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The Influence of Concussion History and Progressively Increasing Cognitive Load on Jump Landing and Cutting Reaction Time, Biomechanics, and Task Demands

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Abstract

<u>Context:</u> There is a 2-4x increased risk for musculoskeletal injury after concussion. A potential reason for the increased risk is aberrant biomechanics. The majority of prior research has focused on single-task biomechanics, but dual-task biomechanics may better represent athletic competition.

<u>Objective:</u> To compare (1) jump landing and cutting biomechanics, (2) dual-task cost cognitive outcomes, and (3) perceived task difficulty/demands under single- and dual-task conditions (no-counting, serial 3s, serial 7s) between individuals with and without a concussion history.

<u>Design:</u> Cross-sectional.

<u>Setting:</u> Biomechanics laboratory.

<u>Participants:</u> Twenty-three individuals with (age:20.2±1.9years, BMI:22.9±2.7kg/m^2, 60.9% female, 44.7 months [95% confidence interval=23.6, 65.7] post-concussion) and 23 individuals without (age: 20.7±1.7years, BMI: 22.4±2.3kg/m^2, 60.9% female) a concussion history participated.

<u>Main Outcome Measures:</u> Jump landing and cutting trunk lower extremity kinematics and kinetics under single- and dual-task conditions. Cognitive accuracy and response rate during dual-tasking. NASA Task Load Index questionnaire.

Results: During the jump landing, all participants exhibited a significantly faster reaction time during no counting versus serial 3s ($p<0.001$, Hedge's $g=1.187$) and serial 7s ($p<0.001$, Hedge's $g=1.526$). During the cutting, all participants exhibited a significantly faster reaction time during no counting versus serial 3s ($p<0.001$, Hedge's $g=0.910$) and serial 7s ($p<0.001$, Hedge's $g=1.261$), and serial 3s versus serial 7s ($p=0.002$, Hedge's $g=0.319$). All participants reported lower task demands during jump landing and cutting for no counting versus serial 3s ($p<0.001$) and serial 7s ($p<0.001$), and serial 3s versus serial 7s ($p<0.001$).

Conclusion: Concussion history did not affect any of our outcomes, possibly because lingering biomechanical deficits may have resolved in our sample. Task demands did increase with increasing cognitive load, which may be beneficial for progressively manipulating the dual-task cognitive component during rehabilitation.

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Key Words: mild traumatic brain injury, musculoskeletal injury, cognitive hierarchy, counting, serial subtraction

Key Points:

1. Single-task reaction time was faster than dual-task, but there was no difference between dual-task conditions (serial 3s vs 7s).
2. All participants reported lower task demands (NASA Task Load Index) in a hierarchical fashion (no counting $<$ serial 3s $<$ serial 7s).

Following a concussion, there is an increased risk for upper and lower extremity musculoskeletal injury for up to 1- and 2-years post-concussion, respectively,[1,2] but without a known cause. Typical clinical concussion assessments[3] and mental health measures[4] are not related to future musculoskeletal injury post-concussion. One hypothesis is that individuals with a concussion history have a worsened ability to dual-task.[5,6] Since dual-tasking is crucial for sport, an inability to properly process all necessary stimuli may lead to aberrant biomechanics and injury.[6,7] This is exemplified by dual-task gait performance[8] and working memory performance[9] predicting future musculoskeletal injury post-concussion among adolescents and collegiate athlete, respectively.

Dual-tasking often leads to more aberrant landing biomechanics[7,10,11] and is more representative of a sports environment.[12] During a dual-task cutting maneuver, individuals ~3.1 years post-concussion displayed greater high-risk knee biomechanics compared to controls.[13] However, conflicting evidence from a similar population suggests no differences between single- and dual-task stabilization time or biomechanics during a single-leg hop under dual-task conditions.[14] More evidence is needed to understand the effects of dual-tasking on athletic tasks post-concussion.

Dual-tasking has recently been included as an important part of an adolescent training program to reduce musculoskeletal injuries post-concussion.[15] The majority of research uses post-concussion uses working memory tasks (e.g., serial subtraction, spelling words backwards, reciting months in reverse order). A recent review of dual-task methodology among concussed populations showed that 60.9%, 26.1%, and 13.0% of the 23 reviewed studies used the aforementioned working memory tasks, auditory Stroop, or visual Stroop task, respectively.[16] However, using Stroop tasks are not as clinically feasible compared to participants simply counting backwards. Further, working memory tasks have shown to negatively affect both the cognitive and motor task whereas verbal fluency and visual Stroop tasks only effect the motor portion.[17] Within the working memory tasks, there is no clear hierarchy of difficulty for the cognitive component of dual-tasking for appropriate progression.[18]

During a timed up-and-go test, increasing the cognitive load from serial 3s to 7s led to a longer time to completion for adults post-stroke and healthy controls.[19] Similar results were found among adolescents—as the complexity of the dual-task increased during gait (easy, medium, hard), the center of mass anterior velocity decreased.[20] Introducing various levels of dual-tasking into sport-specific movements (e.g., jump landing) will create a hierarchy of difficulty which clinicians can follow to properly progress athletes during rehabilitation. Unfortunately, little is known about how this hierarchy of difficulty translates to athletic tasks and no research has been done on perceived task demands which means clinicians are left in the dark about proper implementation.

It is important to understand the self-reported task demands of single- and dual-task athletic movements because patients are more than just their biomechanical outcomes. For example, if a concussion patient is going through jump training rehabilitation to reduce their risk of musculoskeletal injury, it may be more beneficial to utilize a task that requires a high degree of self-perceived task demands at the beginning of the rehabilitation session. Incorporating a higher level of demanding task at the beginning of the session may be optimal since the patient is fully energized and not fatigued (as the patient may be at the end of the rehabilitation sessions). Or, a clinician may choose to use a higher level of demanding task at the end of the session in order to encourage a higher level of focus when the patient is fatigued to mimic end of game scenarios in competition. However, none of these decisions can be made by clinicians until the task demands of various dual-tasking difficulties and athletic tasks are explored.

This study aimed to compare (1) jump landing and cutting biomechanics and functional reaction time, (2) dual-task cost cognitive outcomes, and (3) perceived task difficulty/demands under single- and dual-task conditions (no-counting, serial 3s, serial 7s) between individuals with and without a concussion history. We hypothesized that (1) individuals with a concussion history would display worse landing biomechanics and functional reaction time across all cognitive conditions, and all individuals (regardless of concussion history) would display worse landing biomechanics and functional reaction time as cognitive load increased (no counting to serial 3s to serial 7s), (2) dual-task cognitive outcomes would be worse for the concussion history group, but would get progressively worse from serial 3s to serial 7s for all participants, and (3) individuals with a concussion history would perceive dual-tasking to be more difficult compared to controls, but all individuals would perceive task difficulty to increase with cognitive load.

Methods

This study was part of a larger 2-day protocol (clinicaltrials.gov #: NCT06093295), and all methods were approved by the University's institutional review board (PROJECT00007759). All jump landing and cutting tasks presented in this study occurred before the intervention portion of the clinical trial on day 1. Participants provided written and informed consent before participation and received an honorarium for their participation.

Participants

Participants were included if they self-reported being physically active for at least 90-minutes per week and were 18-30 years old. Concussion history was self-reported and collected with the National Institutes of Health common data element form.[21] A concussion was defined as a "traumatic brain injury caused by a direct blow to the head, neck or body resulting in an impulsive force being transmitted to the brain" per the 6th International Consensus Statement.[22] All mechanisms were included.

