



Functional impairment of knee muscles after walking with backpack load: a systematic review

review paper

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ABSTRACT

To review the available literature on the acute and temporal effects of backpack load carriage on knee muscle force production post-walking. Data sources: The databases were PubMed, Lens, ScienceDirect, Scopus, BVS, and EBSCO. Study selection: The eligibility criteria were: sample aged between 18 and 45 years old, backpack load carriage walking, knee flexor and/or extensor muscle strength measurement comparing post-walking with pre-walking or with no-load walking; articles that reported at least one acute response, and/or temporal response; randomised controlled trials and prospective cohort studies that have a longitudinal design that compared two or more groups, or one group with a test and re-test output described and written in English. This systematic review was conducted in accordance with the PRISMA 2020 Statement. We used the Joanna Briggs Institute Critical review tool for randomised controlled trials and prospective cohorts to assess the methodological quality of the studies. A total of 1004 records were screened, and five studies were included in the review. Data extraction: Participant details, study design, load carriage system, load carriage conditions, walking conditions, and method and instrument used to measure strength. Conclusions: The acute and temporal neuromuscular impairments are load-dependent and are independent of the intervention performed. Acute impairments seem to occur due to a decreased ability to modulate motor output rapidly and accurately, and temporal impairment by eccentric motor activity increased by the external load. Carbohydrate or whey protein accelerates the recovery of neuromuscular function after prolonged load carriage occurs in isometric strength, but not in isokinetic strength.

Key words: walking, muscle strength, load carriage, backpack, knee muscles, muscle impairment

Introduction

Backpacking is the most prevalent method of load carriage (LC) [1]. In many professional environments, the ability to carry loads is a fundamental requirement.

The addition of a load during walking requires changes in the movement pattern [2] and alters the spatiotemporal, kinetic, and muscle activity parameters of the quadriceps and hamstrings [3]. For example, it has been shown that external LC with at least 30% of body weight increases joint moments in the lower extremities [4, 5]. On the other hand, in loads less than 15 kg, only the knee extensor moment in-

creases, clearly indicating that the knee seems to be the most sensitive lower extremity joint to external loads [4]. In addition, LC generates an increase in the peak impact force on the ground [6], leading to a decrease in the inhibited energy in the kinetic chain and the ability to dissipate forces [7]. The consequences of this are increased energy expenditure and muscle fatigue due to the increased activity demand of the locomotor and antigravity muscles [8], affecting the ability of the musculoskeletal system to attenuate and dissipate the reaction forces arising from the impact with the ground [7, 9–11].

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When associated with LC the trunk and lower extremities are the regions subjected to a significant amount of mechanical stress [12, 13]. The development of fatigue is mediated by a number of intrinsic and extrinsic factors [14]. Muscle fatigue decreases the ability of muscles to complete a task over time with a constant load and is generally of short duration and reversible. Its main causes are related to overuse, deconditioning, or injury [15] and have been studied and discussed using different exercise models, protocols, and assessment methods [16–21]. Considering that muscle fatigue can be characterised as any exercise-induced reduction in the ability of a muscle to generate force or power [22] reliable and valid measures should include the assessment of maximal voluntary contraction force or power, or the force generated by electrical stimulation [21]. In this sense, muscle force production capacity and peak torque are reliable indicators of muscle functionality in healthy individuals and have been considered strong predictors of physical function, reflecting joint integrity and stability [23–27].

In the last decade, several aspects related to the effects of LC tasks, both in civilian and military populations, have been addressed by numerous reviews, such as physical training [28, 29], physiology [30, 31], biomechanics [1, 32–34], injuries [33, 35], and occupational performance [29, 30, 36–40]. However, no review has addressed the acute and temporal effects of backpack LC on the ability to produce force at the knee post-march. Therefore, it is clear that the scientific literature has demonstrated the negative effects of LC on various occupational tasks, as well as demonstrating that the ability to produce force is associated with beneficial effects on performance in carrying out these tasks. Along these lines, understanding the magnitude of the deleterious effects of the LC can add quality to the development of training plans, recovery of neuromuscular function, and mitigation of the negative effects. Therefore, the objective of this study is to review the available literature on the effects of walking with backpack LC on the force production capacity of the knee flexor and extensor muscles.

Material and methods

This research was conducted according to the PRISMA 2020 Statement, recommended to be addressed in a systematic review protocol [41]. The review was registered in PROSPERO – International Prospective Register of System Reviews (CRD42023427799).

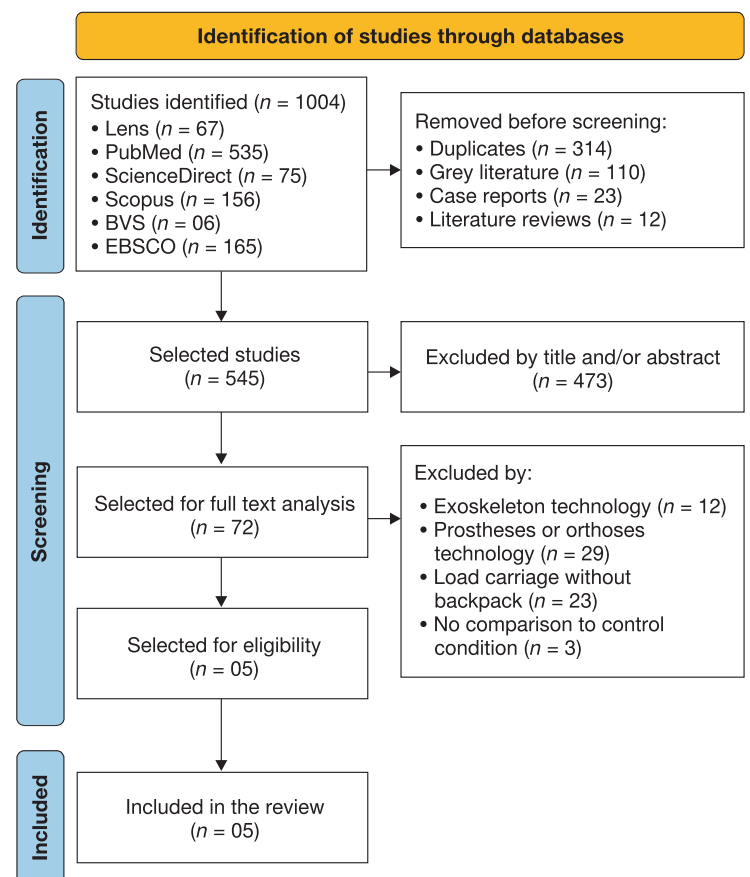
Search strategy

Four searches of the selected databases were carried out, with the first search on August 15, 2022, and the last on January 15, 2023. The following databases were used in this study: PubMed, Lens, ScienceDirect, Scopus, BVS, and EBSCO. The strategic search was developed using the following descriptors and Boolean operators: *(backpack OR rucksack) AND (gait OR walking) AND (muscular OR muscle) AND (recovery OR strength OR impairment OR function) AND (isokinetic OR torque)*.

