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SYSTEMATIC REVIEW

The Effects of Cognitive Loading on Motor Behavior in Injured Individuals: A Systematic Review

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Abstract

Background Research suggests that individuals with musculoskeletal injury may have difficulty negotiating physical tasks when they are combined with cognitive loads.

Objective Our objective was to conduct a systematic review to understand the effects of increased cognitive demand on movement patterns among individuals with musculoskeletal injuries.

Methods A comprehensive search of PubMed, MEDLINE, the Cumulative Index for Nursing and Allied Health Literature (CINAHL), and SPORTDiscus was conducted to find research reports that included a population that had previously experienced an ankle, knee, or low back injury, included an uninjured control group, and assessed a dual-task paradigm.

Results Forty-five full-text research reports were assessed, of which 28 studies (six ankle injury, nine knee injury, and 13 low back pain studies) were included in the review. Included studies were assessed for methodological quality and the study design extracted for analysis including the participants, cognitive and physical tasks performed, as well as outcome measures (e.g., three-dimensional kinematics, center of pressure, etc.). All studies included were cross-sectional or case–control with methodological quality scores of 17.8 ± 2.2 out of a possible 22. Twenty-five of the 28 studies found changes in motor performance with dual-task conditions compared with single tasks. Furthermore, 54% of studies reported a significant group by task interaction effect, reporting at least one alteration in injured groups' motor performance under dual-task conditions when compared with an uninjured group.

Conclusion The results of this systematic review indicate that motor performance is further impaired by placing a cognitive load on individuals in populations with musculoskeletal injury. More demanding tasks such as gait appear to be more affected in injured individuals than simple balance tasks. Future investigators may want to consider the difficulty of the tasks included as well as the impact of dual-task paradigms on rehabilitation programs.

Key Points

The addition of cognitive load leads to changes in motor performance that increase with the difficulty of the motor task.

Injury is associated with increases in this change in motor performance, particularly in patients with anterior cruciate ligament injury and low back pain.

Rehabilitation may consider incorporating cognitive demand to minimize this impact during return to activity.

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1 Introduction

Musculoskeletal injury has a notable impact on world healthcare systems, with costs incurred secondary to initial treatment of the injury, loss of time from work or duty, addressing sequelae of that injury, and prevention of long-term health impacts [1–3]. These problems are often compounded by the high recurrence rate of many of these injuries. For instance, re-injury rates for anterior cruciate ligament (ACL) tears and ankle sprains may be as high as 30% and 70%, respectively [4, 5]. Similarly, low back pain (LBP) has been observed to recur in 25–80% of individuals, often contributing to a notably decreased quality of life [6, 7]. These high re-injury rates occur despite extensive rehabilitation protocols that appear to restore normal functional outcomes in clinic-based settings. However, upon return to real-world activities, injury and/or sensations of instability appear to recur, indicating limited transfer of gains from rehabilitation. A potential explanation for this discrepancy is that these individuals are not able to maintain appropriate movement patterns as levels of arousal and/or cognitive demand increase throughout activities of daily living or athletic competition compared to the controlled clinic-based setting [8]. The inability to negotiate this increased cognitive demand throughout activity may therefore be a key contributing factor to recurrent injury and subsequent decreased physical activity and health-related quality of life observed across populations of injured individuals.

There is a long-established relationship between the level of arousal and motor performance, suggesting that some degree of arousal is necessary to achieve optimal performance on a motor task [9, 10]. This relationship has often been investigated using dual-task paradigms, whereby concurrent cognitive and motor tasks are performed simultaneously to understand the interference between the two tasks. It is believed that individuals have a limited processing capacity and that every task requires portions of that overall processing capacity [11]. While some level of cognitive demand may contribute towards optimal performance, when these demands for the task exceed the processing capacity, performance on the motor and/or cognitive task decreases. This relationship is observed to be complex in nature, with decrements depending on the type of motor and cognitive task involved [12, 13]. For instance, structural interference may occur when the cognitive and motor task require identical resources, leading to a further degradation in performance of both tasks [14]. Alternately, cross-talk or central bottlenecking may lead to a disruption in functional networks, impairing task performance [15, 16]. While offering certain limitations, the dual-task paradigm is a crucial model as performance of tasks throughout daily living and sport are dependent on negotiating cognitive decision-making and visual interference during the simplest motor tasks [17, 18].

Among injured populations, a similar relationship may exist but with more significant implications. Individuals with ligamentous injury (i.e., ACL rupture, ankle sprain) have demonstrated potentially maladaptive neuroplasticity within the brain whereby motor and premotor areas of the cortex are more active during simple movement tasks than uninjured individuals [8]. This, therefore, likely increases the processing demand for the primary motor task and may limit the residual processing capacity for subsequent cognitive tasks. When real-world demand imposes constraints that may increase cognitive demand or increase the difficulty of the motor task, these injured individuals may have less capacity to handle these constraints, resulting in movement patterns that may lead to subsequent re-injury. This would subsequently explain the inconsistent research findings suggesting balance and gait deficits among injured individuals versus uninjured controls [19–22].

Understanding the interaction of cognitive demand and musculoskeletal injury on movement patterns is a key component towards addressing secondary injury prevention and restoring function in the large subset of individuals experiencing these injuries. Determining if cognitive load is a key component explaining the degradation of movement patterns leading to re-injury has the potential to modify rehabilitation paradigms [23]. While the theoretical framework for this relationship is in place, the implementation is limited by the scope and variability in the available research. Variability in populations, methodologies, cognitive demands, and outcome measures have made it difficult to draw conclusions, limiting their clinical application. We therefore aimed to conduct a systematic review of the literature to understand the effects of increased cognitive demand on movement patterns in relation to individuals with musculoskeletal injuries compared with uninjured individuals. We specifically aimed to answer this question among the most common injuries observed in the literature: ankle sprains, ACL rupture, and chronic LBP.

2 Methods

2.1 Literature Search Strategy

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement was used as a basis for the systematic search of the literature (see Electronic Supplementary Material Appendix S1) [24]. Electronic database searches were carried out in PubMed, MEDLINE, Cumulative Index for Nursing and Allied Health Literature

(CINAHL), and SPORTDiscus using the following search terms and Boolean operators: ("dual-task" OR "dual-task" OR attention OR cognit*) AND (balance OR "postural control" OR "postural sway" OR kinetics OR kinematics OR gait) NOT (concussion OR "traumatic brain injury"). This search was then combined using the operator "AND" with the injuries of interest: ("anterior cruciate ligament" OR ACL), ("ankle sprain" OR "ankle instability"), and ("back pain") as separate searches. The search was performed separately by two reviewers (ARN and LC). Papers published between database inception and 1 October 2018 were included in the search.

2.2 Inclusion and Exclusion Criteria

Research reports identified by the two independent investigators were screened against inclusion and exclusion criteria agreed upon a priori by the study team. The following were considered inclusion criteria:

- Participants included a population of individuals that had previously experienced a musculoskeletal injury. Specifically, articles were included if they included a group of individuals that had chronic ankle instability (CAI), history of ankle sprain, ACL-deficiency, ACL-reconstruction, or history of chronic or recurrent LBP.
- Participants included a control group of individuals without the index injury of the experimental group and/or included a comparison to the uninjured side in the case of unilateral lower extremity injury.
- A direct comparison was made between performance on single- and dual-task conditions, with the dual-task condition including one motor task (e.g., balance, gait) and one cognitive task.
- Outcome measures included a measure of motor performance related to function. Specifically, outcome measures based on gait parameters, balance performance, or other measures of functional performance must be reported.
- All articles had to have been available in the English language and published in full within a peer-reviewed journal.

The following criteria were used to determine if articles needed to be excluded:

- Relevant outcome measures were not recorded during both single- and dual-task conditions.
- Groupings represented unnatural injury descriptions, such as experimentally induced injury.
- Articles appeared only in abstract format, or did not include a sufficient amount of detail to gauge study quality and extract results.

2.3 Study Selection

The search strategy is displayed in Fig. 1. The two reviewers independently screened all abstracts for those potentially meeting inclusion criteria, and full texts of those articles were subsequently retrieved. The reviewers then met with the entire review team and disagreements were resolved via consensus.

The initial search yielded 289 publications excluding duplicates (29 CAI, 104 ACL, and 156 LBP). Following screening of titles and abstracts, 45 (11 CAI, 15 ACL, 19 LBP) full-text articles were retrieved. Full-text review was completed to determine final inclusion, with 28 articles meeting criteria for inclusion into this systematic review (six CAI, nine ACL, 13 LBP).

