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THE EFFECTS OF MULTIPLE MODALITIES OF COGNITIVE LOADING ON DYNAMIC POSTURAL CONTROL IN INDIVIDUALS WITH CHRONIC ANKLE INSTABILITY

Elizabeth L. Watson, Anna C. Bearden, J. Horton Doughton, Alan R. Needle*

Department of Health & Exercise Science, Appalachian State University, Boone, NC USA

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ABSTRACT

Background: Evidence of neuroplasticity after joint injury has suggested that individuals with chronic ankle instability (CAI) may have degraded movement when facing cognitive demand. To date, research into these effects have been limited to static balance models, and typically only incorporate a single type of cognitive demands.

Research question: We aimed to determine the effects of multiple modalities of cognitive load (quantitative, verbal-memory, visuospatial) on dynamic postural control strategies in a sample of patients with CAI compared to uninjured controls.

Methods: Thirty-two participants (16 CAI, 16 healthy) performed a series of 20 hops-to-stabilization while either under no cognitive load (CON), or while performing Benton's judgment of line orientation (JLO), the symbol digit modalities test (SDM), or a serial seven task (SVN). Dynamic postural stability indices and mean muscle activation from the lower leg muscles were extracted and assessed via analysis of variance.

Results: Healthy subjects demonstrated better vertical and dynamic postural stability indices under JLO ($P \leq 0.017$) and SVN ($P \leq 0.010$) conditions compared to CON. Postural stability was unaffected in CAI ($P > 0.050$). Peroneus longus and lateral gastrocnemius activation was lowest in SVN across all subjects ($P \leq 0.033$). Lateral gastrocnemius activation was greatest in SDM ($P \leq 0.033$).

Significance: These results suggest improvements in postural stability under cognitive demand in healthy individuals that did not occur in CAI, suggesting less movement optimization. Quantitative tasks appear to impede stabilizing muscle activation in the leg, while verbal-memory tasks result in a more protective landing strategy.

1. INTRODUCTION

Following ligamentous injury, individuals report frequent episodes of giving-way and re-injury that generate a significant impact on health-related quality of life [1–3]. At the ankle, frequent bouts of giving-way following an initial ankle sprain is termed chronic ankle instability (CAI) and has been estimated to affect approximately half of individuals that suffer ankle sprains [4]. A confounding factor for this pathology is that individuals may present with strength, motion, and balance equal to uninjured controls, yet continue to re-injure themselves [5]. Recent evidence has suggested these individuals utilize increased planning and visual resources to execute simple movement patterns [6]. Therefore, when placed under task and environmental constraints that require increased cortical resources and/or an attentional shift away from the motor task, movement quality may degrade leading to subsequent re-injury.

Theories describing changes in central nervous system function in patients with musculoskeletal injury generally report two key adaptations: decreased motor excitability and increased cortical activation in planning & visual areas [6,7]. Collectively, this indicates *cortical spread*, in which greater brain activation is needed to overcome decreased motor cortex excitability. Thus, since more cortical activation is needed, when these pathways are otherwise occupied by task complexity, such movement would degrade [6]. Hence, participants may display full functional status in the clinic with full attention towards the task, but experience re-injury when distracted in the real world [8,9]. The large degree of heterogeneity in laboratory-based case control studies of static & dynamic postural control in subsets of healthy and functional unstable ankles may thus be due to assessment of postural stability in highly controlled environments, not simulating real-world

* Corresponding author at: ASU Box 32071, 1179 State Farm Road, Room 422, Boone, NC 28608, USA.
E-mail address: needlear@appstate.edu (A.R. Needle).

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constraints [9,10].

Dual-task paradigms, in which secondary motor or cognitive tasks are added to assessment of balance or gait, may increase our understanding of this phenomenon [11,12]. Under these conditions, motor control may degrade due to limited cortical resources (i.e. limited capacity theory) [11], or cause delays as tasks are processed consecutively rather than simultaneously [12,13]. A recent systematic review concluded cognitive demand impairs motor behavior in individuals with musculoskeletal injuries, with deficits more clear with greater task complexity [9]. In CAI, results were more varied; however, some limitations existed including simple motor tasks (i.e. static balance, unimpeded gait) and the use of mostly quantitative cognitive tasks (e.g. serial subtraction). One previous investigation implemented multiple modalities of cognitive loading with a static balance task among individuals with chronic ankle instability, but failed to uncover group differences [14].