Preliminary screening

A three-stage review process of the identified records was undertaken. During the three stages, the inclusion criteria, created based on the mnemonic PICOS, and the exclusion criteria for each step, were applied independently to each identified record by three reviewers (Figure 1). Disagreements were discussed among the reviewers to reach a consensus.

Stage 1: The search strategy was applied in databases and identified 1004 eligible studies. After initial



From: Page et al. [41]

Figure 1. Flowchart of the study selection

screening, duplicate articles (314 studies) were removed using the Zotero software (version 6.0.27), as was grey literature (110 studies), case reports (23 studies), and literature review (12 studies). At the end of Stage 1, 545 studies were selected for analysis in stage 2.

Stage 2: After Stage 1, the 545 selected studies had their titles and abstracts reviewed and 473 were excluded, leaving 72 studies for the full-text review.

Stage 3: The 72 studies selected at the end of Stage 2 were subjected to full-text assessment and were selected according to the exclusion and inclusion criteria defined by the PICOS guidelines described below in the study selection. After the full-text assessment, 67 studies were excluded. The reasons were exoskeleton technology (12 studies), prosthetic or orthotic technology (29 studies), load carriage without a backpack (23 studies), and no comparison with the control condition (3 studies). Secondary searches were undertaken on the reference lists of all selected articles to retrieve articles potentially missed during the computerised search. In addition, relevant systematic reviews were examined for potentially relevant studies. Finally, after carrying out the 3 steps, 5 studies were selected for inclusion in the review.

Study selection

Study selection was conducted following the criteria defined in the PICOS (participants, intervention (exposure), comparison, outcome, study design) guidelines: 1. Participants: Study participants were between 18 and 45 years of age; 2. Intervention (exposure): Backpack LC walking over any distance or terrain; 3. Comparison: Knee flexor and/or extensor muscle strength measurement comparing post-walking with pre-walking or with no-load walking; 4. Outcome: Articles that reported at least one acute response (i.e., the immediate response of the torque production capability), and/or temporal response (i.e., the response of the torque production capability over time after exposure) promoted by the backpack LC walking; 5. Study design: Randomised controlled trials and prospective cohort studies that have a longitudinal design that compared two or more groups, or one group with a test and re-test output described. Articles that met the PICOS criteria but met any of the following exclusion criteria were excluded: 1. Language other than English; 2. Studies that used exoskeletons, prostheses, or orthoses; 3. Case reports and literature reviews; 4. Academic grey literature (conference proceedings, research and scientific reports, doctoral dissertations, master's theses, monographs).

Methodological quality assessment and final screening

After applying all inclusion and exclusion criteria, the selected studies were assessed for methodological quality and risk of bias before inclusion in the review using the Joanna Briggs Institute (JBI) Critical appraisal tool for systematic reviews of randomised controlled trials [42] and for prospective cohort studies [43].

Randomised controlled studies were submitted to a tool with 13 items of study quality assessment. The items were scored on a binary scale of points (0 and 1) to determine whether the requirements of the criteria were met: yes meets (1 point); not assessed, does not meet, or is unclear (0 points). The quality of each study was classified as high (≥ 7 points), moderate (4–6 points), or low (≤ 3 points). While prospective cohort studies were submitted to a tool with 11 items and the quality was classified as high (≥ 6 points), moderate (4–5 points), or low (≤ 3 points). Disagreements were discussed to reach a consensus. In the final screening, only studies classified as having high methodological quality were included in this review.

Data extraction

For all included studies, the following data were extracted: participant details, study design, LC system, LC conditions, walking conditions, and method and instrument used to measure force pre- and/or post-walking.

Results

Selection and methodological quality

The search of studies in the databases identified a total of 1004 results, of which 314 studies were duplicates and were removed. Finally, five studies were selected for methodological quality/risk of bias assessment. The flow of screening and selection of articles is presented in the adapted PRISMA study selection flowchart (Figure 1).

During the screening process, the reviewers independently extracted data and assessed the methodological quality of the five selected studies according to JBI assessment tools (Tables 1 and 2). Disagreements were discussed to reach a consensus.

All 5 studies were classified as high-quality methodological studies, considered to have a low risk of bias, and therefore included in the review. The summary of the main results and conclusions extracted are presented in Table 3.

Table 1. Assessment of the quality and risk of biases using the Joanna Briggs Institute tool for randomised controlled trials

Criterion/Article	Blacketer et al. [44]	Blacketer et al. [45]	Blacketer et al. [46]	James et al. [11]
1. Was true randomisation used for the assignment of participants to treatment groups?	1	1	1	1
2. Was allocation to treatment groups concealed?	0	1	0	1
3. Were treatment groups similar at the baseline?	1	1	1	1
4. Were participants blind to the treatment assignment?	0	1	0	0
5. Were those delivering the treatment blind to the treatment assignment?	0	0	0	0
6. Were the outcome assessors blind to the treatment assignment?	0	0	0	0
7. Were the treatment groups treated identically other than regarding the intervention of interest?	1	1	1	1
8. Was follow-up completed and, if not, were differences between groups in terms of their follow up adequately described and analysed?	1	1	1	1
9. Were the participants analysed in the groups to which they were randomised?	1	1	1	1
10. Were the outcomes measured in the same way for the treatment groups?	1	1	1	1
11. Were the outcomes measured in a reliable way?	1	1	1	1
12. Was an appropriate statistical analysis used?	1	1	1	1
13. Was the trial design appropriate, and any deviations from the standard randomised controlled trial design (individual randomisation, parallel groups) accounted for in the conduct and analysis of the trial?	1	1	1	1
TOTAL OF POINTS	9	11	9	10

0 – does not meet the criteria; unclear whether it meets criteria or not evaluated; 1 – yes meets the criteria

