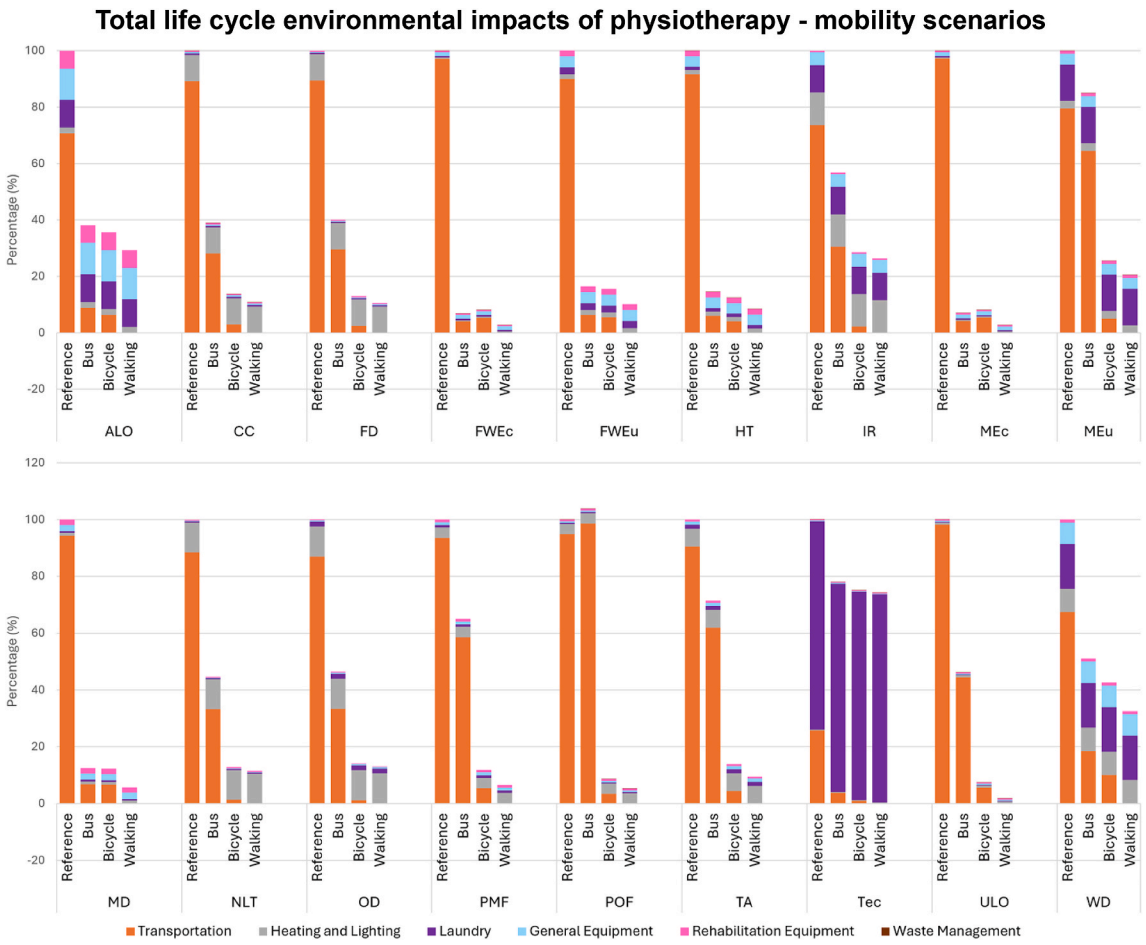

Fig. 8. Relative contributions of activities associated with physiotherapy for each environmental impact category and each mobility scenario. The total relative contributions of the reference scenario are set to 100 % and the other scenarios are displayed in relation to these values. ALO = Agricultural land occupation, CC = Climate change, FD = Fossil depletion, FWEc = Freshwater ecotoxicity, FWEu = Freshwater eutrophication, HT = Human toxicity, IR = Ionising radiation, MEc = Marine ecotoxicity, MEu = Marine eutrophication, MD = Metal depletion, NLT = Natural land transformation, OD = Ozone depletion, PMF = Particulate matter formation, POF = Photochemical oxidant formation, TA = Terrestrial acidification, TEc = Terrestrial ecotoxicity, ULO = Urban land occupation, WD = Water depletion.

depletion and ionising radiation. In the broader European context, HVAC and electricity appear to be the second hotspot of environmental burden, even with car trips, since the European energy mix has a greater dependence on fossil fuels, which negatively affects almost all environmental impact categories, with the exception of ionising radiation and water depletion.