2.4 Assessment of Study Quality

Our criteria restricted inclusion of studies to those with case control or other observational designs. As such, articles were assessed using the checklist put forth by the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement [25]. Two reviewers (ABR, CJB) independently assessed each article against the 22 criteria put forth in the STROBE statement to determine a score indicating the reporting quality of included articles. Disagreements in STROBE scores across reviewers were resolved by consensus.

2.5 Data Extraction

For each study that met the full inclusion and exclusion criteria, information regarding the study design including the participants, cognitive and physical tasks completed as well as outcome measures (e.g., three-dimensional kinematics, center of pressure, etc.) were extracted. In addition, the major results of each study were briefly summarized, which were particularly focused on the differences between groups during the dual-tasking conditions.

3 Results

Ultimately, 28 manuscripts were assessed, with six CAI (Table 1) [26–31], nine ACL (Table 2) [32–40], and 13 LBP (Table 3) [41–52].

3.1 Movement Task Outcome Measures

Single-limb stance (CAI = 4, ACL = 6, LBP = 1) [26–29, 32, 35–38, 45], double-limb stance (CAI = 0, ACL = 2, LBP = 7) [33, 38, 41, 44, 47–50, 53], gait (CAI = 2, ACL = 3, LBP = 4) [30, 31, 34, 39, 40, 42, 43, 46, 51], and sitting (CAI = 0,

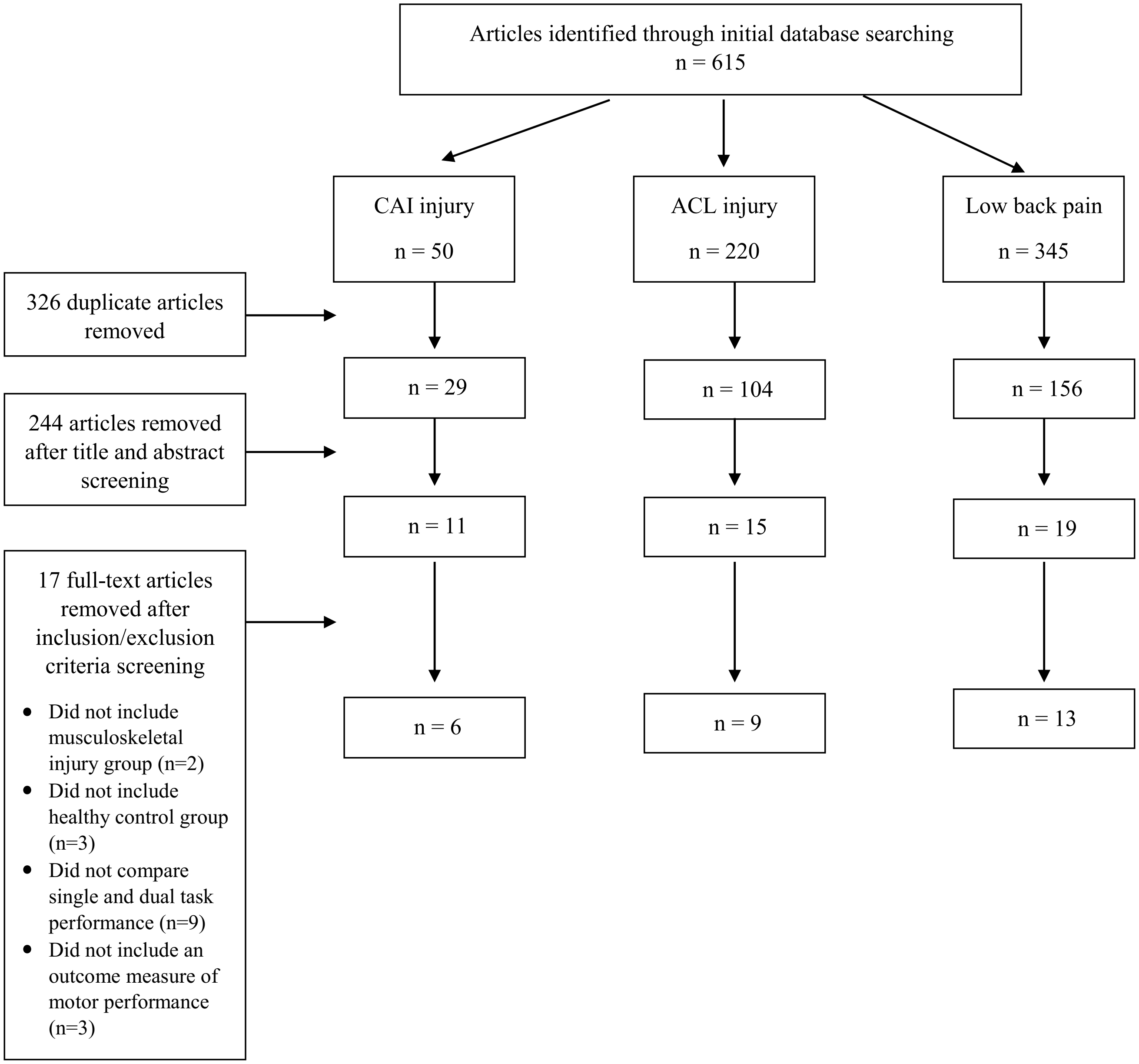

Fig. 1 Preferred reporting items for systematic reviews and meta-analyses (PRISMA) flowchart of articles included in the systematic review. *ACL* anterior cruciate ligament, *CAI* chronic ankle instability

ACL = 0, LBP = 1) [52] were the movement tasks reported across studies. Force plate assessments (mainly based on center of pressure measures) were the most common outcome measures (CAI = 4, ACL = 4, LBP = 6) [26–29, 33, 35, 37, 38] followed by spatial–temporal measures (CAI = 1, ACL = 3, LBP = 4) [30, 32, 34, 40] and kinematic variables (CAI = 1, ACL = 1, LBP = 4) [31, 39].

3.2 Cognitive Task Implementation

A description of neurocognitive tests and their outcome measures described in the literature used as part of the dual-task paradigms can be found in Table 4. The most commonly used paradigms included number generation or digit span tasks (CAI = 2, ACL = 4, LBP = 5) [26, 28, 36–39, 44, 47, 48, 52, 53], serial subtractions (CAI = 4, ACL = 1, LBP = 1) [27, 29–31, 33, 45], and Stroop tests (CAI = 0, ACL = 2, LBP = 4) [32, 35, 41, 46, 49, 50].

3.3 Major Results

Inspection of the major results of the included studies yielded 54% of studies that reported a significant group by task interaction effect (CAI = 3, ACL = 3, LBP = 9) [28,

Table 1 Results for articles investigating populations of individuals with ankle instability

References	Participants	Physical task(s)	Cognitive task(s)	Outcome measure	Results			STROBE
					Group by task interaction	Group	Task	
Burcal and Wikstrom [26]	20 controls 19 CAI	Single-limb balance	1) Backwards counting 2) Manikin test 3) Random number generation	AP and ML time to boundary minimum, mean, and standard deviation	Non-significant	Non-significant	Non-significant	18
Hung and Miller [27]	16 CAI	Single-limb balance	Serial subtraction	OSI	Not assessed	Not assessed	Significant. All participants performed worse during cognitive demand protocols	11
Rahnama et al. [28]	15 controls 15 FAI	Single-limb balance	Serial subtraction	OSI, APSI, MLSI, cognitive errors	Significant for OSI and MLSI. Participants with CAI had worse balance during dual-task than single-task, whereas controls did not	Non-significant	Non-significant	18
Shiravi et al. [29]	8 unilateral CAI	Single-limb stance	Serial subtraction	AP and ML COP sway and velocity	Not assessed	Non-significant (adverse effect)	Significant. COP area significantly decreased during dual-task compared with single-task. AP sway decreased in injured limb only during dual-task compared with single-task	17
Springer and Gottlieb [30]	16 controls 16 CAI	Gait	Serial subtraction	Stride time and length variability, errors	Significant. Differences in stride time variability during fast-paced walking with dual-tasking in CAI group but not control group	Not reported	Not reported	18

Table 1 (continued)

References	Participants	Physical task(s)	Cognitive task(s)	Outcome measure	Results			STROBE
					Group by task interaction	Group	Task	
Tavakoli et al. [31]	19 controls 21 FAI	Gait	Serial subtraction	Three-dimensional ankle kinematics, errors	Significant. Greater ankle inversion and plantarflexion in FAI during dual-task than in controls. FAI group had worse cognitive task performance during walking	Significant difference in frontal plane kinematics between groups	Significant differences in sagittal plane motion during the dual-task compared with single-task	19