Concussion history participants were excluded if they self-reported being admitted to the hospital post-concussion or reported ≥13 symptom severity on the Sport Concussion Assessment Tool symptom inventory.[23] To mitigate the risk of participants with persistent symptoms (i.e., post-concussion syndrome) the cut-off was chosen. The cut-off of ≥13 was chosen based on normative data that athletes report a ~3 symptom severity when not-concussed (e.g., baseline, preseason).[23] The reliable change parameter (i.e., the cut-point for determining clinical impairment) was 10 from the same study.[23] Control group participants were excluded if they self-reported experiencing a concussion in their lifetime. All participants were excluded if they self-reported having attention deficit hyperactivity disorder, attention deficit disorder, uncorrected vision problems, history of neurological disease or seizures, structural brain lesions (e.g., stroke), currently using antidepressants, currently experiencing a high fever, or undergoing immunosuppressive therapy. We did not exclude based on musculoskeletal injury history; however, we did exclude if participants were currently experiencing an MSKI.

Groups were matched by age (±2 years), sex, and body mass index (±2 kg/m^2). One of the concussion history participants did not feel comfortable performing the cutting task with their current style of shoes and is only included in the jump landing analyses. The concussion history's matched control was also removed from the cutting analysis.

Demographics

Demographics included age, sex, height, mass, Sport Concussion Assessment Tool symptom inventory,[24] Godin Leisure Activity Questionnaire,[25] Lower Extremity Functional Scale,[26] a self-reported musculoskeletal injury form), and dominant limb. The self-reported musculoskeletal injury form was adapted from prior research.[14] The original form[14] asked participants to report whether they had sustained any musculoskeletal injury to the lower extremity or back within the past 5 years. We asked participants to report traumatic injuries across their lifetime (e.g., any fractures, muscle tears, ligament tears). Dominant limb was defined as which limb participants prefer to kick a soccer ball for distance.

The Tampa Scale of Kinesiophobia 11 (TSK11)[28,29] was also collected, but the TSK11 was collected after jump landing and cutting due to it being a question in the larger 2-day study. The TSK11 is reported as a demographic variable and has shown good-excellent test-retest reliability (ICC=0.87)[28] and convergent validity (r=0.60).[29]

Single-task *Serial Subtraction*

Participants performed a baseline single-task serial subtraction by 3s and 7s from a random integer between 90 and 200.[30] Trials lasted 20 seconds. One practice trial and 3 recorded trials were completed per condition (6 total trials). Participants were instructed to subtract as quickly and as accurately as possible. Participants were audio-recorded to be scored offline.

Serial 7s and 3s were chosen because research showed no differences in gait biomechanics between the commonly used assessments of serial subtraction, spelling words backwards, and reciting months in reverse.[31] However, serial 7s has been proven to be more difficult than serial 3s during single-task conditions.[30] Since the most recent Sport Concussion Assessment Tool 6 only requires serial subtraction during gait for dual-task conditions,[32] we opted to compared serial 3s and 7s.

Single- and Dual-task Jump Landing and Cut

A 30cm box was placed half the participants' height away from two force plates.[33] Participants stood on the box, and assumed an athletic position when the researcher said, "Get set".[27] An audible buzzer was randomly played 2-5 seconds after the "get set" cue. The buzzer sound cued the participants to jump forward toward two force plates embedded in the ground. Participants were instructed to react as quickly as possible. For the jump landing, participants landed with both feet simultaneously on the two force plates (one foot per plate). Immediately upon landing, participants jumped straight up into the air as high as possible. For the cut, participants only used their nondominant limbs. Participants were asked to land on their nondominant limb and cut 45 degrees in the opposite direction. All participants were given at least one practice trial for all conditions and continued to practice until they reported feeling comfortable.

For dual-task conditions, the participants performed serial subtraction by either 3s or 7s starting from an integer between 90-200. Participants were instructed to subtract as quickly and as accurately as possible, as and to perform the motor task to the best of their abilities. Participants started counting while on the box, continued counting when performing the movement, and continued to count until the researcher said: “stop”. The research team let the participant complete/attempt ~2-3 words after landing from the jump landing and running after the cut before saying “stop”.

The jump landing and cutting tasks were block randomized such that all conditions of the jump landing were completed before moving on to the cutting, or vice-versa. Single-task conditions were always completed first. Serial 3s and Serial 7s were randomized after single-task conditions. All trials of one condition were completed before moving on to the next condition.

Three jump landings and three cuts off the nondominant limb were collected for each cognitive condition (9 jump landing trials; 9 cut trials). A failed trial was discarded and repeated. Failed trials included: stepping off the box before the light, not landing with the whole foot inside the force plate, not landing with both feet simultaneously on the force plates (jump landing only), not sprinting to the cones during the cut, clear and obvious avoidance of the serial subtraction, forgetting to continue subtracting after landing or while sprinting to the cones.

National Aeronautics Space Association (NASA) Task Load Index

The NASA Task Load Index was administered after each of the six conditions. For example, the NASA Task Load Index was administered immediately after completion of the jump landing with no counting, jump landing with serial 3s, and jump landing with serial 7s.

Data Reduction and Processing

Cognitive and dual-task effect calculations are described in Table 1. During jump landing and cutting, the serial subtraction duration is between the start of counting and when the research team said, “stop”. Dual-task effect was calculated as described in Equation 1. Negative dual-task effect represents worse performance during the dual-task vs single-task condition (i.e., dual-task cost), and a positive dual-task effect represent better performance during the dual-task vs single-task condition (i.e., dual-task benefit).[34]

Equation 1: $\left(\frac{(dual-task\ performance)-(single-task\ performance)}{(single-task\ performance)}\right)\times 100$

[Insert Table 1 Here]

Equation 2: $\left(\frac{Correct\ Responses}{Trial\ Time}\right)$

Equation 3: $\left(\frac{Correct\ Responses}{Attempts}\right)\times 100$

For jump landing and cutting, retroreflective markers (~14 millimeters in diameter) were placed bilaterally on the acromioclavicular joints, iliac crests, greater trochanters, and anterior superior iliac spines. Additionally, markers were placed bilaterally on both limbs' medial and lateral femoral epicondyles, medial and lateral malleoli, calcaneus, 5th metatarsal, and 2nd metatarsal. A marker was also placed on the sternal notch.[7] A cluster of noncolinear markers (3/4 markers per cluster) was placed on the posterior superior iliac spines and sacral body and placed bilaterally on the nondominant thigh, shank, and foot.[7] Marker position data were sampled at 240 Hz with a 10-camera Qualisys motion capture system (MIQUIS; Qualisys Systems, Göteborg, Sweden). Force plate data were sampled at 2400 Hz with two Bertec force plates (Bertec, Columbus, OH).

Raw marker position data and force data were exported to Visual 3D software (C-Motion Inc., Rockville, MD, USA) for analysis. All data (marker and force) were processed with a fourth-order, low-pass Butterworth, at 10 Hz similar to prior research.[27,35,36] Marker and force data were filtered at the same frequency to reduce joint moment artefacts.[37,38] The anterior and posterior superior iliac spines defined the pelvis, hip joint centers were estimated using the Bell Method, knee joint centers were estimated using the midpoint between medial and lateral femoral epicondyles, and ankle joint centers were estimated using the midpoint between the medial and lateral malleoli. Euler/Cardan angles (YXZ rotation sequence) were used to calculate the hip, knee, and ankle angles. Hip motions were defined as the thigh relative to the pelvis, knee motions were defined as the shank relative to the thigh, and ankle motions were defined as the foot relative to the shank. Trunk motion was defined relative to the lab (absolute angles). Rotation about the y-axis, x-axis, and z-axis was defined as flexion/extension, abduction/adduction (trunk lateral bending), and internal/external rotation respectively. Outcomes of interest were calculated during the eccentric portion of the task (initial ground contact [when vertical ground reaction force exceeded 10N] to the lowest point of the center of mass).