The American study by Silva de Souza Lima Cano et al. (2025) also identified single-use products as being the top hotspot of environmental burden, followed by HVAC; their study setting did not include transportation of patient and staff. Since the French study presented their results in terms of environmental impacts associated with either graft preparation, fixation or lateral extra-articular procedures (Karam et al., 2024), a comparison with present findings proves impractical.

This hotspot ranking identified here differs from what had been described in other types of surgeries in the review by Drew et al. (2021), which generally shows HVAC as the first hotspot of environmental burden, the use of anaesthetic gases as the second and single-use products as the third. This difference can first be explained by the electricity mix used in the HUG, significantly relying on hydropower for electricity production, which is less carbon intensive than some other sources commonly used in the United States, United Kingdom or Australia, where the majority of surgery LCAs have been previously performed (Drew et al., 2021; IEA, 2023). Secondly, the relatively low share of emissions that can be attributed to pharmaceuticals (and anaesthetic gases in particular) in this study's results can be explained by the HUG's decision to completely phase out desflurane use in the beginning of 2023 (personal communication, HUG staff, March 2023). Desflurane's global warming potential is almost 20 times larger than that of sevoflurane (Sulbaek Andersen et al., 2012). Both of these differences can also explain why transportation contributes a higher share of environmental impacts in the Swiss and European contexts than the 10 % according to (Morris et al., 2013). All other categories (waste management, laundry, sterilisation, medical equipment and devices) were found to have minimal environmental impacts, as in previous studies (Drew et al., 2021; Silva de Souza Lima Cano et al., 2025). However, it is important to keep in mind that the overall comparison potential between these studies is limited, since they differ in terms of system boundaries and impact categories included in the assessment.

These findings call for a specific set of recommendations that align with existing literature: investing in reusable equipment, replacing cotton with other types of textiles, streamlining surgical instrument trays (providing rationalised trays with the necessary equipment only), continuing fossil fuel phase-out and opting for occupancy-based HVAC (Drew et al., 2021; MacNeill et al., 2017; Perry et al., 2022; Pradere et al., 2022; Rizan and Bhutta, 2021; Silva de Souza Lima Cano et al., 2025). The HUG have already been implementing strategies to discourage the use of individual motorised transport, and promoting alternatives (HUG, 2022).

Regarding physiotherapy, results indicate that a large share of environmental impacts can be attributed to transportation (up to an