AP anteroposterior, *APSI* anteroposterior stability index, *CAI* chronic ankle instability, *COP* center of pressure, *FAI* functional ankle instability, *ML* mediolateral, *MLSI* mediolateral stability index, *OSI* overall stability index, *STROBE* Strengthening the Reporting of Observational Studies in Epidemiology

30–32, 34, 35, 41–44, 48–52], 32% reported non-significant interactions (CAI = 1, ACL = 5, LBP = 4) [26, 33, 36–38, 40, 45–47, 53], and the remaining 14% did not report or assess interactions (CAI = 2, ACL = 1, LBP = 0) [27, 29, 39]. Significant differences between injured and uninjured groups were reported by 46% (CAI = 1, ACL = 5, LBP = 7) [31, 34, 36, 38, 40–43, 46, 47, 49, 53], whereas 39% reported no differences (CAI = 3, ACL = 2, LBP = 6) [26, 28, 29, 33, 35, 44, 45, 48, 50–52] and 14% did not report or assess this (CAI = 2, ACL = 2, LBP = 0) [27, 30, 32, 39]. Significant task or condition differences between single- and dual-tasking were reported by 68% (CAI = 2, ACL = 6, LBP = 11) [29, 31, 33–37, 39, 41, 43–52], whereas 21% reported no differences (CAI = 3, ACL = 0, LBP = 2) [26, 28, 29, 42, 53] and 11% did not report or assess this (CAI = 1, ACL = 2, LBP = 0) [30, 32, 40].

3.4 Quality Assessment

All of the studies included were cross-sectional or case–control, limiting the level of evidence of included studies to levels 3 and 4. The average STROBE score across all of the evaluated studies was 17.8 ± 2.2 out of a possible 22, and broken down by system the scores were 16.8 ± 2.9 for CAI studies (Electronic Supplementary Material Table S1), 19.0 ± 1.4 for ACL studies (Electronic Supplementary Material Table S2), and 17.5 ± 1.9 for LBP studies (Electronic Supplementary Material Table S3). Several disagreements in STROBE scoring occurred and were resolved through consensus, with disagreements most often related to the reporting of settings and locations, level of detail for participants or results, whether or not the authors had a cautious interpretation of their findings and limitations, and if the authors provided sufficient discussion on the external validity of their results.

4 Discussion

The purpose of this systematic review was to identify how dual-tasking affects motor behavior in individuals with musculoskeletal injury. All but three [26, 40, 53] of the 28 manuscripts evaluated in this review described a change in motor performance (e.g., worsened balance, increased variability in performance values) under dual-task conditions as assessed by significant task or interaction effects. However, when investigating the interaction between dual-tasking and injury, results were more varied: 54% of investigations in patients with CAI, 71% of investigations in patients with ACL injury, and 69% of investigations of patients with LBP reported at least one alteration in motor performance under dual-task conditions when compared with a control group. Generally, it is reported that patients with musculoskeletal

Table 2 Results for articles investigating populations of individuals with anterior cruciate ligament injury

References	Participants	Physical task(s)	Cognitive task(s)	Outcome measure	Results			STROBE
					Group by task interaction	Group	Task	
Akhbari et al. [32]	25 healthy 25 ACLD 25 ACLR	Single-limb stance	Stroop	Reaction time, latency and amplitude to balance perturbations	Not reported Significant differences reported during large cognitive perturbations in ACLR participants	Not assessed	Not assessed	21
Lion et al. [33]	21 controls 19 ACLR	Double-limb stance	Serial subtraction	COP sway area and path	Non-significant	Non-significant	Significantly smaller sway path and area during dual-task condition than single task All groups were worse during eyes closed than eyes open and with foam pad than with stable surface	20
Mazaheri et al. [34]	19 healthy 17 ACL-injured	Gait during two base of support conditions	Backwards counting	Step length, step velocity, coefficient of variation of step length and velocity	Significant for step velocity. In the narrow base of support condition, ACL participants demonstrated lower step velocity during dual-task conditions	Significant for all variables. ACL participants had greater variability in step length and velocity than the healthy group	Significant. All participants had lower step length and width variability during dual-task conditions	21
Mohammadi-Rad et al. [35]	17 ACLR 17 matched controls	Single-limb stance	Auditory Stroop test	Overall stability index, AP stability index, ML stability index	Significant for overall and AP stability indices. Balance was worse in ACLR subjects during level 6 eyes-opened condition	Non-significant	Significant for ML stability indices. Participants demonstrated worse balance during dual-task conditions than single-task	17

Table 2 (continued)

References	Participants	Physical task(s)	Cognitive task(s)	Outcome measure	Results			STROBE
					Group by task interaction	Group	Task	
Negahban et al. [36]	25 ACLR 25 controls	Single-limb stance on wobble board	Silent backward digit span test	Contact frequency and contact time	Significant group by cognitive difficulty interaction. Patients with ACLR demonstrated worse balance (greater contact frequency and contact time) than healthy controls during dual-task conditions	Significant. Increased contact frequency in the injured group compared with uninjured	Significant for contact frequency. Increased frequency in dual-tasking condition compared with single-task	19
Negahban et al. [37]	27 ACLD 27 matched controls	Single-limb stance	Backward digit test	Mean COP velocity, phase plane portrait, and standard deviation of velocity in AP and ML directions; cognitive errors	Non-significant	Significant. ACLD patients had worse balance than controls. ACLD patients demonstrated greater cognitive errors than healthy controls	Significant. All participants performed worse during dual-tasking	18
Negahban et al. [38]	27 ACLD 27 matched controls	Double and Single-limb stance	Backward digit span	% determinism, Shannon entropy in AP and ML	Non-significant	Significant for all variables except AP entropy in single-limb stance. During double-limb stance ACLD patients had greater AP and ML % determinism and entropy than healthy controls	Significant. Cognitive difficulty increased determinism and entropy in AP and ML	18
Shi et al. [39]	25 ACLR	Gait	Backward counting	Three-dimensional kinematics of the hip and knee	Significant. Inter-limb differences in hip and kinematics during the cognitive loading trials on injured side	Not assessed	Significant. Decreased peak knee flexion angle and moments during cognitive demand compared with single-task	19

Table 2 (continued)

References	Participants	Physical task(s)	Cognitive task(s)	Outcome measure	Results			STROBE
					Group by task interaction	Group	Task	
Stone et al. [40]	20 ACLR 20 controls	Gait	1) Trail Making Test 2) Reaction time test (card-flip test) 3) Pursuit rotor test 4) Purdue pegboard	Limb excursion, stance time, step length, and double support; test performance	Non-significant	Significant. ACLR group had better performance on Trail Making Test. No significant differences for kinematic variables	Not reported	18

ACL anterior cruciate ligament, *ACLD* anterior cruciate ligament deficient, *ACLR* anterior cruciate ligament reconstructed, *AP* anteroposterior, *COP* center of pressure, *ML* mediolateral, *STROBE* Strengthening the Reporting of Observational Studies in Epidemiology

conditions often have deficits in balance and alterations in gait; however, recent evidence has suggested that this finding may be more complicated, with these individuals demonstrating an increased dependence on attentive resources and visual feedback during simple movement tasks [8, 54–56]. The data from this review support this assertion, as the majority of studies indicated that motor behavior was further impaired by placing a cognitive load on individuals.

4.1 Balance

4.1.1 Role of Dual-Tasking on Balance

Similar to many lower extremity motor tasks, balance typically requires few cognitive resources, with tonal alterations in the lower extremity regulated subconsciously by subcortical structures [57]. However, it has been hypothesized that following injury, more cortical resources are dedicated to balance in individuals with musculoskeletal injury [8]. Although the effects of dual-tasking on balancing in the general population have been described as varied, with levels of cognitive demand potentially improving balance [58], the results of this review showed the majority of studies reported a balance deficit under dual-task conditions, and no studies reported improvements with increased cognitive demand. Balance was found to decrease when using outcomes including traditional and non-linear center of pressure variables [29, 33, 37, 38, 41, 47, 48], stability indices from the Biodex Stability System [27, 35, 50], the Star Excursion Balance Test [45], and performance on an instrumented wobble board [36]. These outcome variables account for maintenance of static stability, believed to involve increased reactive neuromuscular control, together with dynamic postural control and variability analyses that are believed to reflect feedforward neuromuscular control abilities [59, 60]. These differences also include a variety of cognitive interference tasks, such as counting, numeric, and digit-span tasks, as well as verbal word-matching and Stroop tasks. We might therefore conclude that taxing executive resources during balance leads to disruptions in descending neuromuscular control that potentially affect the ability to appropriately regulate motor activity to compensate for normal fluctuations in balance.

