THE EFFECT OF A DUAL-TASK PARADIGM ON JUMP-LANDING PERFORMANCE

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Thesis submitted to the faculty at the University of North Carolina at Chapel Hill in partial fulfillment of the requirements of the degree of Master of Arts in the Department of Exercise and Sport Science in the College of Arts and Sciences.

Chapel Hill
2017

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ABSTRACT

Kevin M. Biese: The Effect of a Dual-Task Paradigm on Jump Landing Performance
(Under the direction of Darin Padua)

Introduction: Dual-task (DT) paradigms use a cognitive test paired with functional movement. A jump-landing task and biomechanical evaluation using the Landing Error Scoring System (LESS) has not been used in a DT paradigm to date.

Purpose: To determine if LESS scores and cognitive test variables would change during a jump-landing DT paradigm.

Participants: 20 participants (age = 21.1 ± 1.45 years, height = 176.5 ± 9.9 cm, weight = 71.9 ± 11.5 kg) were recreationally active college students.

Procedures: Participants underwent 3 baseline cognitive tests. Then participants performed 12 jump-landing tasks, 9 jump-landings with a concurrent cognitive test and 3 jump-landing tasks with no concurrent cognitive test.

Results: There was no change in LESS scores. Reaction time (RT) was significantly slower during DT.

Conclusion: RT of a jump-landing task was negatively affected by a DT paradigm. These results demonstrate individuals sacrifice reaction time to create a safe jump-landing motor plan.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ABBREVIATIONS

ACL	Anterior Cruciate Ligament
BVT	Brooks Visuospatial Task
DYME	Dynamic Integrated Movement Enhancement
DT	Dual-task
LESS	Landing Error Scoring System
RT	Reaction time
SCWT	Stroop Color Word Test
SDMT	Symbol Digit Modalities Test

CHAPTER 1: Introduction

Athletes are bombarded with copious amounts of information, whether it comes from their environment, teammates, or internal thoughts and pressures. It is rare in sports for an athletic movement to occur where the individual can focus solely on that specific movement. Therefore, most athletic movements occur under a multi-task situation, which means that he or she must complete two or more tasks at once. This reality is why dual-task (DT) research became an important area of research for athletes. Even though this combination of movement and decision-making exist in sports, most DT research has focused on gait or postural control.[1-15] Even in simple tasks research found that DT paradigms affect an individual's biomechanics.[13,16-20] These observed changed became a theory and phrase coined by Shumway-Cook et al. called "posture first," which is a strategy that people initiate to keep from falling while standing or walking.[21] It was hypothesized that this occurs because the body will use whatever resources necessary to decrease the risk of falling.[21]Therefore, it is logical to assumed that more sport-specific, complex movements may also be affected by a DT paradigm. Sport-specific movements have also been an irrupting area of research especially in attempts to identify movement patterns that place individuals at risk of injury. Specifically, attempting to identify individuals at risk for lower extremity injuries has long been a priority in the health care profession. There have been several tests used to help clinicians identify individuals who are at an increased risk for sustaining lower extremity injuries such as the Star Excursion Balance Test and Landing Error Scoring System (LESS).[22,23] The LESS particularly has been effective at identifying individuals at risk for an anterior cruciate ligament (ACL) tear.[23-25] Although the LESS has been used primarily for understanding ACL injury prevention and risk,[23,26,27] movement patterns observed during the LESS have also been identified as movement patterns that place individuals at risk for other knee injuries.[28] The LESS is a valid and reliable movement quality test used to evaluate a jump-landing task by scoring 17 common movement pattern errors.[23,24,27,29,30] The joint movements observed during the LESS are movements common in sports that require jumping, landing or a cutting movement. The LESS is not only sport-specific, but it is also cost effective. Traditional LESS scoring can be done with two video recording cameras as opposed to force plates and motion monitors often used in the current DT literature.