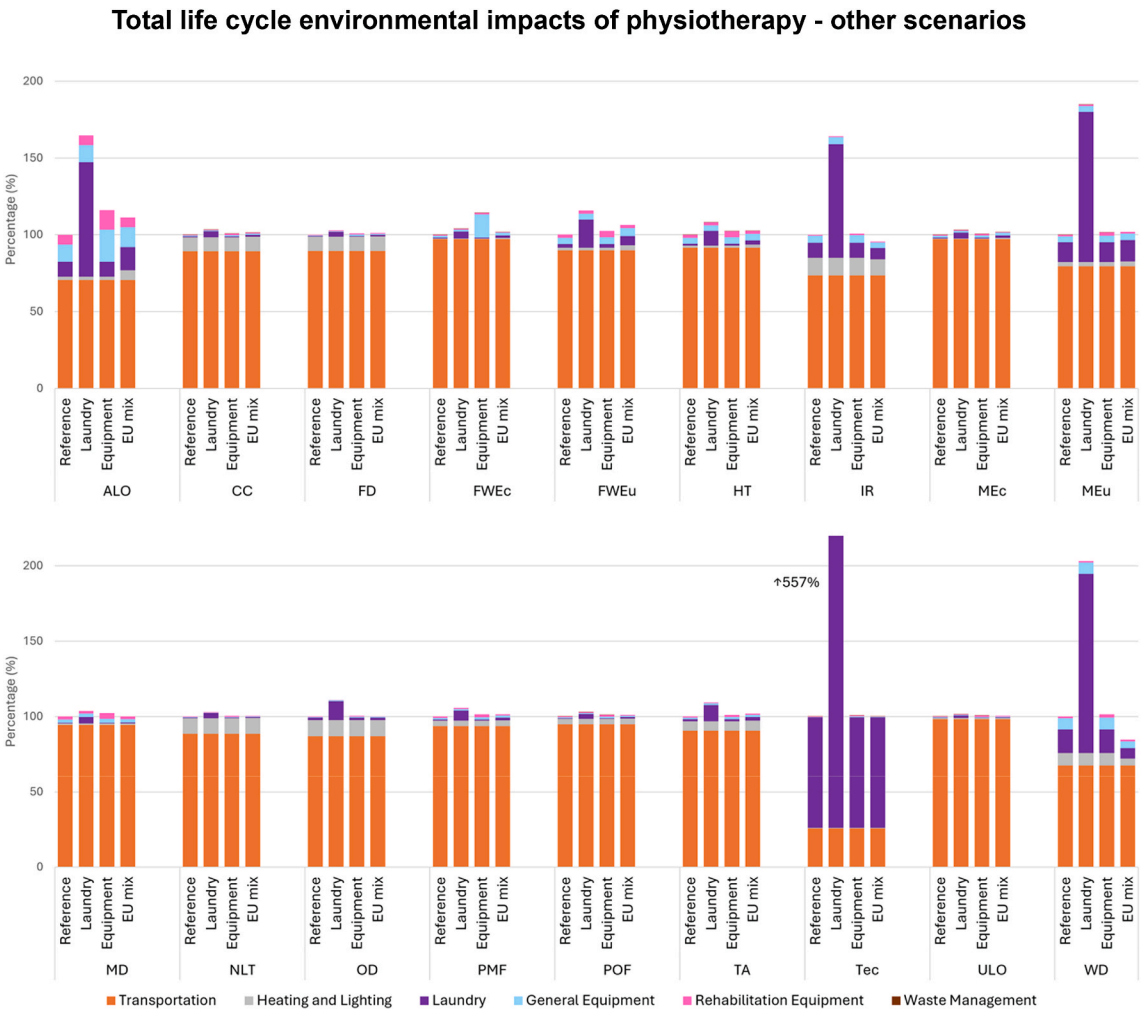

Fig. 9. Relative contributions of activities associated with physiotherapy for each environmental impact category and other modelled scenarios (laundry, equipment and electricity mix variations). The total relative contributions of the reference scenario are set to 100 % and the other scenarios are displayed in relation to these values. ALO = Agricultural land occupation, CC = Climate change, FD = Fossil depletion, FWEc = Freshwater ecotoxicity, FWEu = Freshwater eutrophication, HT = Human toxicity, IR = Ionising radiation, MEc = Marine ecotoxicity, MEu = Marine eutrophication, MD = Metal depletion, NLT = Natural land transformation, OD = Ozone depletion, PMF = Particulate matter formation, POF = Photochemical oxidant formation, TA = Terrestrial acidification, TEc = Terrestrial ecotoxicity, ULO = Urban land occupation, WD = Water depletion.

average of 84 %), be it in the Swiss or European context. Total environmental burden turned out to be particularly sensitive to modal choice, since they appear to drop quickly with transportation becoming more sustainable, and space heating taking over the biggest share of impacts as soon as patients and staff travel by bicycle or by foot. LCIA also revealed that towel washing and drying can be an important source of environmental burden as well, especially in the case of frequent laundry (one towel per session), where it accounts for up to 21 % of impacts, even in the case of transportation by car. General and rehabilitation equipment usually have smaller overall contributions; the contribution of waste management is minimal.

Since this study seems to be the first LCA of paramedical consultations, the possibility of comparison with other findings is limited. However, a carbon footprint of primary (first contact) medical care practices in Switzerland by Nicolet et al. (2022) also found that staff and patient transportation have the largest share of GHG emissions, followed by space heating.

The hotspots of environmental burden established here support some recommendations already described in the literature (Bruyneel, 2020; Ferchichi et al., 2021; Palstam et al., 2022). First, encouraging, whenever possible, soft mobility among patients and staff can be particularly relevant in light of present results, since such an initiative can avoid substantial environmental impacts related to physiotherapy. However, as mentioned before, after an ACL injury the patient can only safely be recommended to cycle after some degree of recovery, and the possibility of walking depends highly on proximity between the patient's home and the physiotherapy clinic. Secondly, promoting early patient's self-management might also reduce the number of physiotherapy sessions needed to complete rehabilitation, which could also be enhanced by therapeutic education, as well as online sessions (Dunphy et al., 2017). The total number of appointments might also be reduced by fostering evidence-based practice among physiotherapists, as well as regular progress assessments (Coppens et al., 2018), since only 54 % of physiotherapists seem to follow evidence-based guidelines when managing musculoskeletal conditions (Zadro et al., 2019). This reduction is particularly important in the SP, where physiotherapy accounts for more than half of the environmental impact in 12 out of 18 impact categories. Finally, the risk of secondary injuries should be prevented by assessing the patient's psychological readiness to return to sporting activities (Coppens et al., 2018).