Table 2. Assessment of the quality and risk of biases using the Joanna Briggs Institute tool for prospective cohort studies

Criterion\Article	Grenier et al. [47]
1. Were the two groups similar and recruited from the same population?	0
2. Were the exposures measured similarly to assign people to both the exposed and unexposed groups?	0
3. Was the exposure measured in a valid and reliable way?	1
4. Were confounding factors identified?	1
5. Were strategies to deal with confounding factors stated?	0
6. Were the groups/participants free of the outcome at the start of the study (or at the time of exposure)?	1
7. Were the outcomes measured in a valid and reliable way?	1
8. Was the follow-up time reported and sufficient to be long enough for outcomes to occur?	1
9. Was the follow-up complete and, if not, were the reasons for the failure to follow up described and explored?	1
10. Were strategies to address incomplete follow-up utilised?	1
11. Was an appropriate statistical analysis used?	1
TOTAL OF POINTS	8

0 – does not meet the criteria; unclear whether it meets criteria or not evaluated; 1 – yes meets the criteria

Table 3. Data extracted from articles included in the review

Reference	Participants	Study design	Walking conditions	Equipment and load carried	Method of assessing muscle strength	Instrumentation	Results	Conclusion
Blacker et al. [45]	10 civilian men 179.0 ± 5.0 cm 30.0 ± 8.0 years 79.4 ± 8.3 kg 15.1 ± 2.8% body fat	Randomised repeated measures paired pre- and post-walk with two-way crossed	Laboratory ~22°C 2 h at 6.5 km · h ⁻¹ Motorised treadmill D1: level (0%) D2: downhill (-8%) Shorts and underwear	D1 and D2: Backpack: 25 kg	Non-dominant knee • <i>Time point:</i> Pre- and post-walk (0, 24, 48 and 72 h) • <i>Isometry:</i> 3 reps of 3 to 5 s Rest 2 min IMVC Ext 90° • <i>Isokinetics:</i> Flexion and extension Concentric 1 set 5 reps at 60° s ⁻¹ Rest 30 s 1 set 5 reps at 180° s ⁻¹ RM 70° in flexion and 0° in extension	• <i>Isometry:</i> S-beam load cell • <i>Isokinetics:</i> Cibex II	• <i>Isometry:</i> Acute effect: <i>Extensors</i> - There was no main effect for 0% and -8% - 0% and -8%; pre > post <i>Flexors</i> - Not evaluated Temporal effect: <i>Extensors</i> - There was a main effect pre > post - There was no interaction effect between 0% and -8%; - 0% and -8%; pre > post 24 h pre > post 48 h pre = post 72 h <i>Flexors</i> - Not evaluated • <i>Isokinetics:</i> Acute effect: <i>Extensors</i> - 60° s ⁻¹ 0% and -8%; pre > post - 180° s ⁻¹ 0% and -8%; pre > post <i>Flexors</i> - 60° s ⁻¹ 0% and -8%; pre > post - 180° s ⁻¹ 0% and -8%; pre > post Temporal effect: <i>Extensors</i> - There was a main effect at 60° s⁻¹ and 180° s⁻¹ - There was no main effect between 0% and -8% at 60° s ⁻¹ and 180° s ⁻¹ - There was no interaction effect between 0% and -8% at 60° s ⁻¹ and 180° s ⁻¹ ; pre > post 24 h pre = post 48 h pre = post 72 h - 180° s ⁻¹ in 0% and -8%; They suffered no effects <i>Flexors</i> - There was a main effect at 60° s⁻¹ and 180° s⁻¹ There was no main effect for 0% and -8% - 60° s ⁻¹ and 180° s ⁻¹ there was no interaction effect between 0% and -8%; - 60° s ⁻¹ in 0% and -8%; pre > post 24 h pre = post 48 h pre = post 72 h - 180° s ⁻¹ in 0% and -8%; pre > post 24 h pre = post 48 h pre = post 72 h	• Marching with a backpack load on a downhill (-8%) and level (0%) resulted in similar reductions in lower limb muscle force production • The most lasting reduction in force occurs in knee extensor isometrics after marching with a backpack load on a downhill (-8%) and level (0%) • A reduction in muscle function can increase the risk of musculoskeletal injury and can impair performance after marching with a backpack load