In order to better understand the role that competition for cognitive resources may play on expressing injury-prone biomechanics, we aimed to determine the effects of multiple modalities of cognitive load (quantitative, verbal-memory, visuospatial) on dynamic postural control strategies in a sample of individuals with CAI compared to uninjured controls. We hypothesized that all cognitive loads would impair dynamic postural control and muscle activation, with this decrease being more severe in subjects with CAI.

2. METHODS

2.1. Study Design

This study utilized a case control design. Dependent variables included dynamic postural stability indices (DPSIs), as well as average muscle activity from the tibialis anterior (TA), peroneus longus (PL), and lateral gastrocnemius (LG). The primary independent variables were group (CAI versus healthy) and cognitive task, while dynamic postural stability direction and timing of muscle activation (pre- vs post-activation) relative to landing were secondary independent variables.

2.2. Participants

Thirty-two participants were recruited for this study from a University population. Participants were stratified into a CAI group and a control group using recommendations set by the International Ankle Consortium [15]. CAI participants had ≥ 1 ankle sprain more than 1 year ago, and a score ≥ 11 on the Identification of Functional Ankle Instability (IdFAI) questionnaire [16]. Healthy controls had no history of ankle sprain or other relevant lower extremity injuries, and an IdFAI score ≤ 10. All subjects were free of lower-extremity injury for 3-months prior to testing, and had no vestibular or cognitive deficits. Participants were asked to wear any corrective eyewear that they would use throughout daily activity for testing. For healthy subjects, and participants with bilateral CAI, a test leg was randomly determined using a coin flip.

2.3. Procedures

Participants reported to the laboratory for a single test session. First, participants were seated in a quiet office and provided University-approved informed consent, and completed questionnaires providing demographic information and confirming inclusion criteria. In this setting, participants were then tested for baseline performance on three cognitive tests. Benton's Judgment of Line Orientation (JLO) was a visuospatial task that tested the participants' ability to match randomly aligned rays to a series of reference angles, numbered 1 to 11. Participants were assessed for the time taken to complete the 30-item inventory, and the number of correct items. The Symbol Digit Modalities Test (SDM) tested verbal-memory by having subjects read through a list of symbols by using a reference key to match the symbols to numbers. Participants were instructed to read as many correct numbers in 90 seconds as possible, and were assessed for the number of correct matches in that time. Serial Seven subtractions (SVN) tested quantitative ability by having participants count backwards from a randomly generated number between 200 and 300 by consecutively subtracting 7 from the previous number. Participants were instructed to perform a total of 10 subtractions, with performance time and number of correct subtractions used as measures of performance. Each test was explained to the participant, and a practice set was provided for each, consisting of 5 pages of the JLO, 10 symbols on the SDM, and 5 subtractions for SVN. Tests were presented in a random order [17].

Participants were then brought into the laboratory where they were instrumented with electromyography (EMG) electrodes over the TA, PL, and LG of the test leg. Each muscle was palpated, shaved, cleaned with 70% alcohol solution, and abraded prior to Ag/AgCl electrodes being placed along each muscle and affixed with a double-sided sticker [18]. The leg was then wrapped with an elastic wrap to minimize electrode movement, a reference electrode was placed on the tibial tuberosity, and all electrodes were connected to an amplifier (Bagnoli, Delsys, Inc., Boston, MA).

Participants were assessed for dynamic balance through a hop-to-stabilization [19,20]. Participants were provided a 15-foot walkway leading up to a force plate (Kistler Instrument Corp, Amherst, NY). A 10 cm hurdle was placed a distance of the participant's leg length from the base of the force plate. Participants were instructed to take a 2-step approach – beginning with the test leg – and to hop forward off the non-test leg, over the hurdle, and onto the force plate (Fig. 1). Upon landing, participants were instructed to stabilize on the test limb, place their hands on their hips, and maintain that position for 15 seconds. Participants were provided up to 5 trials to practice the maneuver before beginning test trials.