Gap in the literature

Even though some research in gait and posture has shown that a cognitive task performed concurrently during gait or balancing tasks can decrease the performance of the functional task in healthy young adults,[13,16-20] this phenomenon has not been seen in all DT research as some research has found that the DT paradigm decreases postural sway or has no effect on postural sway.[31-34] Fraizer and Mitra hypothesized that inconsistencies in DT research may exist because the methods and equipment for measuring posture and gait slightly differ between studies.[35] However, it is also possible that the functional tasks, walking or standing still, are too simple of tasks for a cognitive load to create noticeable changes,[34] which may be why DT research on young, healthy individuals is inconclusive. Walking and balance are two major concerns for those at risk of falling like the elderly and those with neuromuscular disorders; therefore, the majority of DT literature is on these two population.[8,13,36,37] These populations are extremely important areas of research however, the ability to multitask is also necessary for many athletes. To the best of our knowledge, to date no DT literature has focused on young, healthy athletes and how their movements change under a DT paradigm during a sport-specific movement. Most

DT research done on the young, athletic population has looked at athletes who have suffered a concussion.[38,39] These studies are in line with other gait and DT research, which show that concussed individuals have more conservative gait patterns than healthy control subjects.[4,15,38-43] To date, no study has looked at how dynamic tasks, like a jump-landing task, change under a DT paradigm in healthy athletic individuals. It is reasonable to assume that noticeable changes in jump-landing biomechanics would occur during a DT paradigm and would provide the same, if not more, information on the effects of dual-tasking on lower extremity biomechanics.

Furthermore, no DT research to date has used a jump-landing task with the LESS to evaluate biomechanics. A jump-landing task and LESS score can be done by the majority of clinicians and does not require expensive equipment or extensive training compared to the majority of postural and gait DT studies. For DT conditions to be used more prevalently in the clinic, DT methodology must become quicker and easier for the traditional clinic setting.[15] Therefore, a DT paradigm using a jump-landing task and a valid and reliable biomechanics grading system could greatly improve the future use of DT paradigms in the clinic.

Clinical Relevance

The standard LESS procedure in the literature usually tests subjects in a lab setting or away from distractions.[24,29] Therefore, unlike an athletic situation, the subject can completely focus on the jump-landing task. Adding a continuous cognitive task to the LESS procedure may produce a LESS score that better reflects an individual’s movement during athletic endeavors. Furthermore, recent research shows that concussed athletes are at a greater risk for lower extremity injuries after returning to activity.[44-46] Using a DT to assess the performance on a standard clinical assessment of movement quality, with the addition of a cognitive load, may lead to future research using a jump-landing and DT paradigm in concussed athletes to identify those at risk for sustaining a lower extremity injury after they are medically cleared from a concussion. This is an area of great importance identified by Register-Mihalik et al. and the methodology used in this study can advance research in that direction.

The goal of this study was to evaluate the effects of a DT (cognition and jump-landing) on lower extremity biomechanics in healthy, college-aged athletes. The clinical impact of this study could help improve knowledge of the effects of a DT condition during a jump-landing task that is used to evaluate lower extremity biomechanics, and it could also illustrate how a high cognitive load affects movement quality during sport-specific tasks in athletes. We hypothesized that a jump-landing task combined with a cognitive test would increase LESS scores and reaction time (RT) in healthy, college aged athletes. We administered three different cognitive tasks: visual Stroop Color Word test (SCWT), the Symbol Digits Modalities test (SDMT) and Brooks Visuospatial Task (BVT). We hypothesized that the SCWT would elicit the greatest increase in LESS scores and RT compared to the SDMT and BVT.

CHAPTER 2: Literature Review

Lower extremity injuries in sport

Research has shown that lower extremity injuries comprise a majority of injuries that occur in collegiate athletics.[47-50] Sports like American football are seeing an overall increase in the amount of lower extremity injuries when comparing injuries in the 2009-2010 season to injuries in the 2014-2015 season.[49] Some lower extremity injuries can be debilitating and few lower extremity injuries are as devastating as an ACL tear. Even though ACL injuries accounted for only 3% of injuries for 15 sports in the National Collegiate Athletic Association over a 16 year time frame, these injuries also caused a substantial amount of time lost from activity.[50] Hootman et al. even address the fact that establishing risk factors and interventions would be beneficial to the athletic community.[50] Researchers have attempted to identify risk factors associated with lower extremity injuries, especially biomechanical anomalies that may be associated with such injuries. The key to creating a clinically useful tool for identifying these risks is not only the tool's overall effectiveness at identifying those at risk, but also its cost effectiveness for all clinicians to be able to implement such a tool.