Reaction time was calculated as the participants' first movement after the audible buzzer sound. First movement was when the sacral body marker moved more than 3 cm in either the sagittal or transverse plane relative to the mean marker position for 0.5 s during the "get set" phase before movement.[39]

Biomechanics variables of interest included: reaction time, vertical ground reaction force, vertical loading rate (first derivative of the vertical ground reaction force slope),[27] trunk flexion angle, trunk lateral bending angle, hip flexion angle, hip adduction angle, knee flexion angle, knee abduction angle, external knee flexion moment, external knee abduction moment, and ankle dorsiflexion angle. Vertical ground reaction force and vertical loading rate were normalized to bodyweight (BW) and bodyweight per second (BW/sec), respectively. All joint moments were calculated with standard inverse dynamics, resolved in the proximal segment coordinate system, and normalized to a product of bodyweight and height (BW×HT).

For the cut, trunk lateral bending was calculated as the largest displacement towards (away from straight up and down [0 degrees]) the nondominant (planted) limb.[27] Since jump landing is primarily a sagittal plane movement, we did not calculate trunk lateral bending. We only performed the analysis for the nondominant limb because prior research has shown the non-dominant limb to be most commonly influenced by concussion history.[27,40]

Statistical Analysis

An alpha level of ≤0.05 was established *a priori*. Age, height, mass, and body mass index were compared between groups with independent samples t-tests and Hedge's g effect sizes. Godin Leisure Activity Questionnaire, Lower Extremity Functional Scale, Sport Concussion Assessment Tool symptom inventory (total symptoms and symptom severity), and TSK11 were compared with Mann-Whitney U Tests and Cliff's delta effect size. Dominant limb (right/left), sex (male/female), and traumatic injury history (yes/no) were compared between groups with a Fisher's exact test and odds ratio effect size. Response rate and response accuracy during single-task serial subtraction were compared with a 2 (group [concussion, no concussion]) x 2 (cognitive load [serial 3s, serial 7s]) mixed model analyses of variance.

For Aim 1, we used separate 2 (group [concussion, no concussion]) x 3 (cognitive load [no-counting, serial 3s, serial 7s]) mixed model analyses of covariance for each biomechanics outcome and task (jump landing, cut). We covaried for mean-centered months since the most recent concussion.[27,41] For Aim 2, we used separate 2 (group [concussion, no concussion]) x 2 (dual-task cost [serial 3s, serial 7s]) mixed model analyses of variance for dual-task cost cognitive outcomes during jump landing and cutting. For Aim 3, we used a 2 (group [concussion, no concussion]) x 3 (cognitive load [no-counting, serial 3s, serial 7s]) mixed model analysis of variance to compare NASA Task Load Index scores for jump landing and cutting.

We included the mean center months since most recent concussion as a covariate in Aim 1 analysis because time since concussion has been shown to influence landing biomechanics.[42] There was no significant correlation between months since most recent concussion and dual-task cost outcomes for jump landing or cutting (p-range=0.093-0.993). There was no relationship with single- or dual-task NASA Task Load Index scores for either jump landing or cutting (p-range=0.405-0.907) (Supplementary Table 1). Serial 3s percent correct dual-task cost during jump landing did significantly correlate with months since most recent concussion (r=-0.509, p=0.015), but including mean centered months since most recent concussion in the analysis did not alter the results.

Greenhouse-Geiser corrections for sphericity were used when needed. When post-hoc testing was necessary for interactions and main effects (e.g., cognitive load), we used False Discovery Rate corrections. Partial eta-squared effect sizes were used for analyses of variance and covariance. Partial eta-squared (η_p^2) effect sizes were interpreted as small (≤0.06), medium (0.06 to 0.13), and large (≥0.14). Hedge's g effect size was interpreted as small (<0.50), medium (0.50-0.80), and large (>0.80). Cliff's delta was interpreted as small (≤0.33), medium (0.34-0.47), and large (≥0.48).

Results

A total of 46 participants completed this study (23 concussion history, 23 controls). The concussion history group was a mean of 44.7 months (95% confidence interval [95%CI]=23.6, 65.7) and a median of 31.0 (interquartile range=10.5, 61.0, **range=1.0, 222.0)** post their most recent concussion. The concussion history group reported significantly more total symptoms (p=0.014) and symptom severity (p=0.021) (Table 2).

[Insert Table 2 Here]

For single-task response rate, there was no significant group by cognitive load interaction (F=3.70, p=0.061, η_p^2=0.079) or group main effect (F=0.05, p=0.817, η_p^2=0.001). There was a significant cognitive load main effect (F=221.86, p<0.001, η_p^2=0.838; Table 3). All participants, regardless of concussion history, had a faster response rate during serial 3s compared with serial 7s (mean difference [95%

confidence interval (95%CI)]=0.30 [0.26, 0.34] responses/sec, $p<0.001$, Hedge's g=1.507).

For single-task response accuracy, there was no significant group by cognitive load interaction ($F=3.72$, $p=0.060$, $\eta_p^2=0.080$) or group main effect ($F=2.16$, $p=0.149$, $\eta_p^2=0.048$). There was a significant cognitive load main effect ($F=24.44$, $p<0.001$, $\eta_p^2=0.362$). All participants, regardless of concussion history, were more accurate during serial 3s versus serial 7s (mean difference [95%CI]=7.98 [4.73, 11.24] %, $p<0.001$, Hedge's g=0.951; Table 3).

[Insert Table 3 Here]

Aim 1: Single- and Dual-Task Biomechanics

The $ICC_{3,k}$ (95% confidence interval) for jump landing reaction time no counting and serial 7s were 0.870 (0.779, 0.924) and 0.824 (0.700, 0.897), respectively, indicating good test-retest reliability.

For jump landing reaction time, there was no significant group by cognitive load interaction ($F=0.47$, $p=0.592$, $\eta_p^2=0.011$) or group main effect ($F=2.68$, $p=0.109$, $\eta_p^2=0.059$), but there was a significant cognitive load main effect ($F=36.05$, $p<0.001$, $\eta_p^2=0.456$; Table 4; Supplementary Table 2). All participants had a faster reaction time during no counting compared to serial 3s (mean difference [95%CI]=0.18 [0.12, 0.24] sec, $p<0.001$, Hedge's g=1.187) and serial 7s (mean difference [95%CI]=0.18 [0.14, 0.22] sec, p<0.001, Hedge's g=1.526). There was no reaction time difference between serial 3s and serial 7s (mean difference [95%CI]<0.01 [-0.04, 0.05] sec, p=0.924, Hedge's g=0.011).

For all other jump landing biomechanics variables, there were no significant group by cognitive load interactions (p-range=0.092-0.992), group main effects (p-range=0.109-0.656), or cognitive load main effects (p-range=0.276-0.940; Table 4; Supplementary Table 2).

[Insert Table 4 Here]

For cut reaction time, there was no significant group by cognitive load interaction (F=0.54, p=0.575, η_p^2=0.014) or group main effect (F=2.18, p=0.148, η_p^2=0.053), but there was a significant cognitive load main effect (F=38.06, p<0.001, η_p^2=0.494; Table 5; Supplementary Table 3). Specifically, all participants had a faster reaction time during the no counting compared to serial 3s (mean difference [95%CI]=0.11 [0.07, 0.14] sec, p<0.001, Hedge's g=0.910) and faster reaction time during no counting compared to serial 7s (mean difference [95%CI]=0.15 [0.10, 0.19] sec, p<0.001, Hedge's g=1.261) conditions. Additionally, participants displayed significantly faster reaction time during serial 3s than serial 7s (mean difference [95%CI]=0.04 [0.01, 0.08] sec, p=0.002, Hedge's g=0.319).