This study's findings also moderate the relevance of recommendations to promote group physiotherapy sessions for environmental reasons (Ferchichi et al., 2021), since this might have a marginal effect only if patients travel with individualised motorised transport. At last, it

could be recommended to avoid frequent laundry and even ask the patients to bring one of their own towels to rehabilitative sessions, as some physiotherapists already do (personal communication physiotherapists, December 2022–January 2023).

While this study provides novel insights into the environmental impacts of surgical versus conservative ACL care pathways, several limitations should be noted. Data was collected within one hospital and involved two physiotherapists, which may limit the generalizability of findings to other healthcare settings or regions. These methodological choices were made based on practical constraints, such as data availability and resource limitations, and reflect the exploratory nature of this environmental assessment.

However, the dominant environmental impacts associated with physiotherapy, namely transportation, heating, and laundry, are common elements across most clinics providing musculoskeletal physiotherapy services. This suggests that, at least within this clinical domain, the results may reasonably reflect broader physiotherapy practices. Furthermore, a sensitivity analysis using the European energy mix confirmed that the conservative pathway remains substantially more environmentally favourable, indicating some applicability beyond the Swiss context. Nonetheless, variations in healthcare infrastructure and practices, patient behaviour, and regional factors could influence outcomes in other settings.

Certain data inputs relied on assumptions due to limited availability of detailed information. For instance, direct communication with manufacturers about single-use items and medical equipment was largely unsuccessful, leading to the use of proxy data or literature estimates, although some of the assumptions were made based on input from hospital personnel familiar with these items.

Future studies could improve the robustness of this assessment by expanding data collection to multiple hospitals, including a larger sample of physiotherapists, collaborating with medical equipment manufacturers, and collecting real-world data on patient behaviour. Since results have been shown to be particularly sensitive to transportation modes, using data specific to healthcare settings can be a very relevant addition. Moreover, this data collection on patient and staff travel behaviour, with distances travelled and transportation methods chosen (which can evolve as rehabilitation progresses) would enable the development of representative probability distributions. This, in turn, could support the use of Monte Carlo simulations to model variability and uncertainty in a statistically robust manner.

Although sensitivity analyses showed that variations in equipment lifespan and session frequency had minimal impact on overall results, refining these parameters could still provide incremental improvements. Including additional elements such as pre- and post-operative consultations, hospital stay, and diagnostic imaging in the surgical pathway could offer a more comprehensive assessment, though these are unlikely to alter the main conclusions and might further increase the relative environmental burden of surgical care.

Finally, expanding environmental evaluations to other musculoskeletal conditions and conducting more high-quality clinical trials comparing surgical and conservative outcomes would help contextualize and validate the findings of this study.

5. Conclusion

In the case of an anterior cruciate ligament (ACL) injury, the large difference found between the surgical and conservative pathways could support the inclusion of environmental considerations when allocating patients. These results also provide an essential argument for the importance of a careful, evidence-based patient selection for an ACL surgery, aligning with general recommendations such as avoiding the procedure for patients for whom it may offer limited clinical benefits, and prioritizing conservative treatment pathways whenever possible, as emphasized by numerous authors. Allocating a patient to undergo a potentially unnecessary surgical ACL surgery might negatively affect global public health in terms of morbidity, mortality, and disease incidence through the additional environmental burden it generates.

For patients that still need to be undergo an ACL surgery, recommendations to reduce its environmental impacts should prioritise investing in reusable equipment, streamlining surgical instrument trays, and opting for occupancy-based HVAC. To reduce the environmental impacts originating from physiotherapy, recommendations should first encourage soft mobility, when possible, as well as patient's self-management and compliance of physiotherapists with evidence-based guidelines for ACL injury management. Reducing the frequency of laundry in physiotherapy clinics can also be relevant. Overall, the magnitude of the difference found between surgical versus conservative care for the studied case indicates a need and the potential value of conducting more comparative studies of this type for different types of frequently occurring pathologies.

CRediT authorship contribution statement

Polina Boiko: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Anne-Violette Bruyneel:** Writing – review & editing, Validation, Supervision, Methodology. **Nicolas Ray:** Writing – review & editing, Validation, Supervision, Methodology. **Philippe M. Tscholl:** Writing – review & editing, Resources. **Martin K. Patel:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study would not have been possible without the tremendous help of numerous colleagues from HUG as well as the physiotherapists that accepted to help us gather all the necessary data.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

During the preparation of this work the authors used ChatGPT in order to improve the readability and clarity of some sentences. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.147136.

Data availability

All data has been made available in the appendix.

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