Tests like the Star Excursion Balance Test have been used as a clinical tool to identify individuals at risk of lower extremity injuries in basketball players.[22] However, the Landing Error Scoring System (LESS) has been researched in multiple sports and the reliability and validity of the scoring system has also been established.[23,24,27,29,30,51] The overall idea of the LESS is to have an individual perform a jump-landing task from a selected height and distance. The jump-landing task requires the individual to start on a thirty-centimeter box placed 50% of the subject's body height away from the target landing area. [23,24,27,29,30] Two video cameras are set up to capture frontal and sagittal plane movement.[23,24,27,29,30] The subject is asked to jump from the box to the target landing area with as little vertical movement as possible.[23,24,27,29,30] As soon as the subject lands in the target area, he or she must jump as high as possible.[23,24,27,29,30] The researcher reviews the sagittal and frontal plane videos and scores the subject on 17 individual movement errors during the jump landing.[23,24,30] The higher an individual scores on the LESS, the more errors that person performed during their jump landing.[23,24,30]

Key findings using the LESS

Researchers have used the LESS in several different populations to demonstrate its effectiveness at identifying individuals at risk of lower extremity injuries, specifically ACL tears. Patients who have reconstructed ACL injuries are more likely to sustain another ACL injury even after following standard return to play ACL rehabilitation criteria.[24] This group of people have also been found to have higher LESS scores when compared to healthy control subjects.[24] Similarly, youth soccer athletes who score higher than 5 on the LESS have been shown to be at an increased risk of ACL injuries.[23] Because ACL injuries are such a debilitating, sometimes career ending, injury, studies using the LESS have primarily focused on populations who have sustained or are at a higher risk of sustaining an ACL injury. It is no surprise that injury prevention protocols have been developed to help decrease the occurrence of ACL tears and other debilitating lower extremity injuries. There are some injury prevention programs that have been shown to reduce the rate of lower extremity injuries.[26,52] To solidify the LESS's ability to identify those at risk for ACL tears, Padua et al. used a proven ACL injury prevention program to see how it affects LESS scores. Both short duration ACL injury prevention program and extended duration ACL injury prevention programs decreased the participants' LESS scores significantly compared to their pre-test.[27,53] Similarly, The Dynamic Integrated Movement Enhancement (DIME) warm-up was developed to train individual's movement patterns in order to reduce the risk of lower extremity injuries.[54] A study using the DIME warm-up found that it reduced the amount of all lower extremity injuries compared to other warm-up programs.[54] Although this study did not look at the actual biomechanical changes that are related to the increase in injury, the idea of the exercise was to improve joint movement and proprioception that occur during a jump-landing task. Therefore, it is quite possible that these subjects would have improved LESS scores as well as decreased lower extremity injury rates. Some biomechanical factors evaluated in the LESS have also been identified as risk factors of other common lower extremity injuries. These previous studies demonstrate how the biomechanics evaluated in the LESS are related to lower extremity injury biomechanics. Furthermore, these studies provide evidence for the use of the LESS clinically in identifying those who are at increased risk for ACL tears.

Specific movement patterns like a decrease in knee flexion, hip flexion and trunk flexion with an increase in knee valgus, lateral trunk displacement and leg rotation during a jump landing task have all been associated with ACL injuries and other knee ligamentous injuries.[25,28,55] Knee, hip, and trunk flexion and knee valgus are part of the 17 movement patterns evaluated during the LESS, which explains why studies have found LESS scores to be useful for identifying those at risk for an ACL injury. These collective findings illustrate that LESS scores evaluate movement patterns that help identify those at risk of lower extremity injuries, especially ACL tears. The aforementioned research does not necessarily focus on all lower extremity injuries; however, certain lower extremity movement patterns, that can be observed using LESS scoring, have been shown to put someone at risk for lower extremity injuries. These specific movement patterns demonstrate the validity of using the LESS as a screening tool for those at risk of lower extremity injury.