However, this conclusion is confounded by several investigations that did not reveal a significant task effect on primary outcome measures [26, 28, 40, 53]. It is difficult to identify common trends in these manuscripts that may have led to null results; however, these may have been affected by the degree of difficulty of the cognitive tasks perhaps not being sufficient to impair balance, a decrease in cognitive performance being favored over a decrease in motor performance, or participants developing new motor solutions when faced with constraints by altering movement patterns in a

Table 3 Results for articles investigating populations of individuals with low back pain

References	Participants	Physical task(s)	Cognitive task(s)	Outcome measure	Results			STROBE
					Group by task interaction	Group	Task	
Etemadi et al. [41]	20 LBP 20 controls	Two-legged stance with perturbations	Auditory Stroop test	Reaction time, latency, initial velocity and COP amplitude. Reaction time of cognitive performance	Significant for initial velocity. During medium perturbations the LBP had greater velocity whereas the control group's velocity decreased	Significant. Stroop reaction time was slower in LBP patients than in controls	Significant. There were differences in velocity with increased cognitive difficulty across groups	19
Hamacher et al. [42]	12 LBP 12 healthy	Gait	RWF	Stride variability of trunk movements; task performance	Significant group by condition interaction, where there was greater variability in LBP patients than in healthy participants during dual-tasking. No interaction effect for RWF performance	Significant group effect during dual-tasking for variability	No significant effect of condition	13
Hamacher et al. [43]	12 LBP 12 controls	Gait	RWF	Standard deviations of stride time, stride length, and minimum toe clearance	Significant. Stride-length variability increased during dual-task walking in LBP but not in controls	Significant. LBP patients had higher stride-time variability than controls during both single- and dual-tasks	Significant. Stride-time variability increased in both groups during dual-tasking	17

Table 3 (continued)

References	Participants	Physical task(s)	Cognitive task(s)	Outcome measure	Results			STROBE
					Group by task interaction	Group	Task	
Hemmati et al. [44]	25 LBP 25 healthy	Two-legged stance with perturbations	Digit span memory	EMG onset and latency of tibialis anterior, gastrocnemius, rectus femoris, biceps femoris, rectus abdominis, and erector spinae muscles	Significant during predictable perturbations. Tibialis anterior had delayed activation, while gastrocnemius had an earlier pattern in LBP than in healthy participants during dual-tasking Significant during unpredictable perturbations. Earlier activation of the gastrocnemius in LBP patients during dual-tasking	Non-significant	Significant in predictable perturbations. Decreased rectus femoris and biceps femoris activity during dual-tasking	17
Hemmati et al. [45]	40 LBP 40 controls	Single-limb stance, SEBT, 10 m walk, and timed up-and-go	Serial subtractions	One-leg stance time, SEBT, timed up-and-go, and 10 m walk time; cognitive task performance	Non-significant	Non-significant	Significant. During dual-tasking all participants performed worse for all measures except for the SEBT	19
Lamoth et al. [46]	12 LBP 14 controls	Gait	Stroop color-matching tasks	Mean and standard deviations of stride length, time, and frequency. Pelvic-thorax relative phase	Non-significant	Significant. LBP group had shorter and less variable strides than controls	Significant. Shorter stride length and decreased stride frequency during dual-tasking control condition	16

Table 3 (continued)

References	Participants	Physical task(s)	Cognitive task(s)	Outcome measure	Results			STROBE
					Group by task interaction	Group	Task	
Mazaheri et al. [47]	20 current LBP 20 recent LBP 20 controls	Two-legged stance	Counting digits	COP standard deviation in AP and ML directions, COP path length; mean power–frequency in AP and ML directions, sample entropy; task performance	Non-significant	Significant. Those with current LBP had significantly lower mean power–frequency in the ML direction than those with recent LBP. The current LBP group had significantly lower sample entropy during most conditions than the control and recent LBP groups	Significant for COP ML standard deviation and path length indicating poorer balance in dual-tasking than controls	16
Mazaheri et al. [48]	22 LBP 22 controls	Standing with eyes open, eyes closed stable, and eyes closed foam	Backward digit span task	% recurrence, % determinism, entropy and trend in the AP and ML directions. Intrusion, omission, and order errors for cognitive task	Significant for AP % recurrence, % determinism, and AP trend. AP % determinism was different in the healthy group in the dual-task condition	Non-significant	Significant. Differences observed in AP % recurrence, AP and ML % determinism, AP and ML entropy, AP and ML trend as well as errors in dual-task condition	19
Salavati et al. [53]	22 LBP 22 controls	Standing with eyes open, eyes closed stable, and eyes closed foam	Backward digit span task	COP AP and ML displacement	Non-significant	Significant. Individuals with LBP had less postural sway than healthy controls	Non-significant	20

Table 3 (continued)

References	Participants	Physical task(s)	Cognitive task(s)	Outcome measure	Results			STROBE
					Group by task interaction	Group	Task	
Shanbehzade et al. [49]	19 LBP with low pain anxiety 19 LBP with high pain anxiety 20 controls	Standing with eyes open and closed, eyes closed with and without vibration	Auditory Stroop test	COP mean total velocity, area, AP and ML range	Significant for COP area and AP range. LBP patients with high anxiety had less sway area in the dual-task than the single-task. LBP patients with high pain anxiety had decreased AP range during the dual-task condition compared with single-task	Significant for COP area and mean velocity. LBP group with high pain anxiety had less COP area than the control and low pain anxiety groups. The LBP low pain anxiety group had higher COP mean velocity than the control and high pain-related groups	Significant. Reaction times were increased across groups during dual-tasking	18
Sherafat et al. [50]	15 LBP 15 healthy	Two-legged stance with different postural task difficulties	Auditory Stroop task	OSI, APSI, and MLSI	Significant for OSI and APSI in the eyes closed condition. The dual-task had worse postural control than in the single-task only in participants with LBP during the eyes closed condition	Non-significant	Significant. Stability indices decreased in dual-task conditions	17
Smith et al. [51]	14 LBP 14 control	90º ipsilateral walking turns	N-back test	Post-turn step length and width. Stride–stride variability. Trunk–pelvic joint excursion. 2-Back task error	Significant for step length variability and hip frontal plane excursion. Decreased step length variability was observed in the control group during dual-task but not LBP	Non-significant	Significant for coordination variability, trunk–pelvic frontal variability, hip axial, hip sagittal and hip axial variability	17

Table 3 (continued)

References	Participants	Physical task(s)	Cognitive task(s)	Outcome measure	Results			STROBE
					Group by task interaction	Group	Task	
Van Daele et al. [52]	21 LBP 21 controls	Stable and unstable sitting	Backward counting task	Angular deviation of trunk flexion/extension, rotation, and lateral flexion	Significant. In the unstable sitting condition there were significantly increased lateral flexion and rotation angular deviations in the control group during dual-task conditions but not in the LBP group	Not significant	Significant. During stable sitting both groups demonstrated increased rotational and lateral flexion angular deviations during the dual-task compared with the single-task	19

AP anteroposterior, *APSI* anteroposterior stability index, *COP* center of pressure, *EMG* electromyography, *LBP* low back pain, *ML* mediolateral, *MLSI* mediolateral stability index, *OSI* overall stability index, *RWF* Regensburger word fluency test, *SEBT* Star Excursion Balance Test, *STROBE* Strengthening the Reporting of Observational Studies in Epidemiology

non-deleterious manner. Determining whether participants prioritize the cognitive or the motor task is a challenge to this type of research, with instructions playing an important role in determining how subjects perform on each task [61]. It is possible that participants would choose to prioritize the less familiar cognitive tasks when presented with a more familiar static balance task. The conflicting results in this review are unsurprising, as a recent systematic review evaluating effects of dual-tasking in healthy participants found that approximately 50% of studies found acute deficits in balance under cognitive demand, while 30% of studies reported improved balance under such demand [58]. While no improvements were described in our studies, this may have been influenced by the inclusion of groups with musculoskeletal injuries.

4.1.2 Effects of Injury on Balance Ability During Dual-Tasking

Given results that suggest a general effect on balance under dual-task constraints, we anticipated that these performance trade-offs would be greater in patients with musculoskeletal injury. However, less than half of the investigations supported this assertion as investigators failed to uncover a group by task interaction effect. This was consistent across injury models in studies that assessed the group by task interaction, with one of two investigating CAI [28], three of five assessing ACL injury [32, 35, 36], and three of six articles investigating LBP [48–50] observing an increased effect of dual-tasking on balance. These inconsistencies may not be surprising given the nature of each injury, their common treatments, and their effects on the central nervous system.