Participants performed a total of 20 successful hop-to-stabilizations, with 5 performed under each of four conditions: JLO, SDM, SVN, and a control condition (CON). Successful hops were those in which the subject land and maintained single-limb balance for the full 15-seconds. For the JLO and SDM, cues of the line angles with reference, and symbols and key were projected onto a screen 10-feet in front of the force plate. One JLO item was presented at a time, while the full grid of SDM items with key were presented at once, with a cursor used to aid eye tracking. Participants were instructed to begin performing the task, and at a random point within 10-seconds, the PI gave a "go" cue to begin the hop. Once given the cue, participants were instructed to perform the hop-to-stabilization while continuously performing the cognitive task. The number of items within each task completed were recorded by investigators and reported in Table 1.

2.4. Data Reduction

Force plate and EMG data were synchronously collected at 1000 Hz in custom LabVIEW software (National Instruments, Austin, TX). Postural stability indices were calculated in the anteroposterior (APSI), mediolateral (MLSI) and vertical (VSI) planes, as described by Wikstrom et al. [21], as well as calculating an overall DPSI. Muscle activation was bandpass filtered (20-400 Hz), rectified, and low-pass filtered (10 Hz) to create a complete linear envelope. Activation was normalized to the ensemble peak across all hops. Mean muscle activation was extracted in three time periods: 250-ms prior to landing (PRE), 0-250-ms after force plate contact (POST-1), and 250-500-ms after force plate contact (POST-2) [19,22,23]. Force plate contact was determined as the point vertical ground reaction force exceeded 50 N [19,23].