The development of patellofemoral pain syndrome was analyzed in a previous study and found that a decrease in peak knee flexion angle, decreased knee flexion angle and increased hip internal rotation were all correlated with the development of patellofemoral pain syndrome.[56] Patellofemoral pain syndrome is an overuse injury that is usually present in runners, but can occur in most other sports. Patellofemoral pain syndrome is caused by repetitive low forces at the knee that can cause damage and injury to the tendons and other soft tissue structures of the knee. According to this study, these forces can be increased due to poor biomechanics at the knee and hip.[56] The LESS looks at similar biomechanics listed in the previously mentioned study, which demonstrates that the biomechanics evaluated during the LESS can be used to identify faulty biomechanics of multiple types of lower extremity injuries and not just those at risk for ACL injuries. The biomechanics evaluated and the research behind the LESS demonstrate that the LESS is a valuable clinical tool in understanding lower extremity biomechanics and identifying individuals that may be at risk for lower extremity injuries.

Reaction time

RT is a key component of any sport. Athletes have a flood of stimuli from their environment as well as from their own perceptions and pressures to perform. RT has also been hypothesized to be a key component for avoiding injuries as the first association between RT and an increased risk of injury was found in soccer players.[57,58] Furthermore, a simple clinical RT task was associated with an individual’s ability to react and defend themselves from an oncoming object.[58] The study apparatus was in a laboratory, however the movements and objects used in the study were the most sport-related to date. Further research went on to examine if training RT could decrease the rate of injuries. A study used football players and tested their visuomotor RT skills at baseline.[59] The study found that football players who were categorized as "slow" for the visuomotor RT also had higher rates of sprains and strains prior to testing.[59] Those same individuals were taken through a period of visuomotor training and many of them made RT improvements after this training period.[59] It is unclear whether or not these individuals sustained more, less, or a similar amount of injuries after the training, but it is possible that the individuals saw some type of improvements.

Measuring RT with a jump-landing task further improves the clinical and sport related relevance of the jump-landing task. The RT measured in this study is a gross movement reaction, which may be more applicable to sport as the ability to cut or jump out of the way of an opposing player requires whole body movement. Therefore, using RT and biomechanics grading with the LESS may give future researchers and clinicians a more global method for evaluating individual's risk of sustaining a lower extremity injury.

Incorporating LESS with a dual-task

Even with extensive research on the LESS, no group has attempted to understand how the LESS is affected under a DT paradigm. The DT paradigm defines a situation or scenario where an individual must focus and perform two separate tasks. Dual-tasking can also give an overarching idea of the efficiency which an individual's brain functions. The connection between attention and biomechanics is not completely understood, but recent research has shown that those who perform worse on neurocognitive tests exhibited movement patterns associated with ACL injuries.[60] Although this study did not directly look at dual-tasking, it helps illustrate the importance of how cognitive function and motor function coexist. This understanding is especially important because dual-tasking is experienced in most everyday life, for example walking while talking on a cell phone or texting on a cell phone.[61] In a task we see as mundane or simple, like texting and walking, there are actual biomechanical changes that occur.[61] When people in this study were asked to text, walk, and respond to a visual task (the visual task was attempting to represent visual recognition of street signs, moving objects, etc.) their gate speed and texting speed decreased while medial-lateral movement during walking increased.[61]

The rational for why a DT paradigm causes biomechanical or cognitive changes has been hypothesized by several researchers. One of the leading hypotheses is that the total amount of attention and information that can be processed by the brain is limited, and when these resources are exhausted, usually when an individual is concentrating on more than one task, performance of one or more of these tasks will be decreased.[16] Gait and postural control are the two most common motor functions assessed during a DT paradigm.[15] A decrease in one or two tasks has been demonstrated in several gait studies, which illustrated how healthy individuals tend to perform worse during gait analysis when presented with a cognitive test.[7,9,18,37,40,42] Similarly, previous studies observing postural control during a DT paradigm, have demonstrated that postural control is negatively impacted by the DT paradigm.[19,62] However, DT research is not always consistent, especially in postural control studies. Several studies using a DT paradigm with young, healthy individuals found no changes in postural control.[12,34,36,63,64] To complete the spectrum of postural, DT studies, other studies found that postural sway decreased when presented with a cognitive test.[11,33] This seems contrary to other DT research, however one study hypothesized that the subjects became stiff when presented with an attention demanding task to prevent falling or injury.[11] Whereas another study found that although postural sway improved, the single leg squat biomechanics changed.[33] This study is one of a few studies to look at dynamic tasks besides postural control and gait.