It has been posited that balance ability under dual-tasking would be more affected in injured individuals secondary to maladaptive injury-induced neuroplasticity that places an increased demand on cortical areas to produce simple movement [8]. Many of these neuroplasticity-based changes are described as adaptations to sensory inputs common across injury models, such as the presence of pain and development of muscle inhibition that generates long-term decreases in cortical and segmental motor excitability [8, 62]. While these may be common across injury models, there are several notable differences. For instance, LBP and CAI are both highly heterogeneous pathologies, with variable presentations across participants that are not controlled for in study recruitment efforts (e.g., non-specific LBP and functional vs. mechanical joint instability) [63, 64]. Alternatively, while ACL tears are an injury that presents with more homogeneity, studies include both ACL-deficient and ACL-reconstructed individuals who may have undergone more extensive rehabilitation than CAI and LBP counterparts. Although patient-reported outcome measures have the potential to allow for normalization of injury severity,

Table 4 Description of neurocognitive tests and their outcome measures outlined in the literature as being used as part of the dual-task paradigms

Cognitive task	Description	Outcome measure
Number-based tasks		
Digit span	Participants recall a randomized set of numbers	Error scoring (*n*)
N-back test	Participants are presented with a sound or word and they have to remember if that was the same word or sound *n*-trials prior	Error scoring (*n*)
Random number generation	Participants generate a random set of numbers	Turning Point Index
Serial subtraction	Participants count backwards from a number, typically by 7 s or 3 s	Error scoring (*n*), time (s)
Visual-oriented tasks		
Card-flip test	Computer-based test, where a deck of cards is presented to the subject and the participant has to respond when the card is flipped over	Time (s)
Color digit counting	Several digits are displayed to the participant on a screen and they are asked to count the number of digits displayed in a specified color	Error scoring (*n*)
Manikin test	Participants are asked to identify the orientation of a stick-figure that rotates in two planes	Error scoring (*n*)
Purdue peg board	Participants place small metal pegs on a board	Time (s)
Pursuit rotor task	Participants track a dot moving around a circle	Time (s)
Stroop	Participants are asked to match (or ignore) the font color to the word meaning	Error scoring (*n*), time (s)
Trail Making TEST	With a pen and paper, the participant draws lines and connects numbers randomly on a piece of paper	Time (s)
Commission tasks		
Auditory Stroop	Participants are asked to match (or ignore) the sound to the word meaning (i.e., high pitch vs. low pitch)	Error scoring (*n*), time (s)
Regensburger word fluency test	Participants are asked to produce as many words as possible based on a given category during a time period (i.e., name all words you can think of that start with the letter 'A' in 60 s)	Number of words (*n*)

the general variability of questionnaires across studies and their use as inclusion criteria make this standardization difficult. Without sufficient control across studies with regard to population parameters and outcome measures, conclusions would be mostly speculative.

Despite these differences in methodology, it appears dual-tasking results in a decreased ability to balance regardless of injury. However, it is possible that the motor demands of postural control during these tasks were not sufficient to exacerbate these deficits in injured participants. While single-task static balance deficits are consistently reported in the literature, the reported effect sizes are typically small [20, 22, 65]. Only one investigation using static balance reported an interaction between group and cognitive load [49]. It may be hypothesized that static balance may be an insufficiently challenging motor task; that is, it does not generate enough cortical demand to produce sufficient degradation in cognitive task performance. However, controlled dynamic balance—such as that on a wobble board or Biodex Stability System—may be a more demanding balance task and result in greater motor performance trade-offs. In fact, 67% of investigations that did show deficits among injured individuals under dual-task conditions did so while investigating balance on unstable surfaces [28, 35, 36, 50]. Therefore, we might expect that the deficit among injured populations increases proportionally with the functionality and difficulty of the balance task.

4.2 Gait

4.2.1 Role of Dual-Tasking on Gait Parameters

Gait, like balance, is a lower extremity task that is largely regulated by subcortical structures, with several notable differences. Unlike balance, gait is a patterned dynamic movement involving processes that are regulated by central pattern generators in the central nervous system [66]. Additionally, gait is among the most practiced tasks in the nervous system, and is frequently carried out under dual-task conditions, such as while conducting a conversation, or manipulating a mobile device. Despite this level of practice, two-thirds of investigations evaluating the effects of cognitive loading on gait parameters reported altered gait during dual-task conditions. These findings are consistent with those reported among healthy older adults [67]. Most often, dual-tasking has been described as contributing to a slowing effect, where individuals decrease gait velocity and cadence while facing increased cognitive demands in order to ensure normal movement quality [51].

In the studies investigated through this review, variables typically included variability of kinematic (e.g., joint angles) [31, 39] or spatiotemporal (e.g., step length) [30, 34, 40, 42, 43, 46, 51] outcomes between gait cycles. These outcome measures inform us about the flexibility versus rigidity of movement patterns, determining individuals' ability to either behave 'predictably' or adapt to changing environments. Some conflicting data exist regarding the overall effect of dual-tasking on gait variability, with stride time variability reported to increase during the Regensburger word fluency test [43]; however, step length and width variability were decreased during a backwards counting task [34]. While increased variability may represent the flexibility of the gait pattern to allow for optimal performance on both cognitive and motor tasks, the decreased variability may indicate a more conservative strategy, encouraging automaticity and thus increasing the predictability of movement patterns.

4.2.2 Effects of Injury on Gait Parameters during Dual-Tasking

Compared to evidence on changes in balance while dual-tasking, there is more support for the hypothesis that gait is altered while dual-tasking in injured populations. In CAI, 100% of studies supported changes under dual-tasking [30, 31], 67% in the ACL literature [34, 39], and 75% of studies in LBP patients [42, 43, 51]. Among patients with LBP, studies reported either an increase in movement variability during dual-tasking [42, 43, 51] or no decrease when compared with a control group [46]. Similar effects were seen in CAI patients, suggesting that while dual-tasking these participants have potentially more flexible, or less predictable, movement patterns [30, 31]. While increased variability may be helpful to accommodate changing environments [68], many of these studies were performed in controlled laboratories, where variable movement patterns were not needed. It may be a more likely explanation that these individuals were potentially using attentive cortical resources to contribute to consistent movement patterns, and that consistency is lost when completing cognitive tasks, leading to unpredictability and potential re-injury.

In addition to changes in variability, injured populations also demonstrated both spatiotemporal and kinematic changes under cognitive demand. In ACL-reconstructed individuals, participants demonstrated decreased gait velocities during narrow walking—a task that also incorporates a balance component [34]. This suggests individuals may be prioritizing the cognitive task and decreasing performance on the motor task, potentially due to competition for resources. Additionally, ACL-injured individuals demonstrated increased injured limb to uninjured limb differences while cognitively loaded [39], while patients with CAI demonstrated more injury-prone kinematics (i.e., increased inversion and plantarflexion in gait) [31]. These data collectively support hypotheses that to display 'normal' movement patterns, injured individuals are recruiting a greater proportion of available neural resources than their uninjured counterparts. Then, as those attentive resources become stressed by the addition of a secondary task, these individuals express biomechanical patterns that may predispose them to further injury.

A common finding in healthy individuals is that gait speed and cadence are decreased under dual-task conditions [67], and the results of our systematic review support this finding for people with musculoskeletal injury. One explanation for the observed slowing down of gait is likely competition for resources in the cortex. One of the more common theories explaining dual-task interference is that there is a finite capacity of cortical resources, and trade-offs in performance of one or both tasks result when tasks are simultaneously competing for the same resources [16]. A common example of such a relationship is text messaging while walking [69]. Schabrun et al. [69] found decreased gait speed and increased deviations from a straight trajectory when participants were walking while text messaging on a cell phone. The shift in attention or focus is a key factor in determining which task takes priority of cognitive resources, based on the goals of the individual [16, 70]. The cognitive tasks that were commonly used in these studies are not difficult tasks to perform in isolation, and it is likely that the laboratory environment of the studies leads an individual to place more emphasis on the cognitive task.

4.3 Other Movement Tasks

4.3.1 Role of Dual-Tasking on Other Movement Tasks

Although balance and gait were clearly the most investigated in terms of dual-task performance trade-offs, several studies utilized other movement tasks, such as reactions to balance perturbations [32, 41, 44], performance on the timed up-and-go test [45], sitting [52], and turning during gait [51]. Such tasks are often selected to potentially reflect increasing degrees of difficulty—such as requiring a response in addition to balance maintenance—or to reflect measures more applicable to everyday function. The studies that investigated muscular responses to postural perturbations reported increased latency while dual-tasking, suggesting that cognitive processing slows reaction times in the absence of injury [32, 41, 44].