2.5. Data Analysis

Baseline differences between groups for demographics and

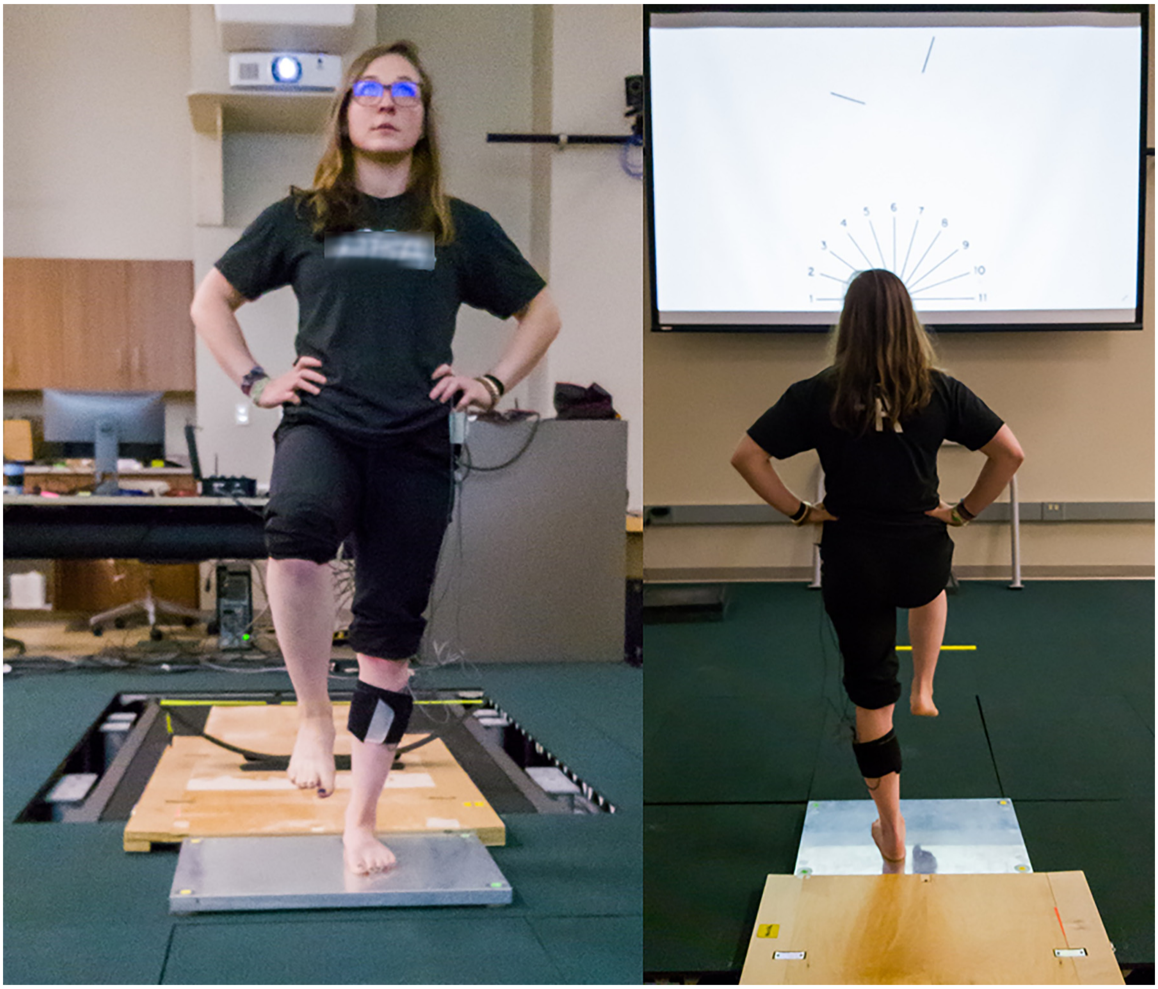

Fig. 1. Experimental set-up featuring runway, hurdle, and force plate with placement of screen.

cognitive task performance were assessed using independent sample t-tests. For dynamic postural stability, a three-way analysis of variance (ANOVA) was used with the between-subjects factor of group (CAI vs. healthy; 2 levels) and within-subjects factors of task (JLO, SDM, SVN, CON; 4-levels) and direction (APSI, MLSI, VSI, DPSI; 4-levels). For EMG activation, 3-way ANOVA's were conducted for each muscle with the between-subjects factor of group (CAI vs. healthy; 2 levels) and within-subjects factors of task (JLO, SDM, SVN, CON; 4-levels) and time (PRE, POST-1, POST-2; 3-levels). In the case of significant interaction or main effects, Fisher's least significant difference was used for post hoc comparisons. Effects sizes were determined using partial eta-squared (η_p^2) and Cohen's d, with $\eta_p^2 = 0.02$ or $d = 0.3$ considered a small effect, $\eta_p^2 = 0.06$ or $d = 0.5$ considered a medium effect, and $\eta_p^2 = 0.14$ or $d = 0.7$ considered a large effect. An a priori level of significance was set at 0.05.

Table 1
GROUP DEMOGRAPHICS.

	HEALTHY	CAI	P-value	95% CI
N (M/F)	17 (9/8)	16 (7/9)		
Age (years)	21.74 (3.10)	21.44 (2.19)	0.777	−1.65, 2.17
Height (cm)	171.82 (9.75)	174.23 (8.47)	0.456	−8.90, 4.10
Weight (kg)	69.73 (14.40)	73.72 (12.93)	0.410	−13.73, 5.75
IdFAI Score	1.56 (2.73)	16.41 (3.95)	< 0.001‡	−17.18, -12.53
JLO Baseline Correct (%)	79.02 (15.00)	78.22 (9.75)	0.862	−8.47, 10.07
JLO Baseline Time (s)	127.71 (18.80)	138.23 (29.28)	0.245†	−28.78, 7.72
JLO Correct per Hop (n)	5.40 (0.99)	5.50 (1.66)	0.843	−1.07, 0.88
SDM Baseline Correct (n)	63.71 (10.66)	61.88 (9.89)	0.613	−5.48, 9.15
SDM Baseline Correct (%)	96.90 (2.91)	99.01 (1.90)	0.020*†	−3.85, -0.36
SDM Correct per Hop (n)	15.69 (2.18)	16.34 (2.55)	0.426	−2.31, 1.00
SVN Baseline Correct (%)	83.92 (13.35)	88.44 (9.91)	0.291	−13.11, 4.06
SVN Time (s)	102.69 (62.15)	88.91 (37.91)	0.451	−23.06, 50.62
SVN Correct per Hop (n)	4.36 (2.47)	5.40 (3.33)	0.308	−3.11, 1.01