For cut vertical loading rate, there was no significant group by cognitive load interaction ($F=2.93$, $p=0.061$, $\eta_p^2=0.067$) or group main effect ($F=2.26$, $p=0.141$, $\eta_p^2=0.052$), but there was a significant cognitive load main effect ($F=7.83$, $p<0.001$, $\eta_p^2=0.160$; Table 5; Supplementary Table 3). Specifically, all participants displayed a lesser vertical loading rate during no counting compared to serial 3s (mean difference [95%CI]=2.96 [0.34, 5.58] BW/sec, p=0.011, Hedge's g=0.220), and lesser vertical loading rate during no counting compared to serial 7s (mean difference [95%CI]=4.15 [1.44, 6.86] BW/sec, p=0.001, Hedge's g=0.328). There was no difference between serial 3s and serial 7s (mean difference [95%CI]=1.19 [-1.10, 3.49] BW/sec, p=0.202, Hedge's g=0.088).

There were no other significant group by cognitive load interactions (p-range=0.061-0.960) group main effects (p-range=0.122-0.974), or cognitive load main effects (p-range=0.111-0.981) for the cutting task.

[Insert Table 5 Here]

Aim 2: Dual-Task Effect Cognitive Outcomes

All participants, on average, had improved cognitive performance during dual-task (serial subtraction while jumping or cutting) versus single-task (baseline serial subtraction), resulting in a "dual-task benefit" and not a "dual-task cost". For dual-task effect response rate during jump landing, there was no group by cognitive load interaction ($F=1.43$, $p=0.238$, $\eta_p^2=0.032$) or group main effect ($F=0.09$, $p=0.763$, $\eta_p^2=0.002$), but there was a significant cognitive load main effect ($F=11.70$, $p=0.001$,

η_p^2=0.214). Interestingly, there was a smaller dual-task *benefit* response rate for serial 3s compared to serial 7s (mean difference [95%CI]=21.29 [8.74, 33.85], p=0.001, Hedge's g=1.179; Figure 1A), indicating that response rate increased more during the more difficult counting task in a dual-task context.

For response accuracy during jump landing, there was no significant group by cognitive load interaction (F=1.15, p=0.289, η_p^2=0.026). group main effect (F=0.46, p=0.503, η_p^2=0.010), or cognitive load main effect (F=2.54, p=0.118, η_p^2=0.056).

For response rate during cutting, there was no significant group by cognitive load interaction (F=3.95, p=0.053, η_p^2=0.086) or group main effect (F=1.58, p=0.216, η_p^2=0.036), but there was a significant cognitive load main effect (F=19.17, p<0.001, η_p^2=0.313). All participants had a smaller dual-task *benefit* response rate for serial 3s compared to serial 7s (mean difference [95%CI]=22.08 [11.90, 32.25], p<0.001, Hedge's g=0.399; Figure 1B).

For response accuracy during jump landing, there was no significant group by cognitive load interaction (F=1.52, p=0.224, η_p^2=0.035), group main effect (F=1.24, p=0.272, η_p^2=0.029), or cognitive load main effect (F=0.99, p=0.325, η_p^2=0.023).

[Insert Figure 1 Here]

Aim 3: NASA Task Load Index

For the NASA Task Load Index assessed after the jump landing task, there was no significant group by cognitive load interaction (F=0.59, p=0.526, η_p^2=0.013) or group main effect (F=0.63, p=0.433, η_p^2=0.014), but there was a significant cognitive load main effect (F=84.33, p<0.001, η_p^2=0.657). All participants reported task difficulty/demands to be significantly lower for no counting compared to serial 3s (mean difference [95%CI]=11.57 [7.15, 15.98], p<0.001, Hedge's g=0.649), lower for no counting compared to serial 7s (mean difference [95%CI]=21.96 [17.08, 26.83], p<0.001, Hedge's g=1.147), and lower for serial 3s compared to serial 7s (mean difference [95%CI]=10.39 [7.24, 13.55], p<0.001, Hedge's g=0.505; Figure 2A).

For the cutting task, there was no significant group by cognitive load interaction (F=0.83, p=0.427, η_p^2=0.019) or group main effect (F=1.71, p=0.198, η_p^2=0.039), but there was a significant cognitive load main effect (F=39.22, p<0.001, η_p^2=0.483). All participants reported task difficulty/demands to be significantly lower for no counting compared to serial 3s (mean difference [95%CI]=11.57 [7.15, 15.98], p<0.001, Hedge's g=0.351), lower for no counting compared to serial 7s (mean difference [95%CI]=21.96 [17.08, 26.83], p<0.001, Hedge's g=0.836), and lower for serial 3s compared to serial 7s (mean difference [95%CI]=10.39 [7.24, 13.55], p<0.001, Hedge's g=0.564; Figure 2B).

[Insert Figure 2 Here]

Discussion

Our hypothesis was partially supported for all aims. In all our aims, we did not see the interaction (group by cognitive load) or group main effect. In Aim 1, as the cognitive load increased, all participants exhibited slower reaction time (slowest to fastest: serial 7s>serial 3s>no counting) during cutting. A similar pattern was displayed for jump landing, except serial 7s and serial 3s had similar reaction times. Vertical loading rate also increased during the cutting task only from no counting to serial 3s/7s, with no difference between serial 3s and 7s. In Aim 2, we found smaller dual-task benefits for serial 3s compared to serial 7s for both jump landing and cutting tasks. In Aim 3, we found NASA Task Load Index increased for both jump landing and cutting as cognitive load increased (least difficulty/demanding to most difficulty/demanding: no counting<serial 3s<serial 7s). Together, individuals with a concussion history were not uniquely influenced by cognitive loads for landing biomechanics, cognitive outcomes, or task demands (see below for discussion about small effect sizes). However, as cognitive load increased, regardless of group, perceived task demands also increased, supporting our hierarchy of difficulty hypothesis.

The primary takeaway for clinicians is that because our results are primarily null ($p<0.050$), choosing either serial 3s or serial 7s as the cognitive task should not have a significant impact on rehabilitation protocols. However, if clinicians simply want to make a specific task feel more challenging (i.e., increase the task demands) then moving from no-counting to serial 3s to serial 7s will accomplish this. Making a task feel more challenging and demanding may help individuals overcome their fear of movement because they are accomplishing a task they perceive as harder. Before our results, clinicians would have to just assume that serial 7s was harder than serial 3s which is harder than no-counting, and assume the participant's biomechanics would alter according to the level of difficulty. With our results, clinicians can make evidence-based decisions for the cognitive component of a dual-task condition

Aim 1: Single- and Dual-Task Biomechanics

We unexpectedly did not find single- and dual-task biomechanics differences between individuals with and without a concussion history. This contradicts some of the prior research which finds individuals with a concussion history displayed greater knee abduction angles[27] and lesser trunk flexion angles[41] compared to controls, as well as increased hip stiffness and decreased knee stiffness compared to pre-concussion[43] during single-task movements. Since dual-task conditions lead to more high-risk landing biomechanics profiles compared to single-task conditions among healthy, non-concussed individuals,[7,10,44] we expected the combination of concussion history and dual-task conditions to exacerbate landing biomechanic differences. Our theory of exacerbation was supported by prior research showing a difference in dual-task cutting biomechanics between those without and without a concussion history.[13] However, prior research did not account for confounding factors such as lower extremity function (Lower Extremity Functional Scale) and kinesiophobia/fear of movement (TSK-11). Since kinesiophobia relates to landing biomechanics,[45] the lack of differences in our study may be why we saw no differences in landing biomechanics.