Blacker et al. [44]	10 civilian men 182.0 ± 7.0 cm 28.0 ± 9.0 years 81.5 ± 10.5 kg 16.4 ± 3.2% body fat	Randomised repeated measures paired pre- and post-walk with three-way crossed – Protein group – Carbohydrate group – Placebo group	Laboratory ~21°C 2 h at 6.5 km · h ⁻¹ Motorised treadmill level (0%) Shorts and underwear Two-week interval between each experimental day	Backpack: 25 kg	Non-dominant knee • <i>Time point</i> : Pre- and post-walk (0, 24, 48 and 72 h) • <i>Isometry</i> : 3 reps of 3 to 5 s Rest 2 min IMVC Ext 90° • <i>Isokinetics</i> : Flexion and extension Concentric 1 set 5 reps at 60° s ⁻¹ Rest 30 seg 1 set 5 reps at 180° s ⁻¹ Range of Motion Flexion: 70° Extension: 0°	<ul style="list-style-type: none"> • <i>Isometry</i>: S-beam load cell • <i>Isokinetics</i>: Cibex II 	<ul style="list-style-type: none"> • <i>Isometry</i>: Acute effect: Extensors – No difference between Carb-Prot-Pla – Placebo: pre > post – Protein: pre > post – Carbohydrate: pre > post Extensors – Not evaluated Temporal effect: Extensors – There were differences between Carb-Prot-Pla – Placebo: pre > post 24 h pre > post 48 h pre = post 72 h – Protein: pre > post 24 h pre = post 48 h pre = post 72 h – Carbohydrate: pre > post 24 h pre = post 48 h pre = post 72 h • <i>Isokinetics</i>: Acute effect: Extensors – No difference between Carb-Prot-Pla pre > post Extensors – There were differences between Carb-Prot-Pla – 60° s⁻¹ Carb-Prot-Pla: pre > post Extensors – No difference between Carb-Prot-Pla – 60° s⁻¹ Carb-Prot-Pla: pre > post Extensors – No difference between Carb-Prot-Pla – 180° s⁻¹ Carb-Prot-Pla: pre > post Temporal effect: Extensors – No difference between Carb-Prot-Pla – 60° s⁻¹ Carb-Prot-Pla: pre > post 24 h pre > post 48 h pre = post 72 h – 180° s⁻¹ Carb-Prot-Pla No effects. Extensors – 60° s⁻¹ no difference between Carb-Prot-Pla – 60° s⁻¹ unchanged over time – 60° s⁻¹ Carb-Prot-Pla: pre > post 24 h pre > post 48 h pre = post 72 h – 180° s⁻¹ Carb-Prot-Pla No effect 	<ul style="list-style-type: none"> • Prolonged LC reduced knee isometric and isokinetic peak torque independently of the supplement consumed • Protein and carbohydrate supplementation accelerated isometric extensor peak torque recovery compared to placebo • The pattern of isokinetic peak torque recovery did not differ between supplemented and placebo groups
Grenier et al. [47]	10 recently retired male military personnel (7 from the French Foreign Legion) 38.9 ± 8.9 years 82.9 ± 9.3 kg 177.0 ± 5.0 cm 19.4 ± 3.1% body fat	Longitudinal study (prospective cohort) with repeated measures paired pre- and post-SMM – Two groups with LC – SMM of 21h – 115 km, ~5.5 km · h ⁻¹ – 15 km, ~5.5 km · h ⁻¹ Combat uniform with rifle	• Laboratory: 3 min at 4 km · h ⁻¹ Motorised treadmill level (0%) • In the field: – 115 km, ~4 km · h ⁻¹ – SMM of 21h – 15 km, ~5.5 km · h ⁻¹ Combat uniform with rifle	• Laboratory: Pre- and post-SMM: NL: sportswear LC: 22.4 ± 1.1 kg LC: 37.9 ± 1.4 kg • In the field: – SMM: – Combat load: 27.4 ± 1.1 kg – March load: 42.9 ± 1.4 kg	Right knee • <i>Time point</i> : Pre- and post-SMM. • <i>Isometry</i> : 3 reps of 5 s Rest 1 min IMVC Ext 90°	<ul style="list-style-type: none"> • <i>Isometry</i>: Strain gauge load cell 	<ul style="list-style-type: none"> • <i>Isometry</i>: Acute effect: Extensors – IMVC decreased in both load groups Extensors – Not evaluated Temporal effect: – Not evaluated 	<ul style="list-style-type: none"> • Extremely long-duration LC induces moderate central and mainly peripheral fatigue in the knee extensors in experienced military personnel

Blacker et al. [46]	10 civilian men 30.0 ± 8.0 years 179.0 ± 5.0 cm 79.4 ± 8.3 kg	Randomised repeated measures paired pre- and post-walk with two-way crossed – LC group: 25 kg – NL group	Laboratory ~21° Celsius 2 h at 6.5 km · h ⁻¹ Motorised treadmill level (0%) Shorts and underwear	D1: NL D2: Backpack 25 kg	Non-dominant knee • <i>Time point</i> : Pre- and post-walk. • <i>Isometry</i> : 1 rep of 3 to 5 s IMVC Ext 90°	• <i>Isometry</i> : S-beam load cell – The interaction effect revealed a change in IMVC between the LC and NL groups. • <i>Isometry</i> : Acute effect: Extensors – NL: pre = post – LC: pre > post Flexors – Not evaluated. Temporal effect: – Not evaluated	• LC on a level gradient caused decreases in the m. quadriceps femoris force-producing capability • Neuromuscular impairment following LC is likely to have a negative impact on performance of strength, endurance and motor control tasks, and may increase the risk of musculoskeletal injury
James et al. [11]	26 men and women • LC group: 10 men and 2 women 22.0 ± 6.0 years 78.3 ± 36.8 kg 179.2 ± 17.9 cm • NL group: 11 men and 3 women 21.0 ± 5.0 years 73.8 ± 34.8 kg 178.0 ± 17.5 cm	Randomised repeated measures pre- and post-walk with two-way crossed – LC group: 32 kg – NL group Tennis, shirt and shorts	Laboratory ~18° Celsius ~50% relative humidity D1 and D2: 2 h at 6.5 km · h ⁻¹ Motorised treadmill level (0%) Tennis, shirt and shorts	Total: 32 kg Webbing: 10 kg Backpack: 15 kg Dummy rifle: 7 kg	Right knee • <i>Time point</i> : D1 (baseline) and D2 Pre- and post-walk D3: only dynamometry • <i>Isometry</i> : 1 set 1 rep IMVC before each Flex/Ext isokinetic series • <i>Isokinetics</i> : Flexion and Extension Concentric 1 set 8 reps at 60°s ⁻¹ Rest 2 min 1 set 8 reps at 180°s ⁻¹ Measurement of torque at internal knee angle from highest recorded. – Flexion: 130° – Extension: 110°	• <i>Isokinetics</i> : Biodex System 3 Pro – The interaction effect revealed a change in all extensor variables (0°s ⁻¹ , 60°s ⁻¹ and 180°s ⁻¹), but not in any flexor variables • <i>Isometry</i> : Acute effect: Extensors – Ext LC: D1pre > D1post – Ext NL: D1pre = D1post Flexors – Flex LC: D1pre = D1post – Flex NL: D1pre = D1post Temporal effect: Extensors – LC: D1pre > D2pre – LC: D1pre > D2post – LC: D1pre > D3 – LC: D2pre > D2post Flexors – NL: No effects were observed in any variable – NL and LC: No effects were observed in any variable • <i>Isokinetics</i> : Acute effect: Extensors – LC 60°s ⁻¹ and 180°s ⁻¹ : D1pre > D1post Flexors – NL: No effects were observed in any variable – NL and LC: No effects were observed in any variable Temporal effect: Extensors – LC 60°s ⁻¹ : D1pre > D2pre – LC 60°s ⁻¹ : D1pre > D2post – LC 60°s ⁻¹ : D2pre = D2post – LC 60°s ⁻¹ : D1pre = D3 – LC 180°s ⁻¹ : D1pre = D2pre – LC 180°s ⁻¹ : D1pre > D2post – LC 180°s ⁻¹ : D2pre > D2post – LC 180°s ⁻¹ : D1pre > D3 Flexors – NL: No effects were observed in any variable – NL and LC: No effects were observed in any variable	• It suggests that limiting the loss of strength in the knee extensors will increase the ability to maintain LC performance • It suggests that extensor fatigue may alter gait due to reduced ability to mitigate the effects of load

IMVC – isometric maximal voluntary contraction, RM – range of motion, SMM – simulated military mission, Rep – repetition, NL – no load in the backpack, LC – with load in the backpack, Pla – placebo, Pro – protein, Car – carbohydrate, D1, D2 and D3 – assessment days, Pre – before the march, Post – after the march

Results column: bold text identifies significant statistical differences

Characteristics of experimental designs

All 5 studies selected [11, 44–47] for analysis in this review had a randomised experimental design with repeated measures, with four studies [44–47] using paired samples and one study [11] using an unpaired sample, performed pre- and post-walking with and without LC in a backpack.