*Significant at $\alpha = 0.05$; † Adjustment used for unequal variances. ‡Non-parametric Mann Whitney U used.
Abbreviations: IdFAI, Identification of Functional Ankle Instability; CAI, chronic ankle instability; 95% CI, 95 percent confidence interval; JLO, Judgment of Line Orientation; SDM, Symbol Digit Modalities Test; SVN, serial sevens

Table 2
POSTURAL STABILITY INDICES ACROSS TASKS AND GROUPS.

		HEALTHY	CAI
APSI	Control	0.188 (0.063)	0.183 (0.027)
	JLO	0.181 (0.025)	0.179 (0.029)
	SDM	0.174 (0.030)	0.182 (0.024)
	SVN	0.178 (0.028)	0.182 (0.027)
MLSI	Control	0.020 (0.011)	0.017 (0.005)
	JLO	0.020 (0.005)	0.017 (0.005)
	SDM	0.019 (0.006)	0.019 (0.004)
	SVN	0.018 (0.006)	0.018 (0.005)
VSI	Control	0.424 (0.118)	0.385 (0.040)
	JLO	0.380 (0.047)[a]	0.376 (0.045)
	SDM	0.388 (0.056)	0.391 (0.047)
	SVN	0.374 (0.045)[a]	0.388 (0.047)
DPSI	Control	0.466 (0.129)	0.427 (0.044)
	JLO	0.423 (0.048)[a]	0.418 (0.045)
	SDM	0.428 (0.051)	0.432 (0.049)
	SVN	0.416 (0.047)[a]	0.430 (0.049)

Abbreviations: CAI, chronic ankle instability; APSI, anteroposterior stability index; MLSI, mediolateral stability index; VSI, vertical stability index; DPSI, dynamic postural stability index; JLO, Judgment of Line Orientation; SDM, Symbol Digit Modalities Test; SVN, serial sevens

[a] Significantly different from the control condition.

3. RESULTS

Group demographics, baseline scores, and cognitive performance during hopping are presented in Table 1. Significant differences were only detected for percent correct on SDM at baseline. The CAI group displayed a significantly higher percentage correct on the SDM (P = 0.020).

DPSIs are presented in Table 2. A significant three-way (Group-by-Task-by-Direction) interaction effect was observed (F = 2.571, P = 0.007, η_p^2 = 0.077). Pairwise comparisons revealed that groups were not different from each other at any direction or task combination ($P > 0.05$); however, among healthy subjects, DPSI and VSI were higher in the control condition than JLO (DPSI: P = 0.017, d = 0.441; VSI: P = 0.011, d = 0.490) or SVN (DPSI: P = 0.010, d = 0.515; VSI: P = 0.006, d = 0.560), while MLSI was higher in JLO than SVN. No differences were observed among CAI ($P > 0.05$).

Muscle activation values are presented in Table 3. For mean TA activation, no significant three-way interaction effect was observed (F = 0.350, P = 0.909, η_p^2 = 0.011). A significant task-by-group effect was observed (F = 3.312, P = 0.023, η_p^2 = 0.097). Pairwise comparisons revealed that while groups were not different for any 2 tests ($P > 0.05$), among healthy subjects EMG activation was greater in the SDM compared to JLO (P = 0.021, d = 0.365) and SVN (P = 0.028, d = 0.394).