A potential factor affecting our results is due to the time since the most recent concussion. A previous study that found lesser trunk flexion compared to controls included recreationally active participants, with a median of 126 days post-concussion (~4 months) in the concussion history group.[41] In contrast, our study had a mean of ~44.7 months (median=31.0) post-concussion. Lower extremity biomechanics are influenced by time since the most recent concussion;[42] therefore, trunk biomechanics may also be influenced. Studying participants at later stages post-concussion is still important because we do not know when biomechanics and neuromuscular control impairments resolve post-concussion. For example, the risk for musculoskeletal injury is increased up to 3 years post-concussion,[46] but longer time frames have yet to be explored. Additionally, gait continues to be impaired 6.3 years post-concussion,[47] indicating long-term neuromuscular control impairments.

We did find that vertical loading rate increased during the cutting task from no counting to serial 3s/7s (i.e., single-task to either dual-task). Greater vertical ground reaction force coupled with shorter stance times (i.e., vertical loading rate) during landing contributes to anterior cruciate ligament tears.[48] There was no difference between serial 3s and serial 7s in our study. A previous study that included vertical loading rate as an outcome during landing showed no single- and dual-task differences.[10] These participants were also recreationally active participants and used serial 7s to introduce dual-tasking.[10] Given that our effect sizes were small and not clinically meaningful, our results agree with the findings from this prior study.[10]

Overall, dual-tasking, as studied here, had limited effects on landing biomechanics. Additionally, the gradation effect we hypothesized going from no counting to serial 3s, to serial 7s, was not supported. This may be due to the complex nature of jumping and cutting. Although the task itself requires simultaneous counting and jumping/cutting, when participants leave the box, they may choose to forgo the counting and focus on landing. Despite task instructions encouraging counting throughout the movement, and after landing, participants may have nevertheless not counted briefly to safely plan their landing, making the intended dual-task more like a single-task paradigm. Future researchers may consider an unanticipated type of dual-task where a decision has to be made mid-air after the jump. Additionally, as this was part of a larger two-day study, participants had already received considerable practice counting during the gait (which occurred before jumping/cutting). Potentially, participants had reached their peak counting ability due to the amount of practice they received during single-task counting *and* dual-task gait conditions (15 total dual-task gait trials, plus practice dual-task gait trials).

We found that reaction time increased (became slower) from single- to dual-task for both jump landing and cutting. However, there was not a meaningful difference between serial 3s and 7s for either task. For jump landing, serial 3s vs 7s was non-significant and had a small effect size (p=0.924, Hedge's g=0.011). For cutting, the p-value was significant, but the effect size was small (p=0.002, Hedge's g=0.319). Furthermore, the mean difference during the cutting of serial 3s vs serial 7s was 0.04 seconds, which is only 0.01 seconds greater than the standard error of measurement (SEM=0.030) for the visual light box version of the test.[39] Dual-tasking negatively affecting reaction time is well reported for both visual and auditory computerized reaction time[49,50] and functional reaction time.[39] Other studies have also shown that as complexity of any kind increases so does reaction time; for example, individuals have slower reaction times during an unanticipated cutting task compared to an anticipated cutting task.[41]

A possible reason for why we found single- and dual-task differences during functional reaction time and not the biomechanics goes back to the dual-task paradigm itself, as previously discussed. Functional reaction time was calculated when participants initiated movement to jump off the box. During this time, it was easy for participants to continue their counting and thereby have their attention split between the counting and the buzzer (buzzer initiates their movement). Whereas once the participants were in the air, the participants may have manipulated their counting to slow down, or stop, and solely focus on the landing. Another explanation for slower reaction time during the dual-task conditions may have been because participants were more cautious covering/jumping the distance to the ground, and therefore prioritized their landing biomechanics due to the heightened risk during the dual-task condition. However, this seems unlikely, although not directly tested in our study, because prior research using a similar functional reaction time test found that slower reaction time was related to more high-risk knee flexion angles during a land-and-cut task.[35] Based on this result we would have expected to have seen more high-risk landing biomechanics as reaction time slowed under dual-task conditions.

Aim 2: Dual-Task Effect Cognitive Outcomes

Participants performed better (e.g., more responses per second) during the jump landing and cutting compared to baseline, resulting in a dual-task *benefit* not a dual-task cost. The dual-task benefit response rate for serial 3s was smaller compared to serial 7s during both jump landing and cutting. This is not surprising as serial 3s were meant to be easier than serial 7s, therefore, there was less room for improvement during the serial 3s when going from baseline (single-task) to dual-task conditions. The increased cognitive performance during the dual-task was surprising given that dual-tasking typically impairs performance on one or both of the tasks being performed.[8,11,20] Reaction time performance was impaired (i.e., slower) for serial 3s and 7s for jump landing and cutting (see above discussion), while cognitive performance improved. Although the participants were instructed to perform both tasks to the best of their ability, perhaps participants focused more on the serial subtraction than the motor task, adopting a “cognitive-first” strategy. It is also possible that participants were able to quickly count when standing on the box (pre-initiation of the jump landing), slow down when in the air and during landing, and quickly account again after landing thereby artificially inflating their cognitive performance during the dual-task condition.

It is unclear how common it is for cognitive performance to increase/improve during jump landing, cutting, or other athletic tasks because most studies do not report the cognitive component. In fact, of the eight studies we found using dual-tasking (serial subtraction, flanker task, choice reaction time, etc.),[7,11,44,51–55] only four reported some form of cognitive outcome. Two of the four studies did not compare cognitive outcomes to a baseline performance,[14,52] and one study descriptively reported the total numbers subtracted during dual-tasking but did not perform any statistics comparing it to baseline, or report response rate or response accuracy.[44]

Only the last study by Ness et al. (2020), statistically compared the cognitive component (recognition of colored dots [“DOTS”], backward digit span [“DIGITS”]) of dual-tasking to a single-task cognitive (e.g., baseline) condition.[55] The authors reported a decrease in cognitive accuracy during a dual-task hopping task for both DOTS and DIGITS compared to the single-task condition.[55] Unfortunately, it is hard to compare this study to our work given the differing cognitive and motor tasks performed.

Aim 3: NASA Task Load Index

We found that perceived task demands as measured by the NASA Task Load Index increased as cognitive load increased for both jump landing and cutting. No other dual-task and jumping/cutting/athletic-task study has incorporated this assessment. One of the goals of this research was to introduce a hierarchy of difficulty for the cognitive component of dual-tasking for rehabilitation. Despite no clear biomechanics differences observed, there may still be a benefit of using the cognitive hierarchy (no counting, serial 3s, serial 7s) presented in our research due to the increasing, self-reported task demands.

Slowly increasing the task demands during dual-tasking may help improve patients’ confidence post-injury. However, based on our results, increasing the task demands (at least with serial subtraction) may not be optimal for challenging landing biomechanics, as there were no clinically meaningful biomechanics differences between cognitive load conditions. There have been calls for the inclusion of more subjective cognitive and task demand assessments for sports training and monitoring.[56] Previous research has begun to use the NASA Task Load Index for sports and military training protocols/paradigms,[57–59] and our results support the concept of using the NASA Task Load Index to monitor workload and task demands for discrete movements useful in rehabilitation. Future research does need to confirm our findings among more acutely concussed populations, and injured populations such as those post-anterior cruciate ligament tear.[60]

Potential Confounding Demographic Factors

Some differences among our demographics may have influenced our results. First, although not significant, the concussion history group had a greater proportion of participants with traumatic musculoskeletal injuries. However, a preliminary comparison shows a mean difference in reaction time between injury history and controls of 0.04 seconds which is equivalent to the standard error of measurement for the test.[39] Additionally, our preliminary results show no significant injury history main effect (p-range=0.295-0.891, n_p^2-range=0.004-0.025) or injury history by cognitive load interaction (p=0.094-0.276, n_p^2-range=0.032-0.055) for jump landing and cutting. There were also no reported differences in the Lower Extremity Functional Scale, TSK11, or Godin Leisure Activity Questionnaire. Second, there was a slightly higher total number of symptoms and symptom severity for the concussion history group. Symptoms influence movement during gait,[61] but no research has focused on sport-like tasks.