Characteristics of the samples

The studies included 66 participants (61 men and 5 women), 56 were civilians with experience carrying load in a backpack [11, 44–46] and 10 military personnel [47] 7 of whom were from the French Foreign Legion, with extensive military experience in LC. The sample used presented the following characterisation data: age 21 ± 5.0 to 38.9 ± 8.9 years, height: 177.0 ± 5.0 to 182.0 ± 7.0 cm, body weight: 73.8 ± 34.8 to 82.9 ± 9.3 kg, body fat percentage: 15.1 ± 2.8 to $19.4 \pm 3.1\%$.

Methods for assessing strength

Knee muscle strength was assessed using isometry [11, 44–47] and isokinetics [11, 44, 45] pre- and post-walking. All 5 studies [11, 44–47] performed acute (i.e. immediately post-walking) measurements and 3 studies [11, 44, 45] performed temporal measurements after walking (24, 48, and 72 h) [44, 45] or for 3 consecutive days [11].

Muscle group assessment

In isometry, all 5 studies [11, 44–47] assessed the knee extensor muscles, and only one study [11] assessed the knee flexors. In isokinetics, 3 studies [11, 44, 45] assessed concentric strength in knee flexion and extension movements at speeds of 60°s^{-1} and 180°s^{-1} .

Speed, load, and walking characteristics

Laboratory experiments with motorised treadmill walking were used by all 5 studies [11, 44–47]. In 4 studies [11, 44–46], the protocol prescribed walking at 6.5 km/h for 2 h. Only in 1 study [47], the protocol prescribed was laboratory walking at 4 km/h for 3 minutes, performed pre and post a simulated military mission (SMM) on appropriate terrain. During the SMM activities, the following were performed: a 15 km march on uphill terrain (~ 4 km/h), a reconditioning period, a displacement through an enemy forest, two sleep pe-

riods, three patrol and reconnaissance periods, a period for the installation of an advanced military base, and a 15 km march on downhill terrain (~ 5.5 km/h). The total duration of the SMM was 21 hours. The treadmill was levelled with gradients (0%) [11, 44–47] and gradients (-8%) [45]. The load carried in the backpack during laboratory [11, 44–46] walks ranged from 22.4 to 37.9, and on the terrain [47], it ranged from 27.4 to 42.9 kg.

Effect on force production

Methodological and sampling characteristics determined specific results for each study. However, overall, all studies [11, 44–47] demonstrated an acute and temporal effect of reducing the ability to produce force in the knee flexors, but mainly in the extensors, which can last up to 72 h after the LC march activity when compared to pre-walking values (Baseline). The results on the effect of walking with and without load on the ability to produce isometric and isokinetic force are presented in Table 3.

Associated measures

The experimental protocol included additional tests beyond the evaluation of strength, such as, voluntary activation after isometric maximal voluntary contraction, electrical stimulation, and isokinetics of the shoulder and trunk [44–46], metabolic analysis using gas exchange [11], electromyographic behaviour, electrical neural stimulation, and central fatigue by the central interpolation method [47].

Discussion

This systematic review aimed to synthesise the existing knowledge in the available literature, rather than create knowledge about the effects of backpack-loaded walking on the ability to produce force in knee flexion and extension and on the recovery time required to restore neuromuscular function. The results demonstrated by our review indicate that the harmful acute and temporal effects on the neuromuscular function are load-dependent and seem to occur by essentially eccentric motor activity performed during the walk. On the other hand, carbohydrate or whey protein supplementation accelerates the recovery of neuromuscular function.

This review did not consider the events that affect excitation-contraction coupling, central fatigue, energy supply, and multifactorial modulation. These factors

affect the fatigue process and can lead to serious limitations in muscle performance. Therefore, it is important to clarify that during this review, the term fatigue will be used to define any exercise-induced reduction in the ability of a muscle to generate force or power [22], i.e., the impairment of the neuromuscular function.

Regarding the walking protocols used, different combinations of variables were found, such as environment (indoor and outdoor), terrain type (treadmill and road), walking time (2 and 21 hours), treadmill incline (0 and -8%), carried load (0 to ~43 kg), and walking speed (~4 to 6.5 km/h). Similarly, the protocols for evaluating the ability to produce force in the knee joint muscles presented different combinations in the muscle group evaluated (flexion and/or extension), instrument used (load cell and/or isokinetic), type of muscle contraction (isometric and/or concentric isokinetic), and evaluation period after walking (0 to 72 h).

Regardless of the different specific sampling and methodological characteristics used in each of the reviewed studies [11, 44–47], the impairment of the neuromuscular function that activates the knee after a backpack-loaded walking activity is evident and unanimous. This suggests that the backpack-loaded walking activity had a significant main (intragroup) acute and temporal effect and, in some cases, an interaction (intergroup) effect on neuromuscular function at the knee joint, mainly in the extensor muscles, despite the mechanical differences generated by the different load-carrying strategies, treadmill incline, speed and walking time, as well as the instrumentation used in the evaluation protocols. Furthermore, it is important to highlight that the type of muscular contraction performed in the evaluation will determine the level of strength reduction which, generally, seems to be lower in concentric than in isometric contractions [48]. This probably occurs due to different physiological mechanisms of fatigue in isometric and dynamic contractions. Therefore, this means that isometric assessment of fatigue cannot be replaced by dynamic assessment and vice versa, i.e., the results from isometric function cannot be used to estimate dynamic function and vice versa [49]. These sampling and methodological differences, as well as the number of studies (5 studies) that met the inclusion criteria of this review, indicate a clear need for the subject to be further explored in future research.