For mean PL activation, no significant three-way interaction effect was observed ($F_{6,\ 186}$ = 1.238, P = 0.289, η_p^2 = 0.038). No significant task-by-group (F = 1.315, P = 0.274, η_p^2 = 0.041. There was a significant main effect of task (F = 4.684, P = 0.004, η_p^2 = 0.131), with post-hoc testing revealing PL activation was least in SVN compared to Control (P = 0.033, d = 0.424), JLO (P = 0.008, d = 0.482), and SDM (P = 0.004, d = 0.518). No significant main effect of group was observed (F = 0.413, P = 0.525, η_p^2 = 0.013).

For mean LG activation, no significant three-way interaction effect was observed (F = 1.660, P = 0.133, η_p^2 = 0.051). A significant time-by-task effect was observed (F = 21.336, $P < 0.001$, η_p^2 = 0.408); however no task-by-group (F = 1.406, P = 0.246, η_p^2 = 0.043) effect was observed. Pairwise comparisons revealed that PRE activity was least under the SVN condition compared to CON, JLO, and SDM ($P \leq 0.001$, $d \geq 0.911$), POST-1 activity was greater in SDM than JLO (P = 0.033, d = 0.449), and POST-2 activity was greatest in SDM and SVN compared to CON (p = 0.012, d = 0.527; P = 0.013, d = 0.514) and JLO (P = 0.001, d = 0.705; $P < 0.001$, d = 0.720). Further, while for CON and JLO, LG activation decreased over time ($P \leq 0.001$, $d \geq 0.434$), SDM displayed a significantly decrease from PRE to POST-1 (P = 0.033, d = 0.436) and POST-2 ($P < 0.001$, d = 0.560), but did not change between POST measurements (P = 0.242). Finally, SVN displayed an *increase* in LG activation from PRE to POST-1 (P = 0.031, d = 0.338). There was no significant main effect of group (F = 0.300, P = 0.588, η_p^2 = 0.010).

4. DISCUSSION

In the current study, we aimed to determine the effect of different modalities of cognitive load on dynamic balance and neuromuscular

Table 3
MEAN EMG ACROSS TIMES AND TASKS.

TA		**PRE**[d,e]		**POST-1**		**POST-2**	
		Healthy	*CAI*	*Healthy*	*CAI*	*Healthy*	*CAI*
	CON	42.10 (13.44)	34.67 (16.88)	55.01 (17.14)	43.46 (18.13)	48.01 (14.31)	43.31 (17.84)
	JLO	42.09 (17.75)	37.65 (19.29)	51.13 (15.61)	44.13 (22.01)	42.85 (13.14)	46.79 (18.42)
	SDM	46.23[a,c] (14.35)	46.79 (18.42)	59.05[a,c] (16.81)	44.74 (19.11)	50.99[a,c] (19.12)	46.34 (20.97)
	SVN	41.74 (15.27)	40.50 (21.18)	50.05 (16.55)	46.81 (18.16)	43.06 (17.01)	50.75 (16.75)
PL		**PRE**[d]		**POST-1**[e]		**POST-2**	
		Healthy	*CAI*	*Healthy*	*CAI*	*Healthy*	*CAI*
	CON[c]	49.47 (17.74)	49.65 (12.97)	52.14 (12.07)	56.03 (12.96)	44.15 (14.97)	45.69 (8.79)
	JLO[c]	49.47 (18.03)	47.95 (11.86)	54.46 (12.28)	57.24 (14.61)	47.86 (15.49)	46.37 (12.67)
	SDM[c]	52.70 (16.53)	50.65 (14.41)	59.05 (16.81)	44.75 (19.12)	51.35 (12.22)	47.77 (11.31)
	SVN	41.74 (15.27)	40.50 (21.17)	50.05 (16.55)	46.81 (18.16)	41.41 (15.43)	42.42 (11.93)
LG		**PRE**		**POST-1**		**POST-2**	
		Healthy	*CAI*	*Healthy*	*CAI*	*Healthy*	*CAI*
	CON	67.83[c,d,e] (16.01)	59.01[c,d,e] (15.05)	43.00[e] (16.19)	44.62[e] (13.03)	34.09[b,c] (17.59)	38.46[b,c] (17.21)
	JLO	65.54[c,d,e] (12.86)	62.54[c,d,e] (12.33)	39.20[b,e] (17.78)	45.61[b,e] (18.65)	31.32[b,c] (17.40)	34.07[b,c] (11.12)
	SDM	64.96[c,d,e] (17.23)	57.45[c,d,e] (17.44)	59.05 (16.81)	44.75 (19.12)	50.99 (19.11)	46.34 (20.97)
	SVN	41.74[d] (15.27)	40.50[d] (21.17)	50.05 (16.55)	46.81 (18.16)	43.06 (17.01)	50.75 (16.75)