Even though the research is not conclusive, it appears that even simple tasks like gait and postural control can be effected by a DT paradigm. Therefore, research has begun to look at more dynamic tasks under a DT paradigm like a single leg squat and jump-landing.[33,65] As previously mentioned, Talarico et al. observed that subjects performed squats slower and with less depth in order to maintain better balance.[33] The change in biomechanics were most likely an adaptation to help the individual reduce the risk of falling during the squat. However, this study did not grade or fully evaluate the mechanics of each subject's squat. More dynamic tasks have been used in the DT literature as well. A jumping task was used in a study with a simple trigger reaction cognitive test.[65] Shinya et al. found that administering a cognitive test during the jumping task decreased the RT of the cognitive test.[65] Unfortunately, this study did not look at how the cognitive test affected the jump-landing performance or biomechanics. Therefore, the only two studies to our knowledge that used more sport specific, dynamic movements did not look at all the possible effects of their DT paradigm. There is reason to hypothesize that, in the previously mentioned study, both the cognitive test and the jump-landing biomechanics would be affected because evidence suggests that a DT paradigm interferes with both the functional task and cognitive task.[12]

Currently no study has ever used the LESS outside of a controlled setting, let alone, while presenting an individual with a DT. The literature on the LESS allows for the subjects to be solely focused on the jump-landing task at hand. The jump-landing task is a viable representation of athletic tasks, besides jumping and landing, like cutting and decelerating. The biomechanical similarities between these athletic movements and a jump-landing task is most likely the reason why the LESS is effective at identifying those with faulty movement patterns. However, these athletic movement patterns are rarely ever done with the individual's complete focus on the functional task. A perfect example is an American Football player making a cut to avoid a tackler. The individual attempting to avoid the defender cannot completely focus on the cutting motion required to evade the tackle. The individual, subconsciously or consciously, has to identify the movement of the defender, identify where he is located in relation to the field and identify the location of other players, teammate or adversary. With all the advantages to the LESS as a clinical tool, there could be improvements made in its ability to more closely mimic movement patterns used when in a game or practice situation. With its clinical relevance in identifying individuals at risk for lower extremity injury, paring the LESS with a cognitive test to create a challenging DT paradigm will improve our understanding of movement patterns and how they change under a cognitive load. Furthermore, this DT paradigm created with the LESS may generate LESS scores that better represent movement patterns during athletic endeavors, which could increase the overall accuracy of the LESS's ability to identify those at risk of lower extremity injury.

Cognitive tests

A cognitive test that can be used concurrently with the jump-landing task needs to be continuous and eliminate the possibility of a feed-forward mechanism for the jump-landing task. Fortunately, most DT research, especially when evaluating gait, use continuous cognitive tests. In an attempt to make the DT paradigm as sport like as possible, while being a controlled pilot test, we believe that the use of a visual-cognitive task would be the most representative of cognitive load occurring during sport. Three visual cognitive tests in the Stroop Color Word test (SCWT), Symbol Digit Modalities test (SDMT) and Brooks Visuospatial task (BVT) have been used previously in the DT literature. These cognitive tests are all continuous and require slightly different brain functions.

Stroop Color Word test

The Stroop Color Word test (SCWT) is a commonly used cognitive test that assesses an individual's executive brain function. It is commonly used in the evaluation of a concussion and has been used in the DT literature.[6,12,66,67] Generally, the SCWT is a computerized test with multiple words on a computer screen or sheet, but has had many adaptations throughout the years. The general format of the SCWT is to create cognitive interference and cause response selection using colors and words.[66,67] There are two general types of SCWTs: congruent and incongruent. A congruent SCWT requires the individual to identify the color of the ink when the ink matches the word. For example, if the word "blue" is displayed in blue ink, the individual would have to identify that he or she recognizes that the color and word are congruent.[67] However, research has shown that the incongruent SCWT is more challenging and individuals record more errors during the incongruent SCWT when compared to the congruent SCWT.[67] Therefore, the incongruent SCWT will be used with this study and all further mentions of the SCWT will be in reference to the incongruent SCWT.