Acute effect on neuromuscular function

All 5 studies reviewed [11, 44–47] reported that adding load to a backpack during treadmill walking had a significant acute effect of decreasing the ability

to produce isometric extensor and isokinetic torque, mainly extensor but also flexor, immediately after the activity when compared to pre-walking values (baseline). This can be explained by the combination of fatigue and structural damage that has been shown following several types of prolonged exercise and is expressed in the reduction in the capacity to produce muscular force, i.e., acute neuromuscular impairment [48]. After prolonged LC, it is likely that the fatigue and mechanical damage to muscle tissue occur due to the greater effort in the lower limbs [50], for example, the greater force absorbed during the eccentric component of the stretch-shortening cycle of the quadriceps femoris muscle during the walk leads to the neuromuscular impairment [46]. On the other hand, some specific results were reported due to the methodological particularities of each study reviewed. Another aspect to highlight is that unloaded walking did not cause acute reductions in flexor and extensor muscle function in any of the studies [11, 46] regardless of the strength measurement method used.

Acute effect on isometric force

The isometric flexor force did not show an interaction effect immediately after the 2-hour marches at 6.5 km/h without and with an external load (belt: 10 kg, backpack: 15 kg, and fake rifle: 7 kg), totalling 32 kg [11]. This suggests that the walking and load conditions generated an insufficient stimulus to cause a reduction in flexor muscle function. These findings were surprising since the backpack load carrying system positions the carried mass on the back, which generates an anterior tilt of the trunk, imposing greater stress on muscle groups that are not accustomed to the work required during a walk [51]. Specifically, in these circumstances, there is a need to increase the eccentric activation of the knee flexors to maintain the position of the pelvis and resist the forward tilt. This mechanism is widely accepted as an acute effect of LC [51, 52], since it requires greater muscle effort to control the load and maintain stability [53–55].

During three consecutive days (D1, D2 and D3) of the force assessment, an interaction effect was demonstrated in the isometric extensor force [11]. In the comparisons with load from D1pre-walk (baseline) with D1post-walk and from D2pre-walk (baseline) with D2post-walk, a significant acute effect of the reduction of extensor force was demonstrated on both days of approximately 20%. Similar results were demonstrated after carrying a 25 kg backpack for 2 h at 6.5 km/h downhill [45] and level [45], with supplementation

[44] (placebo: $14 \pm 7\%$; carbohydrate: $12 \pm 10\%$; and protein: $14 \pm 8\%$) and after a 24-hour SMM [47]. Recent findings [46] demonstrate that there is an interaction effect between the load-carrying and non-load-carrying groups. After a walking protocol similar to previous studies [11, 44, 45], isometric knee extension strength (flexion was not assessed in isometrics) had a significant reduction effect ($15 \pm 11\%$) compared to pre-walk values but did not have an acute effect immediately after non-load walking.

Of the 5 studies [11, 44–47] selected, the study by Grenier et al. [47] used a complex protocol with a total duration of 24 h. We believe that the isometric strength data pre- and post-SMM obtained by Grenier et al. [47] in laboratory trials are not able to establish a cause-and-effect relationship between walking with backpack LC and the ability to produce isometric force at the knee. The reason for this is that the variety of combat activities performed, LC systems used, and mainly the food and recovery periods made available to the troop during the SMM likely introduced biases that make it impossible for the authors to conclude that the acute reduction in the isometric force is caused by LC marching. Another potential limitation of this study [47] which was recognised by the authors, was the delay between the end of the SMM and the start of the laboratory trials, which may have allowed neuromuscular recovery. On the other hand, the goal of the study was to investigate the combined effects of LC on extensor neuromuscular function after an SMM containing various combat situations. Thus, considering the SMM as a single intervention, the results obtained in the study [47], indicate a significant reduction effect ($10.2 \pm 3.6\%$) in the ability to produce isometric extensor force when comparing pre- and post-SMM with load values, results that are consistent with the findings of the other studies [11, 44–46] included in this review.

The results obtained [11, 44–47] were in line with the expectations, considering that the knee muscles increase extensor moments during LC to control the increase in ankle and knee joint flexion [56, 57] and resist the effects of the additional load in the initial support before the ankle muscles respond [4]. This suggests that the knee extensor muscles assume a greater proportion of the load carried than the other muscles of the lower limbs. These mechanical changes in gait, triggered by LC, require increased muscle forces to mitigate the deleterious effects [50]. Emphasising the important role of the quadriceps muscle during backpack carrying, it has been shown that during this task, the amplitude of the electromyographic signal of this muscle is increased [1].

Acute effect on isokinetic torque

The results of isokinetic assessments of knee extension at a speed of 60°s^{-1} showed a significant acute effect of reduced force-producing capacity after carrying a 25 kg backpack for 2 hours at 6.5 km/h on a downhill [45] and level [45, 46], with supplementation [44], and after a 24-hour SMM [47]. In contrast, immediately after unloaded walking, the force-producing capacity did not decrease [11]. At a speed of 180°s^{-1} , knee extension function showed a significant acute effect of reduced force-producing capacity after carrying a 25 kg backpack for 2 hours at 6.5 km/h on a downhill [45] and level [45, 46] and after a 24-hour SMM [47]. However, after carrying a 25 kg backpack for 2 hours at 6.5 km/h, individuals who received protein and carbohydrate supplementation, as well as the placebo, did not show a reduction in muscle function [44]. However, at both speeds (60°s^{-1} and 180°s^{-1}) the study by Blacker et al. [45] did not confirm the authors' hypothesis that walking with a load on a downhill (-8%) would cause greater impairment of neuromuscular function immediately after walking compared to walking with a load on a level surface (0%). The findings of the five studies [11, 44–47] included in this review, which demonstrated very similar reductions in the ability to produce force immediately after carrying a backpack load, can be explained by the fact that when walking while carrying an additional external load, the amount of force that the lower limb muscles involved in load acceptance during the stance phase can produce is significantly increased [55, 56, 58–60]. Due to this increased muscle activity, several biomechanical changes are triggered, such as walking speed [61, 62], stride length [59], and joint range of motion [56, 63]. Therefore, the important role in attenuating the loads applied to the skeletal system carried out by lower extremity muscles can be compromised, and if a process of muscular fatigue sets in, the force-producing capacity and the ability to attenuate the impact of ground reaction forces may be compromised [9, 64, 65]. These changes have been commonly reported in military and civilian populations, are systemic and are triggered by the aggregated inertia of external loads, most commonly carried on the trunk [1, 34, 50].