Limitations

The first limitation of our study was the length of time post-concussion among our participants. Dual-task deficits typically resolve around 2 months for gait.[62] However, little research has focused on dual-task sport-like task recovery post-concussion. It was still important to explore in our current study because we do not know when the increased risk for musculoskeletal injury post-concussion subsides (the longest study to date is 3 years post-concussion).[46] Additionally, neuromuscular control deficits have been reported 6.3 years post-concussion during gait.[47] In other words, impairments still exist long-term post-concussion but may differ by task and individual. Second, our results may not be generalizable outside of recreationally active individuals. We did not account for prior level of sport participation which may have influenced our discussion of biomechanical differences across different populations. Third, we did not track the number of discarded/repeated trials during data collection. It is possible some participants completed more jump landings and cuts than others leading to a concern of physical fatigue. However, participants were always given ~30 second between trial, >1 minute of rest between conditions (motor or cognitive), and were reminded that they could request extra rest if necessary. In the end, all participants had full and complete data for each condition for analysis.

Conclusion

There were no clinically meaningful biomechanics differences between groups or cognitive load conditions. Most likely, any neuromuscular control deficiencies post-concussion had either recovered or differentially affected collegiate athletes versus recreationally active adults (our study population). During dual-task jumping and cutting, our participants showed a dual-task benefit where their response rate was better during jumping and cutting compared to baseline. This may be due to an increase in vigilance during the task, or the increase in practice from the gait trials prior to jumping/cutting (part of the larger 2-day study), but also it may not be out of the ordinary. Prior research does not typically report the cognitive component of dual-tasking for us to know what is typical during athletic movements. Last, the NASA Task Load index was not different between groups but did increase as cognitive load increased. Therefore, introducing cognitive load slowly in a rehabilitation setting may be beneficial to the perceived challenges a patient encounters. However, future research needs to confirm acutely injured person's responses to increasing cognitive load.

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Table 1. Cognitive and spatiotemporal outcomes of interest collected during single- and dual-task conditions

Cognitive Outcomes	Description
Correct Response Rate	The number of correct responses spoken during a given amount of time. The time will be 20 seconds for baseline serial subtraction and time will vary for gait trials (correct responses/second; Equation 2).
Response Accuracy	The percentage of correct responses spoken throughout the trial (% correct; Equation 3).

Table 2. Demographic outcomes

	Concussion History (n=23)	Control (n=23)	p-value	Effect Size
Age (years)	20.2±1.9	20.7±1.7	0.327	0.287
Height (m)	1.74±0.09	1.71±0.09	0.237	0.347
Mass (kg)	69.4±10.6	65.5±9.6	0.201	0.376
BMI	22.9±2.7	22.4±2.3	0.488	0.203
Godin Leisure Activity Questionnaire[a]	63.0 [52.5, 79.0]	62.0 (45.5, 81.5)	0.983	0.006
Lower Extremity Functional Scale[a]	80.0 [78.0, 80.0]	79.0 (78.0, 80.0)	0.412	0.134
Total Symptoms[a]	1.0 [0.0, 3.0]	0.0 (0.0, 1.0)	0.014	0.391
Symptom Severity[a]	1.0 [0.0, 3.0]	0.0 (0.0, 1.0)	0.021	0.371
TSK-11[a]	16.5 [15.0, 18.0]	17.0 (15.0, 20.0)	0.661	0.079
Sex (% female)[b]	60.9% n=14	60.9% n=14	0.999	1.000
Traumatic Musculoskeletal Injury History (% yes)[b]	56.5% n=13	26.1% n=6	0.071	3.683
Dominant Limb (% right)[b]	95.6% n=22	78.3% n=18	0.187	6.111
Months Since Most Recent Concussion	44.7 [23.6, 65.7]	--	--	--
Concussion Frequency (%)				
1	43.4% n=10	--		
2	21.7% n=5	--	--	--
3+	34.7% n=8	--		
Concussion Mechanisms (%)				
Blow to Head or Neck	17.4% n=4	--		
Motor Vehicle Crash	4.3% n=1	--	--	--
Sport Related	78.3% n=18	--		

[a] indicates median (interquartile range) reported, Mann-Whitney U Tests analysis, and Cliff's delta effect size
[b] Fisher's exact test and odds ratio reported
mean [95% confidence interval] and Hege's g effect size reported unless otherwise indicated
One participant in the concussion history group did not fill out the TSK11.

Table 3. Baseline Raw Cognitive Outcomes (mean [95% confidence interval])

		Concussion History	Control	Group Main Effect (p-value)	Cognitive Load Main Effect (p-value)	Interaction (p-value)
Response Rate (#/sec)	Serial 3s	0.68 [0.59, 0.78]	0.63 [0.53, 0.72]	0.817	<0.001	0.061
	Serial 7s	0.34 [0.28, 0.41]	0.34 [0.27, 0.41]			
Response Accuracy (%)	Serial 3s	98.29 [96.60, 99.99]	97.81 [96.12, 99.50]	0.149	<0.001	0.060
	Serial 7s	87.20 [82.70, 91.69]	92.94 [88.44, 97.44]			

Table 4. Jump Landing Outcomes Compared Between Group and Cognitive Load (Covariate Adjusted Means [95% Confidence Intervals])

Outcome	Cognitive Condition	Concussion History	Control	Group Main Effect (p-value)	Cognitive Load Main Effect (p-value)	Interaction (p-value)
Reaction time (sec)[a]	No Counting	0.48 [0.44, 0.52]	0.53 [0.49, 0.58]	0.109	<0.001	0.592
	Serial 3s	0.63 [0.55, 0.72]	0.73 [0.65, 0.82]			
	Serial 7s	0.66 [0.59, 0.72]	0.72 [0.65, 0.78]			
Vertical Ground Reaction Force (BW)	No Counting	1.82 [1.70, 1.95]	1.72 [1.59, 1.84]	0.189	0.276	0.795
	Serial 3s	1.86 [1.72, 2.00]	1.71 [1.57, 1.86]			
	Serial 7s	1.82 [1.69, 1.95]	1.69 [1.57, 1.82]			
Vertical Loading Rate (BW/sec)	No Counting	46.42 [41.38, 51.46]	43.24 [38.20, 48.28]	0.423	0.484	0.917
	Serial 3s	45.11 [40.41, 49.82]	42.68 [37.97, 47.38]			
	Serial 7s	44.74 [40.08, 49.41]	41.91 [37.24, 46.57]			
Dorsiflexion Angle (deg)	No Counting	97.70 [94.53, 100.87]	96.21 [93.04, 99.38]	0.520	0.973	0.925
	Serial 3s	97.80 [94.57, 101.02]	96.64 [93.41, 99.86]			
	Serial 7s	97.90 [95.48100.31]	96.36 [93.95, 98.77]			
Knee Flexion Angle (deg)	No Counting	89.19 [83.67, 94.71]	94.30 [88.77, 99.82]	0.243	0.694	0.899
	Serial 3s	89.89 [84.22, 95.56]	94.11 [88.44, 99.78]			
	Serial 7s	89.63 [84.93, 94.33]	94.14 [89.44, 98.74]			
Knee Angle (+ Adduction, - Abduction) (deg)	No Counting	-11.29 [-14.04, -8.53]	-10.54 [-13.29, -7.78]	0.656	0.544	0.657
	Serial 3s	-11.42 [-14.25, -8.58]	-10.70 [-13.54, -7.87]			
	Serial 7s	-11.79 [-14.44, -9.15]	-10.47 [-13.12, -7.83]			
External Knee Abduction Moment (BW×HT)	No Counting	0.032 [0.025, 0.039]	0.029 [0.022, 0.036]	0.585	0.554	0.904
	Serial 3s	0.031 [0.024, 0.038]	0.028 [0.021, 0.035]			