Abbreviations: TA, tibialis anterior; PL, peroneus longus; LG, lateral gastrocnemius; PRE, 250-ms before force plate contact; POST-1, 250-ms following force plate contact; POST-2, 250-500 ms following force plate contact; CAI, chronic ankle instability; JLO, Judgment of Line Orientation; SDM, Symbol Digit Modalities Test; SVN, serial sevens

[a] Significant difference from JLO.

[b] Significant difference from SDMT.

[c] Significant difference from SVN.

[d] Significant difference from POST-1.

[e] Significant difference from POST-2.

control in individuals with CAI. While we hypothesized the presence of cognitive load would negatively affect balance and muscle activation in CAI, the results of this study suggest a more complex interaction between type of cognitive load and dynamic balance among these populations. Our primary findings were that healthy individuals had *improved* balance when under visuospatial and quantitative cognitive tasks, but not under a verbal-memory task, while balance in CAI individuals was unaffected. Further, we observe trends in muscle activation that indicate the quantitative task (SVN) decreased muscle activation, while muscle activation was highest in the verbal-memory cognitive task.

4.1. Dynamic Balance

All studies investigating the role of cognitive load on balance in individuals with musculoskeletal injury have used a static model, evaluating excursion of the center of pressure [9]. Studying dynamic balance may present a more challenging paradigm to participants, involving a greater degree of feed-forward (preparatory) neuromuscular control, in addition to feedback (reactive) neuromuscular control to quickly and safely stabilize the lower extremity as the center of mass moves [24]. The hop-to-stabilization model has previously been used to successfully differentiate healthy and CAI populations, although with sometimes mixed results [21,25].

In the present study, we failed to establish any direct between-group differences related to DPSIs between groups. Although previous hop-to-stabilization models have established deficits in unstable ankles [25], some differences exist with these previous models including the type of hop (2-step approach versus double-to-single limb) and outcome measures (time-to-stabilization versus DPSIs). These data suggest that our cohort of individuals were able to balance similarly under laboratory conditions despite injury history. Interestingly, with the addition of cognitive loading, changes were observed in our healthy population that suggested *improved* balance under cognitive demand. Specifically, the visuospatial task (JLO) and the quantitative task (SVN) results in lower VSI and DPSI, albeit with small-to-medium effect sizes. As increased arousal within an optimal window is tied to improvements in motor performance, it is possible these visual and quantitative demands provided arousal contributing to better dynamic balance, while verbal-memory either did not sufficiently change arousal or was too great of a change that led to similar performance [26]. It is possible visuospatial (JLO) and quantitative (SVN) tasks may be more representative to the types of challenges individuals are more likely to face during lower extremity motor tasks, as opposed to a verbal-memory (SDM) task that would have a lesser role in athletic performance.

It is notable that a change was observed in healthy subjects that was not observed in CAI. We propose multiple hypotheses to explain these effects. First, it is possible that due to injury-induced neuroplasticity, the increased cognitive demand was not able to optimize motor performance, but rather elicited no change in CAI. Accordingly, this may indicate a lack of motor flexibility in this group, whereby healthy individuals adapt motor patterns under cognitive demand, but CAI does not. These findings were supported in previous work investigation multiple cognitive domains with a motor task among those with CAI [14]. Therefore, these individuals may lack the task flexibility to modify motor patterns under real-world constraints. The lack of improvements in CAI could also be relevant to activation of supraspinal pathways, whereby controls may be able to better regulate the motor task through subcortical structures. Thus, CAI may lack flexibility to reweight feedback, as this population has been shown to have greater reliance on visual processing [27]. Similar findings have been observed in models of low back pain, where those with the pathology are unaffected by increased cognitive demand, but those without the injury change movement patterns, lending itself to similar conclusions [28]. An additional consideration could be within the prioritized task, whereby CAI lent more attention to the motor task allowing for maintenance of balance [9,29]. Quantifying the level of attention to each domain proves quite difficult; however, post hoc analysis revealed no differences in task performance across groups.