Based on these findings, it seems reasonable to state that the reduction in the ability to produce force is load-dependent, resulting from the mechanical demands and specific motor control of the backpack LC task, associated with the ability to adjust to the disturbance caused by the external load carried and the ability to mitigate its deleterious effects.

Temporal effect on neuromuscular function

The studies [11,44,45] included in this review that evaluated the temporal effects of backpack LC on force production clearly demonstrate a long-lasting deleterious main effect on muscle function that can last for more than 72 h. This effect is load-dependent and has been shown to be independent of the intervention performed. This lasting muscular impairment was expected, since the walking activity involves not only the quadriceps muscle but also possibly the fatigue of various lower limb and hip muscles associated with eccentric components. It is likely that this possible fatigue of the lower limb as a whole when walking with load may explain the long-lasting temporal effects on the reduction of flexor and extensor strength demonstrated in this review.

Reinforcing this idea, it has already been shown that carrying loads between 10 and 37 kg increases lower limb muscle activity [56, 58, 59, 66], indicating that even with lighter loads, there is additional muscle activity. This increase in muscle activity required during LC results in greater fatigue [58]. Besides that, during LC walking, the greater muscle effort to control the external load [53–55] acutely increases the eccentric activation of the knee muscles [51, 52]. Like this, one of the effects of repeated eccentric exercise is an acute loss of strength, i.e. during exercise. But this muscular impairment might persist for many days after the effort [67, 68] and may impair the ability to maximally generate muscle force and power [21, 69]. These results are corroborated by studies [48, 70] that demonstrated the long-lasting effects of fatigue and the potential for muscle damage after prolonged exercise, especially after eccentric contractions.

Temporal effect on isometric force

Supplementation with carbohydrates and proteins accelerated the recovery of isometric extensor strength after walking on a motorised treadmill with a 25 kg backpack for 2 hours at 6.5 km/h, reestablishing pre-walking values after 48 hours, while the placebo group returned to pre-walking values at 72 hours [44]. These results demonstrate that both supplementation strategies (carbohydrate and protein) used had a clear beneficial effect, possibly exerting a modulatory role on fatigue induced by LC, accelerating the recovery of the capacity to produce extensor force. These findings reinforce Beelen et al. [71], who state that during post-exercise recovery, optimal nutritional intake is important to replenish endogenous substrate stores and

facilitate muscle damage repair and remodelling. However, it is important to note that differences such as exercise duration, the nature of the assessment, and the amount of ergogenic resources supplemented may explain the differences between the results of the studies conducted [72]. Because it is not part of the objectives of this review, the supplementation strategy used by Blacker et al. [44] will not be discussed. After performing downhill [45] and level [45] marches carrying a 25 kg backpack for 2 hours at 6.5 km/h, the extensor force remained reduced for 48 h, returning to pre-walking values at 72 h in both conditions.

In 3 consecutive days of strength assessment, two of which performed a load-carriage walking protocol similar to the studies by Blacker et al. [44–46], James et al. [11] demonstrated that isometric knee extension showed a significant reduction on D1post-walk, D2pre-walk, D2post-walk, and D3 compared to D1pre-walk, not returning to baseline values (D1pre-walk). On D3, only strength assessments were performed. After the non-load march, the knee extensor force remained unchanged throughout the timeline. These deleterious effects on extensor muscle function demonstrated by James et al. [11] were more prolonged than the effects found by Blacker et al. [44, 45] after an identical walking protocol: 2 hours of walking at 6.5 km/h. This was probably due to accumulated fatigue induced by the stimulus level generated by the two consecutive days of walking performed in James et al.'s [11] study. Additionally, the configuration and magnitude of the load carried in James et al.'s [11] study was 7 kg greater, totalling 32 kg. James et al.'s [11] study was the only one to evaluate the temporal effects on the ability to produce isometric force in knee flexion and demonstrated that marches with and without LC did not have an effect on muscle function.

Temporal effect on isokinetic force

Blacker et al. [45] found a main temporal effect (pre-walk vs. post 0, 24, 48, and 72 h) for extensor and flexor torque at speeds of 60°s^{-1} and 180°s^{-1} . On the other hand, there was no main effect and no interaction between conditions (0% vs. –8%) for extensor and flexor torque at speeds of 60°s^{-1} and 180°s^{-1} . At a speed of 60°s^{-1} , the ability to produce flexor and extensor torque remained reduced for 24 h, returning to pre-walking values at 48 h after walking in both level and downhill conditions (0% and –8%). At a speed of 180°s^{-1} , only the ability to produce extensor torque remained reduced for 24 h, returning to pre-walking values at 48 h after walking in both level and downhill condi-

tions (0% and -8%). The extension movement recovered neuromuscular function 24 h after the acute reduction, therefore demonstrating that it does not suffer from the temporal effects of LC. In the study by Blacker et al. [44], individuals supplemented with placebo, protein, and carbohydrate remained for 48 h after LC, showing a reduction in the production of isokinetic flexor and extensor torque at a speed of 60°s^{-1} , returning to baseline values at 72 h. At a speed of 180°s^{-1} , there was no reduction in the production of flexor and extensor torque. These results suggest that the intake of protein and carbohydrates does not accelerate the recovery of isokinetic strength, as it does isometric strength. For isokinetic assessment, the speeds used should consider the demands of the activity. For the adequate study of peak torque and work, the literature indicates a slow angular velocity ($< 180^{\circ}\text{s}^{-1}$), with 60°s^{-1} being the most commonly used. Therefore, the lower the angular velocity, the greater the torque or work. Intermediate (180°s^{-1}) and fast ($> 180^{\circ}\text{s}^{-1}$) speeds are more suitable for power measurements, where angular velocity is directly proportional to power. The fact that torque values are speed-dependent may explain the effects demonstrated by Blacker et al. [44, 45] only at a speed of 60°s^{-1} , as well as the subtle changes demonstrated at a speed of 180°s^{-1} in all 5 studies included in this review.