These impairments seemingly carried over towards functional tasks. Postural alterations during stable and unstable sitting tasks present similar challenges as studies investigating balance, albeit while decreasing lower extremity influence [52]. Despite a significant increase in the base of support, increased angular deviations of the trunk were observed while cognitively loaded, indicating that motor regulation of posture was negatively affected by cognitive task performance [52]. These findings were similarly reflected during two gait-related tasks, including timed up-and-go performance and gait with turning tasks [45]. Similar deviations in task performance and increases in kinematic variability were observed, providing support for the hypothesis that cognitive demand changes motor performance across functional tasks.

4.3.2 Effects of Injury on Other Movement Tasks During Dual-Tasking

While each of the other movement tasks were found to demonstrate a main task effect, where dual-tasking alone impacted motor performance, this effect was amplified in individuals with musculoskeletal injuries. Whereas balance and gait parameters yielded often conflicting results, all but one investigation [45] assessing these other movement tasks indicated that motor performance was more greatly affected in individuals with musculoskeletal injuries. Given our hypotheses that injured individuals utilize more cognitive resources for simple movement, and the increased demands in these other movement tasks beyond posture and stereotyped movements, these findings are not surprising. However, the relationship may be more complicated than it appears on the surface. For instance, two investigations in patients with LBP demonstrated an interaction effect between dual-tasking and injury groups during perturbations [41, 44]. However, while healthy individuals decreased velocity of responses to perturbations, injured individuals were observed to increase response velocity. While this could be seen as a positive benefit of having faster reactions, these responses are likely less controlled than in those of healthy participants, potentially contributing to re-injury [71]. Follow-up investigations of the associated muscle activity found earlier onset of agonist and antagonist muscle groups, representing a quicker, but likely disorganized, response when compared with healthy controls [41, 44].

In directed movement tasks involving postural and gait-related mechanisms, group interaction effects presented some curious findings. This included two investigations that found increased movement variability among healthy subjects, with no changes occurring in patients with LBP [51, 52]. van Daele et al. [52] reported increased sitting kinematic variability in healthy controls but not LBP patients, while Smith et al. [51] observed increased kinematic variability during a turning task in healthy individuals. On the surface, this would imply there was no detriment to movement performance during dual-task conditions in LBP patients; however, given the pathological population, it is possible that this is negative adaptation, whereby healthy individuals had a trade-off between motor performances while dual-tasking but injured individuals made no such accommodations. This may represent an inability of patients with LBP to appropriately shift attention between tasks. While under laboratory settings this demonstrated consistent movement patterns that would be beneficial for movement, it remains unclear what the lack of trade-off may account for in real-world scenarios.

The LBP literature evaluated in this review included a wide variety of outcome variables, leaving it unclear how similar movement tasks—and notably perturbations and reaction times—might be affected in patients with CAI and ACL injury. The data supporting neuroplasticity affecting motor planning is far more established in these models, providing evidence for increased cognitive demand during simple movement [8]. Further, the onset of pain and re-injury in CAI and ACL injury is far more associated with a single aberrant movement than in LBP models [8]. Further research in this area should be encouraged to understand the motor implications of tasks with increased complexity in patients with CAI and ACL injury.

4.4 Cognitive Task Models

Across the 28 studies, a total of nine different cognitive tasks were utilized as a dual-task load (Table 4). The majority of tasks involved the manipulation or memorization of numbers and/or digits [26–31, 33, 34, 36–39, 44, 45, 47, 48, 52, 53]. These number-based tasks are easy to implement, and may offer greater cognitive stress when compared to tasks with a visual component. As the cortical structures involved with number manipulation and visual working memory are different, clinicians and researchers should take this into consideration when implementing dual-task paradigms of this nature. Although both are known to rely on the prefrontal cortex activity for working memory functions [72], cognitive tasks with a visual component may also utilize resources from cortical areas that are involved with balance and gait, such as the posterior parietal cortex and occipital cortex [73]. It is no surprise that such tasks would have a negative impact on motor performance in injured individuals, as patients with CAI and ACL injury are known to place more emphasis on visual cues during balance [54, 56]. Cognitive tasks with a visual component represent an ideal model for neural interference, where the likely explanation for worsened motor performance during these tasks results from competition for visual processing resources between the motor task and the cognitive task [70]. Non-visual cognitive tasks often rely on the prefrontal cortex for the monitoring of commission, errors, and performance; interference wherein motor performance is decreased during these tasks likely represents a finite capacity model, with both tasks competing for a pool of overall cortical resources or arousal [70]. It is difficult to speculate which category of cognitive task results in greater motor trade-offs; only one investigation compared multiple cognitive task domains (e.g., number-based and those with a visual component), and this was one of two papers that did not identify a main effect of cognitive load on balance [26]. We advise future research be designed to evaluate the differences between cognitive task model and motor performance trade-offs, perhaps through the inclusion of cognitive task difficulty indices.

4.5 Clinical Implications

4.5.1 Implications for Assessment of Injury

Our data indicate that a complex relationship exists between cognitive demand and injury, whereby populations with musculoskeletal injury may not appropriately adjust their neuromuscular control under dual-task implications. Part of the challenge in researchers' understanding the mitigating risk factors for recurrent injury in the cases of CAI, ACL injury, and LBP is the large degree of variability and equivocality in the existing literature, and the lack of control for pre-injury cognitive status [74]. Specifically, in relation to balance, gait, and functional performance, conflicting results and small effect sizes are reported in meta-analyses when describing these deficits [19, 21, 22, 75, 76]. We propose that inclusion of cognitive loading during initial assessment and ongoing care may contribute to the better identification and benchmarking of deficits among these populations, as prospective investigations have tied baseline cognitive status to injury risk—although the interaction of dual-task interference is unclear [74]. However, given the largely equivocal data in this subset, we recommend introducing cognitive demand in the form of more complex movement patterns or utilizing demands beyond simple quantitative tasks. Regardless of the overall effects, assessing the potential degradation of movement patterns under cognitive demand is a potentially useful tool in assessment-based rehabilitation plans for injured individuals.

4.5.2 Implications for Injury Rehabilitation

Although utilizing the findings of this systematic review in the assessment of injuries may not be grounded in the strongest of evidence, there is still much to understand regarding the role of cognitive demand in injury rehabilitation [23]. In multiple cohorts of neurologically compromised populations, incorporation of cognitive tasks into simple gait and balance training has been demonstrated to improve automaticity and ultimately outcomes in this population [77]. It has been demonstrated that injury—specifically ligamentous injury to the ankle and knee—is associated with cortical adaptations not unlike those in these neurologically impaired populations [8]. It might, therefore, be concluded that incorporation of increased cognitive demand, dual-tasking, and decision-making tasks in the rehabilitation setting could potentially be useful for improving the flexibility and automaticity of human movement. Some examples of these could include ball catching tasks during balancing with differential instructions for catching different colored objects, or incorporating backwards counting or serial subtraction into normal rehabilitative exercises [23].

There is still much to understand about the role of cognitive demand in rehabilitation, as no studies published at the time of this review have incorporated cognitive loading into rehabilitation paradigms for musculoskeletal injury. Currently, evidence does exist regarding the use of modifying attentional focus in these populations, with data describing positive changes in movement patterns along with increased retention of these movement patterns [78, 79]. It is possible that increased manipulation of contextual interference in addition to modified attentional focus may serve to improve the rate and retention of motor learning following injury.

4.6 Study Quality and Bias Assessment

Several factors within this systematic review lead us to urge caution with the interpretation of these data, which may limit the generalizability of this systematic review. First and foremost is the relatively low quality of the included manuscripts, particularly for ankle and LBP studies. The largest demerits during STROBE assessment arose from the lack of reporting of research settings, risk of bias, sample size explanation, and addressing potential limitations along with the study's generalizability. The lack of power analyses to justify sample size in many studies is concerning given the variability of results, as we were unable to rule out the possibility of type II error in several studies. Further, the large number of dependent variables reported throughout these investigations, combined with the lack of error rate corrections (e.g., Bonferroni adjustment), also elevates the risk of type I error reporting. However, these do not necessarily detract from the validity of these studies, as error rates have more applicability in interventional studies rather than observational studies, and some recommendations suggest exploring an event-to-variable ratio rather than strict error rate corrections. While cumulative effect sizes would certainly improve the interpretation of these data, the lack of consistency in research designs and outcome measures inhibited our ability to quantitatively evaluate research via a meta-analysis.