4.2. Neuromuscular Control

Dynamic balance presents a larger challenge to neuromuscular control than traditional static balance due to the increased demand on preparatory muscular activation [24]. Few studies have included measures of muscle activation with hop-to-stabilization tasks, nor have studies investigated the effects of cognitive loading on electromyographic activity in the CAI population. Data from other injury models led us to hypothesize that activation would be decreased or delayed under cognitive demand, but our data does not support this hypothesis. Cognitive demand was observed to modify muscle activation; however, only small differences were observed between healthy and CAI, specifically that healthy subjects had higher TA activation in the SDM compared to other conditions. While this could indicate a more protective degree of muscle activation under the verbal-memory task, small effect sizes suggest caution should be used in this interpretation.

Although minimal differences were observed across groups, an effect of cognitive load was seen across all subjects. The largest number of changes were observed in reference to the quantitative task (SVN), where the PL and LG both displayed decreased muscle activation. This was true across all time-points for the PL, and particularly at pre-activation for LG – both crucial muscles for the maintenance of balance, tied to landing softly and making small modulations to the center of pressure [19,24]. The finding that greatest differences were observed for the quantitative task (SVN) is particularly interesting, as it was the only cognitive task that did not involve a visual component. Therefore, it seems that cognitive tasks challenging vision did not seem to impair the amount of muscle activation, nor did it compete for activation resources of the lower leg, while a quantitative task did cause this change. While this seems counterintuitive to our hypotheses, it is possible that during visual tasks, the requirement of visual focus led to an increase in EMG as a protective mechanism. The role of visual feedback on balance tasks is well established in static balance models, but its role in dynamic movements is more ambiguous [27,30].

While SVN generally appeared to decrease EMG activity, SDM generally led to an increased amount of muscle activation. This was evident in the TA among healthy subjects, as well as the LG following landing. An argument could be made that the SDM should have the greatest impact on the ability to stabilize the ankle, due to having both a visual component, and requiring the use of working memory [31]. While we hypothesized that these cognitive loads would decrease muscle activation, it is possible that when under increased challenge, protective increases in muscle activation occurred. While increased working-memory demand appeared beneficial for joint stability, caution should be urged as this was assessed in a laboratory setting.

Some limitations existed within the presented investigation. Subjects were not screened by investigators for visual acuity, but were asked to use corrective eyewear that they would use during normal daily activity. The nature of the task made it difficult to regulate attention towards the motor and cognitive tasks, and the cognitive task outcome measures would be difficult to assess over a short 15-25-second task window. Future investigations could potentially manipulate participant instruction to understand the role of attentional shifts towards the motor or cognitive tasks [29].

5. CONCLUSIONS

This was the first study to compare measures of dynamic balance and muscle activation under cognitive demand in individuals with CAI. Further, our design allowed us to determine how different types of cognitive demand impacted healthy and CAI individuals during this dynamic task. Our findings generally contrast to those previously reported in these populations, with dynamic balance generally unaffected in those with CAI, while healthy individuals demonstrated *improved* dynamic balance under visuospatial and quantitative cognitive demand. We posit that this represents an optimization of balance under cognitive demand in healthy individuals that does not affect those with CAI, potentially indicating a lack of task flexibility. Meanwhile, across all individuals muscle activation was lowest in the quantitative condition, and greatest under the verbal-memory condition. This suggests that cognitive tasks that require more visual and working memory requirements potentially lead to more protective mechanisms during dynamic balance, while quantitative tasks may contribute to a potentially less protective or stable landing.

Declaration of Competing Interest

The authors have no financial or personal relationships with other people or organizations that could inappropriately influence or bias this work.

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