	Serial 7s	0.032 [0.025, 0.038]	0.029 [0.022, 0.035]			
External Knee Flexion Moment (BW×HT)	No Counting	0.187 [0.172, 0.202]	0.174 [0.159, 0.189]	0.337	0.940	0.832
	Serial 3s	0.183 [0.167, 0.199]	0.174 [0.158, 0.190]			
	Serial 7s	0.185 [0.139, 0.201]	0.174 [0.158, 0.190]			
Hip Flexion Angle (deg)	No Counting	98.30 [89.57, 107.02]	102.71 [93.98, 111.43]	0.511	0.380	0.992
	Serial 3s	96.28 [86.52, 106.04]	100.86 [91.10, 110.62]			
	Serial 7s	96.37 [88.10, 104.64]	100.72 [92.45, 108.99]			
Hip Angle (+ Adduction, - Abduction) (deg)	No Counting	-4.11 [-6.56, -1.66]	-5.07 [-7.52, -2.62]	0.615	0.627	0.959
	Serial 3s	-3.80 [-6.11, -1.50]	-4.65 [-6.96, -2.35]			
	Serial 7s	-3.67 [-5.67, -1.67]	-4.42 [-6.42, -2.42]			
Trunk Flexion Angle (deg)	No Counting	39.05 [34.20, 43.89]	40.21 [35.36, 45.05]	0.403	0.343	0.092
	Serial 3s	37.40 [31.78, 43.02]	42.41 [36.79, 48.02]			
	Serial 7s	36.90 [42.16, 31.63]	40.62 [35.36, 45.89]			

[a] significant cognitive load main effect
BW: bodyweight, BW×HT: bodyweight by height, deg: degrees

Table 5. Cutting Outcomes Compared Between Group and Cognitive Load (Covariate Adjusted Means [95% Confidence Intervals])

Outcome	Cognitive Condition	Concussion History	Control	Group Main Effect (p-value)	Cognitive Load Main Effect (p-value)	Interaction (p-value)
Reaction time (sec)[a]	No Counting	0.48 [0.44, 0.53]	0.52 [0.48, 0.57]	0.148	<0.001	0.575
	Serial 3s	0.58 [0.52, 0.64]	0.64 [0.57, 0.70]			
	Serial 7s	0.61 [0.55, 0.68]	0.69 [0.63, 0.75]			
Vertical Ground Reaction Force (BW)	No Counting	2.95 [2.79, 3.11]	2.84 [2.68, 3.00]	0.217	0.128	0.281
	Serial 3s	3.01 [2.83, 3.19]	2.91 [2.73, 3.08]			
	Serial 7s	3.10 [2.95, 3.25]	2.88 [2.72, 3.03]			
Vertical Loading Rate (BW/sec)[a]	No Counting	58.24 [52.17, 64.32]	54.89 [48.82, 60.97]	0.141	<0.001	0.061
	Serial 3s	63.67 [57.02, 70.32]	55..39 [48.74, 62.04]			
	Serial 7s	65.10 [59.21, 70.98]	56.35 [50.46, 62.23]			
Dorsiflexion Angle (deg)	No Counting	106.81 [103.66, 109.95]	105.09 [101.95, 108.24]	0.495	0.565	0.741
	Serial 3s	106.82 [103.55, 110.08]	105.75 [102.49, 109.02]			
	Serial 7s	106.62 [103.62, 109.63]	104.66 [101.65, 107.66]			
Knee Flexion Angle (deg)	No Counting	58.06 [52.91, 63.21]	57.20 [52.05, 62.36]	0.870	0.591	0.803
	Serial 3s	58.74 [53.93, 63.56]	58.92 [54.10, 63.74]			
	Serial 7s	58.59 [53.19, 63.99]	57.45 [52.05, 62.85]			
Knee Angle (+ Adduction, - Abduction) (deg)	No Counting	-8.75 [-11.34, -6.15]	-6.81 [-9.41, -4.22]	0.208	0.822	0.375
	Serial 3s	-9.36 [-11.90, -6.83]	-6.79 [-9.33, -4.26]			
	Serial 7s	-9.43 [-12.03, -6.82]	-6.54 [-9.14, -3.93]			
External Knee	No Counting	0.010 [0.004, 0.015]	0.011 [0.006, 0.017]	0.516	0.332	0.267

Abduction Moment (BW×HT)	Serial 3s	0.009 [0.004, 0.014]	0.011 [0.006, 0.016]			
	Serial 7s	0.022 [0.005, 0.039]	0.009 [-0.008, 0.025]			
External Knee Flexion Moment (BW×HT)	No Counting	0.219 [0.199, 0.239]	0.209 [0.189, 0.229]	0.150	0.267	0.265
	Serial 3s	0.223 [0.203, 0.242]	0.218 [0.198, 0.238]			
	Serial 7s	0.291 [0.207, 0.374]	0.207 [0.124, 0.291]			
Hip Flexion Angle (deg)	No Counting	58.56 [51.02, 66.09]	57.36 [49.82, 64.89]	0.974	0.794	0.651
	Serial 3s	58.22 [49.88, 66.57]	59.05 [49.71, 66.39]			
	Serial 7s	57.14 [49.48, 64.79]	57.92 [50.27, 65.58]			
Hip Angle (+ Adduction, - Abduction) (deg)	No Counting	-10.47 [-13.92, -7.02]	-6.93 [-10.37, -3.48]	0.122	0.111	0.420
	Serial 3s	-9.59 [-13.29, -5.89]	-5.81 [-9.50, -2.11]			
	Serial 7s	-10.12 [-13.58]	-4.88 [-8.35, -1.42]			
Trunk Flexion Angle (deg)	No Counting	39.65 [36.04, 43.26]	38.36 [34.75, 41.97]	0.657	0.284	0.960
	Serial 3s	38.52 [35.03, 42.01]	37.51 [34.02, 40.99]			
	Serial 7s	38.77 [34.75, 42.79]	37.44 [33.42, 41.45]			
Trunk Lateral Bending (+ toward nondom limb, - away from nondom limb) (deg)	No Counting	3.22 [1.32, 5.11]	3.66 [1.77, 5.59]	0.298	0.981	0.236
	Serial 3s	2.33 [0.20, 4.46]	4.01 [1.88, 6.15]			
	Serial 7s	2.25 [0.15, 4.35]	4.66 [2.56, 6.76]			