The literature base regarding dual-tasking in musculoskeletal injuries may suffer from publication bias. In a systematic review, it is difficult to establish the publication bias due to the lack of consistent reporting across studies. One of the important calculations common in conjunction with meta-analyses is the fail-safe *n*, which estimates the number of manuscripts that would reduce a significant effect size to a null result. Giving insight to this factor, we qualitatively observed in included manuscripts that many tested several dependent variables, with most only having significant findings for a small portion of the total. Additionally, we noticed publications with the same author groups potentially creating a duplicate publication bias, which has been identified to be a consistent issue among systematic review publications, and may have influenced the results of our review [80].

5 Conclusions

This systematic review sought to synthesize the available literature regarding the effect of dual-tasking on those with ankle, knee, and low back injuries. A large majority of studies reported a degradation in movement when a dual-task paradigm was applied. In injured populations just over half of the included studies reported increased changes compared with control groups. In addition, the results of dual-tasking were clearly dependent on key components of the study designs, in particular the dependent variables being observed (e.g., gait vs. balance), dual-task paradigms, and patient group. Echoing this, gait appeared to be more affected in injured individuals by dual-task designs when compared with simple postural control tasks. Researchers may want to consider the difficulty of the task, both from a physical (e.g., hopping, landing) as well as the neurocognitive (e.g., verbal vs. memory) perspective, as it appears this has large implications on the results. Lastly, the clinical implications of dual-tasking remain ambiguous. As dual-task paradigms could be a means to reduce persistent performance deficiencies that often exist among individuals with a history of musculoskeletal injury, future work should investigate the impact of including dual-task paradigms in rehabilitation programs.

Data Availability Statement The authors declare that the data supporting the findings of this review are included in the article and/or its supplementary digital content.

Compliance with Ethical Standards

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References

1. Nunez M, Sastre S, Nunez E, et al. Health-related quality of life and direct costs in patients with anterior cruciate ligament injury: single-bundle versus double-bundle reconstruction in a low-demand cohort—a randomized trial with 2 years of follow-up. Arthroscopy. 2012;28(7):929–35.
2. Mather RC 3rd, Koenig L, Kocher MS, et al. Societal and economic impact of anterior cruciate ligament tears. J Bone Jt Surg Am. 2013;95(19):1751–9.
3. Shah S, Thomas AC, Noone JM, et al. Incidence and cost of ankle sprains in United States emergency departments. Sports Health. 2016;8(6):547–52.
4. Grindem H, Snyder-Mackler L, Moksnes H, et al. Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: the Delaware-Oslo ACL cohort study. Br J Sports Med. 2016;50(13):804–8.
5. Anandacoomarasamy A, Barnsley L. Long term outcomes of inversion ankle injuries. Br J Sports Med. 2005;39(3):e14 **(discussion e14)**.
6. Stanton TR, Henschke N, Maher CG, et al. After an episode of acute low back pain, recurrence is unpredictable and not as common as previously thought. Spine (Phila Pa 1976). 2008;33(26):2923–8.
7. Marras WS, Ferguson SA, Burr D, et al. Low back pain recurrence in occupational environments. Spine (Phila Pa 1976). 2007;32(21):2387–97.
8. Needle AR, Lepley AS, Grooms DR. Central nervous system adaptation after ligamentous injury: a summary of theories, evidence, and clinical interpretation. Sports Med. 2017;47(7):1271–88.
9. Oxendine JB. Emotional arousal and motor performance. Quest. 1970;13(1):23–32.
10. Keele SW. Movement control in skilled motor performance. Psychol Bull. 1968;70(6 Pt 1):387–403.
11. Buschman TJ, Kastner S. From behavior to neural dynamics: an integrated theory of attention. Neuron. 2015;88(1):127–44.
12. Kim AS, Needle AR, Thomas SJ, et al. A sex comparison of reactive knee stiffness regulation strategies under cognitive loads. Clin Biomech (Bristol, Avon). 2016;35:86–92.
13. Dault MC, Frank JS, Allard F. Influence of a visuo-spatial, verbal and central executive working memory task on postural control. Gait Posture. 2001;14(2):110–6.
14. Papegaaij S, Hortobagyi T, Godde B, et al. Neural correlates of motor-cognitive dual-tasking in young and old adults. PLoS One. 2017;12(12):e0189025.
15. Strobach T, Torsten S. Mechanisms of practice-related reductions of dual-task interference with simple tasks: data and theory. Adv Cogn Psychol. 2017;13(1):28–41.
16. Pashler H. Dual-task interference in simple tasks: data and theory. Psychol Bull. 1994;116(2):220–44.
17. Fraizer EV, Mitra S. Methodological and interpretive issues in posture-cognition dual-tasking in upright stance. Gait Posture. 2008;27(2):271–9.
18. Ebersbach G, Dimitrijevic MR, Poewe W. Influence of concurrent tasks on gait: a dual-task approach. Percept Mot Skills. 1995;81(1):107–13.
19. Hart HF, Culvenor AG, Collins NJ, et al. Knee kinematics and joint moments during gait following anterior cruciate ligament reconstruction: a systematic review and meta-analysis. Br J Sports Med. 2016;50(10):597–612.
20. Lehmann T, Paschen L, Baumeister J. Single-leg assessment of postural stability after anterior cruciate ligament injury: a systematic review and meta-analysis. Sports Med Open. 2017;3(1):32.
21. Rosen AB, Needle AR, Ko J. Ability of functional performance tests to identify individuals with chronic ankle instability: a systematic review with meta-analysis. Clin J Sport Med. 2017. https://doi.org/10.1097/JSM.0000000000000535.
22. McKeon PO, Hertel J. Systematic review of postural control and lateral ankle instability, part I: can deficits be detected with instrumented testing. J Athl Train. 2008;43(3):293–304.