When evaluating isokinetic strength for 3 consecutive days [11], an interaction effect was demonstrated for all extensor isokinetic variables at speeds of 60°s^{-1} and 180°s^{-1} and no effect for flexor variables. At a speed of 60°s^{-1} , significant reductions in knee extensor torque after LC were demonstrated in comparisons of D2pre-walk and D2post-walk vs D1pre-walk (baseline), returning to baseline values on D3. At a speed of 180°s^{-1} , significant reductions in knee extensor torque after LC were demonstrated in comparisons of D2post-walk and D3 vs D1pre-walk (baseline). At both speeds, the extensor torque was reduced in the comparison D2pre-walk vs D2post-walk in LC activities. These results suggest a high quadriceps activity demand with significant long-lasting deleterious effects on muscle function. It has been shown that quadriceps muscle fatigue affects gait mechanics, regardless of the level of physical activity and the type of gait [32, 73, 74]. Therefore, LC can overload the knee extensors, consequently increasing the loss of strength during LC. In this review, the importance of the knee extensor muscles in LC gait was clear, as all studies [11, 44–47] demonstrated a significant reduction immediately after walking. The extensor muscles required 48 h to more than 72 h to recover the ability to produce torque at pre-walking

levels after level and downhill LC [45]; performed by supplemented individuals [44]; and performed on two consecutive days and three days of strength assessment [11].

Fatigue is task-dependent, meaning that its causes and behaviour vary widely depending on how it is induced [70]. Therefore, it seems reasonable to say that the development of fatigue in dynamic conditions, such as LC walking, as performed in the 5 studies included in this review, does not involve the generation of maximum force during walking activity. On the other hand, it develops motor performance fatigue of multiple lower limb muscles, which can impact muscle recovery time. Linnamo et al. [75] demonstrated that longer recovery times after lower-force contractions are due to greater peripheral factor involvement than in recovery after maximal contractions, where a more central component is suggested. The human body will inevitably produce fatigue after excessive exercise [76], and when fatigued, muscle function temporarily decreases [77]. During recovery, if fatigue cannot be eliminated in time and is accumulated for a prolonged period, it will turn into excessive fatigue [76]. Therefore, considering the negative effects of muscle fatigue generated by LC walking and the relevant role of the quadriceps muscle in walking, we consider it important to know the time required for the adequate recovery of the musculature subjected to this mechanical stress under different conditions.

In this sense, future studies including the flexor musculature are necessary to better understand the agonist-antagonist relationship with the quadriceps, as well as to understand the interaction of multimuscular fatigue associated with LC walk activity that, possibly, exposes the lower limb musculature to greater mechanical loads, resulting in greater impact.

Regarding the flexion movement, the greater functional demand of the knee extensors may be the reason for the exclusion of the flexor musculature from isometric evaluations [44–47]. Nevertheless, flexion was evaluated by one study [11] in isometrics and by three studies [11, 44, 45] in isokinetics. The results indicate a lower functional demand of these muscles during walking, considering that no effects were found generated by two consecutive days of walking with and without LC on the ability to produce isometric and isokinetic torque [11]. On the other hand, Blacker et al. [45] demonstrated that after LC performed on a decline and level surface, the flexor musculature required 48 h to recover the ability to produce isokinetic torque at a speed of 60°s^{-1} and 24 h at a speed of 180°s^{-1} . Corroborating our statement of the importance of evaluating the knee flexor and extensor muscles, Osternig

et al. [78], when investigating the coactivation of the quadriceps and hamstrings muscles on the isokinetic dynamometer, demonstrated greater activity of the flexors during the extensor action than of the extensors during the flexor action. This is most likely due to the greater force production capacity of the quadriceps, which would require greater antagonistic coactivation of the flexors for coordination and deceleration of the movement. More recently, Strazza et al. [79] demonstrated that, during walking, there is a cocontraction of the extensor and flexor muscles, probably to assist knee extension to raise muscle tension, prepare for the load acceptance response and control knee flexion.

The findings of this review demonstrate different patterns of acute and temporal decline and recovery of force production capacity measured through isokinetic and isometric contractions after LC walking exercise. This suggests that these measures of neuromuscular function likely do not use the same physiological mechanisms, indicating that one does not replace the other, but both serve to better understand the consequences of fatigue generated by LC walking on neuromuscular properties.

Limitations of this review

This systematic review provides valuable information on the subject it set out to synthesise; however, there were limitations to be considered in the interpretation of the findings.

The quality of a systematic review depends on how carefully the methods are used to reduce the risk of errors and bias [42]. Based on this concept and aiming to mitigate the limitations of this review, we conducted a detailed and clear description of the methods used.

The results were dependent on the terms used in the search strategy and the efficiency of the search engines used. In an attempt to overcome this limitation, we used a combination of terms that are common to the subject and widely used in other studies.

While extracting data, we identified a study [11] that included both men and women carrying cargo with military equipment, but did not make it clear whether the study participants were military and/or civilians. To minimise this limitation, we contacted the authors via email, and the doubt was clarified by identifying the participants as civilians.

In the sampling, despite the studies using individuals familiar with backpack carrying and physically active, the sample was not homogeneous, containing participants with recreational and/or occupational experience, composed of military men [47], civilian men [44–46], and civilian men and women together [11].

The number of studies that met the criteria for this systematic review was small ($n = 5$), limiting the ability to generalise the findings. In addition, the methodological differences between the included studies did not allow for a meta-analysis.

Conclusions

In this review, information was produced that warrants attention and should be utilised by coaches to develop physical training programs with the goal optimise physical performance during LC and the recovery following LC, and to reduce musculoskeletal injuries.

The harmful acute and temporal effects on the neuromuscular function are load-dependent and are independent of the intervention performed. The acute neuromuscular impairment seems to occur by a decreased ability to modulate motor output rapidly and accurately in response to perturbations and has the potential to affect coordination negatively and to impact motor task performance and exercise tolerance. On the other hand, temporal neuromuscular impairment seems to occur by essentially eccentric motor activity performed during the walk and increased by the external load, which involves the active lengthening of muscle fibres, leading to muscle damage, attributed to mechanical disruption of the sarcomeres, in the days after exercise. As a consequence of this muscle damage, a prolonged decrease in system responsiveness and a loss of adaptability in motor control and maximal force-generating capacity are seen.

Regardless of the supplement consumed, carbohydrate or whey protein, a beneficial effect of accelerating the recovery of neuromuscular function after prolonged load carriage occurs in isometric strength, but not in isokinetic strength.

Based on the number of studies included, it is clear that the activity of walking associated with backpack LC requires additional studies, both in military and civilian populations, to form a database that provides a better understanding of the effects of this activity on lower limb muscles and, thus, makes it possible to optimise the development of specific training protocols for walking activities with backpack LC.

Ethical approval

The conducted research is not related to either human or animal use.

Disclosure statement

No author has any financial interest or received any financial benefit from this research.

Conflict of interest

The authors state no conflict of interest.

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