[a] significant cognitive load main effect

BW: bodyweight, BW×HT: bodyweight by height, deg: degrees, nondom: non-dominant

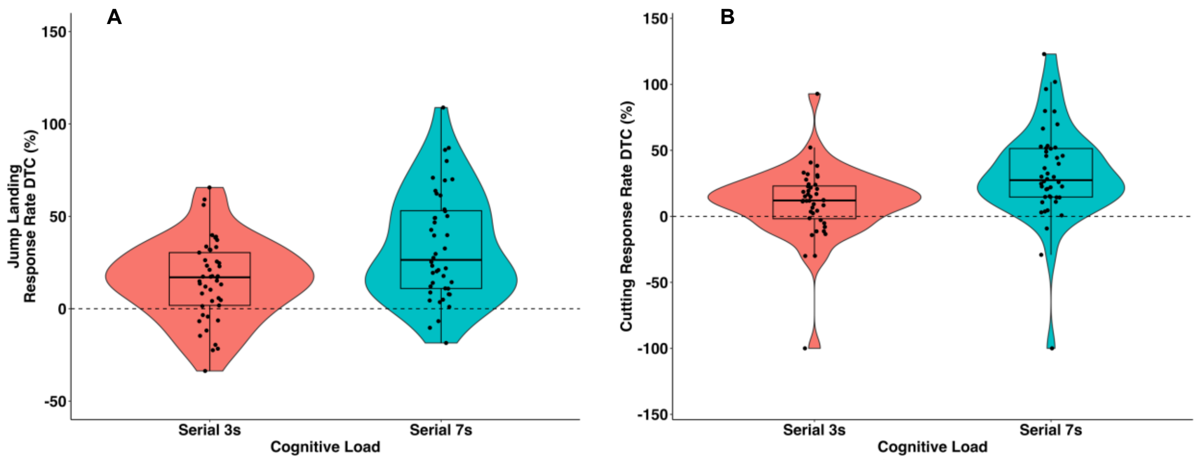

Figure 1. A: Jump landing dual-task cost response rate by cognitive load only. B: Cut dual-task cost response rate by cognitive load only. Positive values represent better performance during dual-task compared to single-task (i.e., dual-task benefit). The dash horizonal line is at 0 and represents equal performance between single- and dual-task conditions.

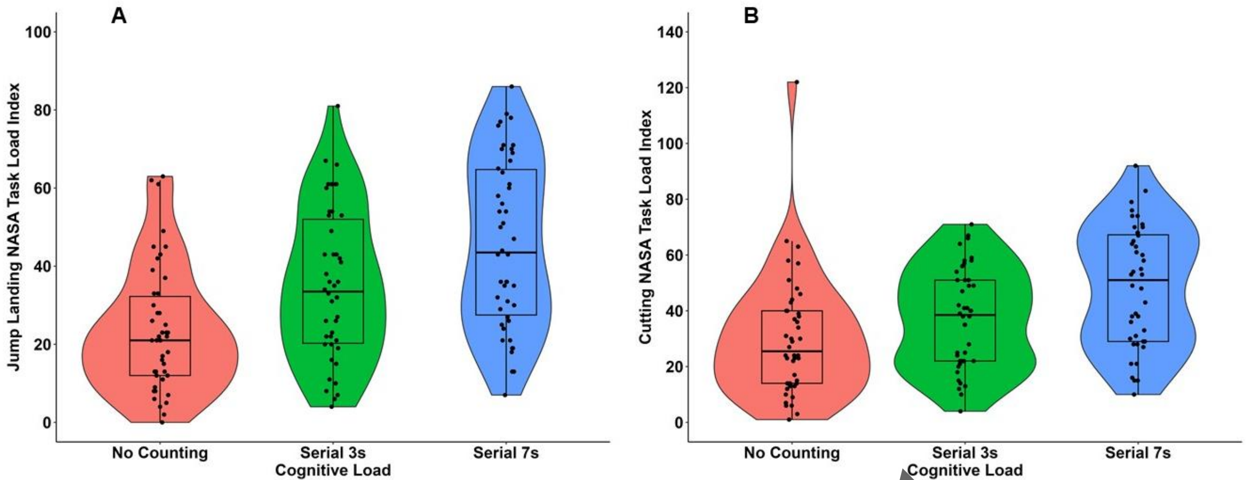

Figure 2. A: Jump landing NASA Task Load Index. B: Cut NASA Task Load Index.

Supplementary Table 1. Correlations With Months Since Most Recent Concussion

	Jump Landing	Cutting
DTC Response Rate		
Serial 3s	r=-0.322 p=0.144	r=0.367 p=0.093
Serial 7s	r=-0.252 p=0.258	r=0.002 p=0.993
DTC Percent Correct		
Serial 3s	r=-0.509 p=0.015	r=0.071 p=0.761
Serial 7s	r=-0.118 p=0.601	r=-0.053 p=0.819
NASA Task Load Index		
No-Counting	r=-0.169 p=0.440	r=-0.102 p=0.652
Serial 3s	r=0.182 p=0.405	r=0.027 p=0.907
Serial 7s	r=0.118 p=0.591	r=0.142 p=0.530

DTC: Dual-task cost

Supplementary Table 2. Jump Landing Model Details

	Group Main Effect			Cognitive Load Main Effect			Interaction		
	F	p-value	η_p^2	F	p-value	η_p^2	F	p-value	η_p^2
Reaction time (sec)	2.68	0.109	0.059	36.05	<0.001	0.456	0.47	0.592	0.011
Vertical Ground Reaction Force (BW)	1.78	0.189	0.040	1.31	0.276	0.029	0.22	0.795	0.005
Vertical Loading Rate (BW/sec)	0.65	0.423	0.015	0.69	0.484	0.016	0.06	0.917	0.001
Dorsiflexion Angle (deg)	0.42	0.520	0.010	0.02	0.973	<0.001	0.05	0.925	0.001
Knee Flexion Angle (deg)	1.40	0.243	0.032	0.34	0.694	0.008	0.09	0.899	0.002
Knee Angle (+ Adduction, - Abduction) (deg)	0.20	0.656	0.005	0.59	0.544	0.014	0.40	0.657	0.009
External Knee Abduction Moment (BW×HT)	0.30	0.585	0.007	0.53	0.554	0.012	0.07	0.904	0.002
External Knee Flexion Moment (BW×HT)	0.94	0.337	0.021	0.05	0.940	0.001	0.17	0.832	0.004
Hip Flexion Angle (deg)	0.44	0.511	0.010	0.95	0.380	0.022	<0.01	0.992	<0.001
Hip Angle (+ Adduction, - Abduction) (deg)	0.26	0.615	0.006	0.45	0.627	0.010	0.04	0.959	<0.001
Trunk Flexion Angle (deg)	0.71	0.403	0.016	1.07	0.343	0.024	2.52	0.092	0.055

Supplementary Table 3. Cut Model Details

	Group Main Effect			Cognitive Load Main Effect			Interaction		
	F	p-value	η_p^2	F	p-value	η_p^2	F	p-value	η_p^2
Reaction time (sec)	2.18	0.148	0.053	38.06	<0.001	0.494	0.54	0.575	0.014
Vertical Ground Reaction Force (BW)	1.57	0.217	0.037	2.11	0.128	0.049	1.29	0.281	0.030
Vertical Loading Rate (BW/sec)	2.26	0.141	0.052	7.83	<0.001	0.160	2.93	0.061	0.067
Dorsiflexion Angle (deg)	0.47	0.495	0.011	0.57	0.565	0.014	0.30	0.741	0.007
Knee Flexion Angle (deg)	0.03	0.870	0.001	0.49	0.591	0.012	0.19	0.803	0.005
Knee Angle (+ Adduction, - Abduction) (deg)	1.64	0.208	0.038	0.19	0.822	0.005	0.99	0.375	0.024
External Knee Abduction Moment (BW×HT)	0.43	0.516	0.010	0.98	0.332	0.023	1.28	0.267	0.030
External Knee Flexion Moment (BW×HT)	2.15	0.150	0.050	1.27	0.267	0.030	1.28	0.265	0.030
Hip Flexion Angle (deg)	<0.01	0.974	<0.001	0.20	0.794	0.005	0.40	0.651	0.010
Hip Angle (+ Adduction, - Abduction) (deg)	2.64	0.122	0.061	2.32	0.111	0.053	0.85	0.420	0.020
Trunk Flexion Angle (deg)	0.20	0.657	0.005	1.27	0.284	0.030	0.03	0.960	0.001
Trunk Lateral Bending (deg)	1.15	0.298	0.027	0.02	0.981	<0.001	1.47	0.236	0.035

BW: bodyweight, BW×HT: bodyweight by height, deg: degrees, nondom: non-dominant