23. Needle AR, Rosen AB. Ligament injury changes brain function: now let's think about it. Athl Train Sports Health Care. 2017;9(5):198–9.
24. Moher D, Liberati A, Tetzlaff J, et al. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. BMJ. 2009;21(339):b2535.
25. von Elm E, Altman DG, Egger M, et al. The strengthening the reporting of observational studies in epidemiology (STROBE) statement: guidelines for reporting observational studies. Lancet. 2007;370(9596):1453–7.
26. Burcal CJ, Wikstrom EA. Cognitive loading-induced sway alterations are similar in those with chronic ankle instability and uninjured controls. Gait Posture. 2016;48:95–8.
27. Hung YJ, Miller J. Extrinsic visual feedback and additional cognitive/physical demands affect single-limb balance control in individuals with ankle instability. World J Orthop. 2016;7(12):801–7.
28. Rahnama L, Salavati M, Akhbari B, et al. Attentional demands and postural control in athletes with and without functional ankle instability. J Orthop Sports Phys Ther. 2010;40(3):180–7.
29. Shiravi Z, Talebian Moghadam S, Hadian MR, et al. Effect of cognitive task on postural control of the patients with chronic ankle instability during single and double leg standing. J Bodyw Mov Ther. 2017;21(1):58–62.
30. Springer S, Gottlieb U. Effects of dual-task and walking speed on gait variability in people with chronic ankle instability: a cross-sectional study. BMC Musculoskelet Disord. 2017;18(1):316.
31. Tavakoli S, Forghany S, Nester C. The effect of dual tasking on foot kinematics in people with functional ankle instability. Gait Posture. 2016;49:364–70.
32. Akhbari B, Salavati M, Ahadi J, et al. Reliability of dynamic balance simultaneously with cognitive performance in patients with ACL deficiency and after ACL reconstructions and in healthy controls. Knee Surg Sports Traumatol Arthrosc. 2015;23(11):3178–85.
33. Lion A, Gette P, Meyer C, et al. Effect of cognitive challenge on the postural control of patients with ACL reconstruction under visual and surface perturbations. Gait Posture. 2018;60:251–7.
34. Mazaheri M, Negahban H, Soltani M, et al. Effects of narrow-base walking and dual tasking on gait spatiotemporal characteristics in anterior cruciate ligament-injured adults compared to healthy adults. Knee Surg Sports Traumatol Arthrosc. 2017;25(8):2528–35.
35. Mohammadi-Rad S, Salavati M, Ebrahimi-Takamjani I, et al. Dual-tasking effects on dynamic postural stability in athletes with and without anterior cruciate ligament reconstruction. J Sport Rehabil. 2016;25(4):324–9.
36. Negahban H, Ahmadi P, Salehi R, et al. Attentional demands of postural control during single leg stance in patients with anterior cruciate ligament reconstruction. Neurosci Lett. 2013;27(556):118–23.
37. Negahban H, Hadian MR, Salavati M, et al. The effects of dual-tasking on postural control in people with unilateral anterior cruciate ligament injury. Gait Posture. 2009;30(4):477–81.
38. Negahban H, Salavati M, Mazaheri M, et al. Non-linear dynamical features of center of pressure extracted by recurrence quantification analysis in people with unilateral anterior cruciate ligament injury. Gait Posture. 2010;31(4):450–5.
39. Shi H, Huang H, Yu Y, et al. Effect of dual task on gait asymmetry in patients after anterior cruciate ligament reconstruction. Sci Rep. 2018;8(1):12057.
40. Stone AE, Roper JA, Herman DC, et al. Cognitive performance and locomotor adaptation in persons with anterior cruciate ligament reconstruction. Neurorehabil Neural Repair. 2018;32(6–7):568–77.
41. Etemadi Y, Salavati M, Arab AM, et al. Balance recovery reactions in individuals with recurrent nonspecific low back pain: Effect of attention. Gait Posture. 2016;44:123–7.
42. Hamacher D, Hamacher D, Schega L. A cognitive dual task affects gait variability in patients suffering from chronic low back pain. Exp Brain Res. 2014;232(11):3509–13.
43. Hamacher D, Hamacher D, Herold F, et al. Are there differences in the dual-task walking variability of minimum toe clearance in chronic low back pain patients and healthy controls? Gait Posture. 2016;49:97–101.
44. Hemmati L, Piroozi S, Rojhani-Shirazi Z. Effect of dual tasking on anticipatory and compensatory postural adjustments in response to external perturbations in individuals with nonspecific chronic low back pain: electromyographic analysis. J Back Musculoskelet Rehabil. 2018;31(3):489–97.
45. Hemmati L, Rojhani-Shirazi Z, Malek-Hoseini H, et al. Evaluation of static and dynamic balance tests in single and dual task conditions in participants with nonspecific chronic low back pain. J Chiropr Med. 2017;16(3):189–94.
46. Lamoth CJ, Stins JF, Pont M, et al. Effects of attention on the control of locomotion in individuals with chronic low back pain. J Neuroeng Rehabil. 2008;25(5):13.
47. Mazaheri M, Heidari E, Mostamand J, et al. Competing effects of pain and fear of pain on postural control in low back pain? Spine (Phila Pa 1976). 2014;39(25):1518–23.
48. Mazaheri M, Salavati M, Negahban H, et al. Postural sway in low back pain: effects of dual tasks. Gait Posture. 2010;31(1):116–21.
49. Shanbehzadeh S, Salavati M, Talebian S, et al. Attention demands of postural control in non-specific chronic low back pain subjects with low and high pain-related anxiety. Exp Brain Res. 2018;236(7):1927–38.
50. Sherafat S, Salavati M, Takamjani IE, et al. Effect of dual-tasking on dynamic postural control in individuals with and without nonspecific low back pain. J Manipulative Physiol Ther. 2014;37(3):170–9.
51. Smith JA, Gordon J, Kulig K. The influence of divided attention on walking turns: effects on gait control in young adults with and without a history of low back pain. Gait Posture. 2017;58:498–503.
52. Van Daele U, Hagman F, Truijen S, et al. Decrease in postural sway and trunk stiffness during cognitive dual-task in nonspecific chronic low back pain patients, performance compared to healthy control subjects. Spine (Phila Pa 1976). 2010;35(5):583–9.
53. Salavati M, Mazaheri M, Negahban H, et al. Effect of dual-tasking on postural control in subjects with nonspecific low back pain. Spine (Phila Pa 1976). 2009;34(13):1415–21.
54. Song K, Burcal CJ, Hertel J, et al. Increased visual use in chronic ankle instability: a meta-analysis. Med Sci Sports Exerc. 2016;48(10):2046–56.
55. Mann L, Kleinpaul JF, Pereira Moro AR, et al. Effect of low back pain on postural stability in younger women: influence of visual deprivation. J Bodyw Mov Ther. 2010;14(4):361–6.
56. Wikstrom EA, Song K, Pietrosimone BG, et al. Visual utilization during postural control in anterior cruciate ligament- deficient and -reconstructed patients: systematic reviews and meta-analyses. Arch Phys Med Rehabil. 2017;98(10):2052–65.
57. Visser JE, Bloem BR. Role of the basal ganglia in balance control. Neural Plast. 2005;12(2–3):161–74 **(discussion 263-72)**.
58. Ghai S, Ghai I, Effenberg AO. Effects of dual tasks and dual-task training on postural stability: a systematic review and meta-analysis. Clin Interv Aging. 2017;12:557–77.
59. Pollock AS, Durward BR, Rowe PJ, et al. What is balance? Clin Rehabil. 2000;14(4):402–6.
60. Needle AR, Baumeister J, Kaminski TW, et al. Neuromechanical coupling in the regulation of muscle tone and joint stiffness. Scand J Med Sci Sports. 2014;24(5):737–48.

61. Burcal CJ, Drabik EC, Wikstrom EA. The effect of instructions on postural-suprapostural interactions in three working memory tasks. Gait Posture. 2014;40(2):310–4.
62. Masse-Alarie H, Beaulieu LD, Preuss R, et al. The side of chronic low back pain matters: evidence from the primary motor cortex excitability and the postural adjustments of multifidi muscles. Exp Brain Res. 2017;235(3):647–59.
63. Hiller CE, Kilbreath SL, Refshauge KM. Chronic ankle instability: evolution of the model. J Athl Train. 2011;46(2):133–41.
64. Meucci RD, Fassa AG, Faria NM. Prevalence of chronic low back pain: systematic review. Rev Saude Publica. 2015;49:1.
65. Berenshteyn Y, Gibson K, Hackett GC, et al. Is standing balance altered in individuals with chronic low back pain? A systematic review. Disabil Rehabil. 2018;30:1–10.
66. Nielsen JB. How we walk: central control of muscle activity during human walking. Neuroscientist. 2003;9(3):195–204.
67. Smith E, Cusack T, Cunningham C, et al. The influence of a cognitive dual task on the gait parameters of healthy older adults: a systematic review and meta-analysis. J Aging Phys Act. 2017;25(4):671–86.
68. Baida SR, Gore SJ, Franklyn-Miller AD, et al. Does the amount of lower extremity movement variability differ between injured and uninjured populations? A systematic review. Scand J Med Sci Sports. 2018;28(4):1320–38.
69. Schabrun SM, van den Hoorn W, Moorcroft A, et al. Texting and walking: strategies for postural control and implications for safety. PLoS One. 2014;9(1):e84312.
70. Baddeley A. Working memory: theories, models, and controversies. Annu Rev Psychol. 2012;63:1–29.
71. DeAngelis AI, Needle AR, Kaminski TW, et al. An acoustic startle alters knee joint stiffness and neuromuscular control. Scand J Med Sci Sports. 2015;25(4):509–16.
72. Lara AH, Wallis JD. The role of prefrontal cortex in working memory: a mini review. Front Syst Neurosci. 2015;9:173.
73. Wittenberg E, Thompson J, Nam CS, et al. Neuroimaging of human balance control: a systematic review. Front Hum Neurosci. 2017;11:170.
74. Swanik CB, Covassin T, Stearne DJ, et al. The relationship between neurocognitive function and noncontact anterior cruciate ligament injuries. Am J Sports Med. 2007;35(6):943–8.
75. Moisan G, Descarreaux M, Cantin V. Effects of chronic ankle instability on kinetics, kinematics and muscle activity during walking and running: a systematic review. Gait Posture. 2017;52:381–99.
76. Ruhe A, Fejer R, Walker B. Center of pressure excursion as a measure of balance performance in patients with non-specific low back pain compared to healthy controls: a systematic review of the literature. Eur Spine J. 2011;20(3):358–68.
77. Pichierri G, Wolf P, Murer K, et al. Cognitive and cognitive-motor interventions affecting physical functioning: a systematic review. BMC Geriatr. 2011;8(11):29.
78. Benjaminse A, Welling W, Otten B, et al. Novel methods of instruction in ACL injury prevention programs, a systematic review. Phys Ther Sport. 2015;16(2):176–86.
79. Torp DM, Thomas AC, Donovan L. External feedback during walking improves measures of plantar pressure in individuals with chronic ankle instability. Gait Posture. 2019;67:236–41.
80. von Elm E, Poglia G, Walder B, et al. Different patterns of duplicate publication: an analysis of articles used in systematic reviews. JAMA. 2004;291(8):974–80.