The format of the SCWT involves showing the word of a color that is printed in different color ink than the word itself.[66,67] For example, in the SCWT test the word "red" may be printed in the color green. The subject has to identify and verbalize the color of the print, so in the previous example the subject would need to recite the word "green" or identify that he or she recognizes that the font and word are incongruent.[66,67] The main purpose of the SCWT test is to assess a person's mental processing speed and how the brain functions when it's attention is divided.[67,68] There is usually a delay in identifying the color of the word and this is believed to occur because the automatic reading response interferes with the subject's ability to correctly and quickly identify the color of the print.[66] The SCWT is mostly used for identifying patients with a concussion, as concussed patients scored significantly lower than their non-concussed counterparts on the SCWT up to 48 hours after their initial concussion.[68] In fact, the SCWT is sensitive enough to identify subjects who had persistent concussion symptoms that lasted up to three months.[66] Those individuals performed worse on the SCWT compared to subjects who had a concussion, but had no symptoms three months after their initial concussion.[66] In line with its use in concussion diagnosis, the SCWT has been used in a DT paradigm for this exact purpose. SCWT has been used concurrently with a postural control test in healthy subjects, and the study found that combining these two tests negatively impacted the time in which the subjects were able to complete the SCWT.[69] Teel et al. found a moderate to high level of reliability in administering the SCWT with the Sensory Organization Test illustrating that DT parameters may be reliable in the clinical setting.[69] However, this study did not find that a healthy person's postural sway was affected by the SCWT.[69] The SCWT has also improved postural control; however, even though postural control improved, the biomechanics of a single leg squat were affected.[33] In a gait study, the SCWT was created into a walking mat (termed the Walking Stroop Carpet) where individuals walked a certain pattern on the mat to respond to the SCWT.[9] The Walking Stroop Carpet was able to identify those with mild cognitive impairments because those individuals walked the Walking Stroop Carpet slower than their healthy counterparts.[9] This study also found that healthy subjects were affected by the Walking Stroop Carpet, however, their changes were in the cognitive task and not in gait.[9]

Others have had success in using the SCWT to identify cognitive and or biomechanical changes under a DT paradigm even in a healthy population. As the previous studies have shown, it appears that in healthy subjects the cognitive test performance usually decreases while the functional task is unaffected. One such study used the SCWT concurrently with stepping in place.[6] Regardless of the stepping frequency, the SCWT was unable to elicit any changes in the stepping movement pattern, but the high frequency stepping tasks decreased RT performance for the SCWT.[6] A limitation if this study was that it did not actually look at gait biomechanics. Stepping in place to a given frequency may be difficult, but it most likely does not require as much concentration as actual walking. This can be illustrated from a study by Grabiner et al. in which both the SCWT performance and gait biomechanics changed.[12] Subjects were placed on a treadmill and had the SCWT projected on a screen in front of them. Subjects verbalized their answer to the SCWT while walking and gait variables, as well as SCWT performance were recorded.[12] Grabiner et al. found that subjects' SCWT performance decreased and subjects adapted a more conservative gait pattern compared to walking without the SCWT.[12]

The SCWT has not only been successfully implemented into DT methodology, but it has also been shown to identify cognitive and functional changes when used in a DT paradigm.[9,12] For these reasons, the SCWT is an appropriate cognitive test to pair with a jump-landing task. If the SCWT was able to affect gait biomechanics, it is possible that it has an even greater effect on jump-landing biomechanics.

Brooks Visuospatial Task

The BVT is classically used as a test to evaluate an individual's working-memory.[70] Working-memory and executive function may seem synonymous, and in fact they do appear to have similar functions.[71] However, a study found that even though they are closely related, they still have enough differences to be considered different aspects of a higher-level cognition.[71] They both have a similar component termed executive attention,[71] which is most likely why both executive function tests and working-memory tests have been used in DT literature. The BVT requires an individual to construct a visuospatial "sketch pad" which means that most individuals create an imaginary grid in order to complete the task.[70] Creating this visuospatial "sketch pad" has been linked with disruption of movement planning.[70] Therefore, it is an excellent test to use in a DT paradigm requiring feed-forward movement planning which may be the process used in a jump-landing task. The BVT has had multiple adaptations, but all adaptions require the individual to memorize and visualize some sized matrix.[40,70] In the BVT, the individual is presented with a matrix, usually 5x5 or 4x4, and is asked to memorize where numbers or letters are in the matrix.[40,70] For a numbered matrix, the numbers 1-8 are usually used and for a lettered matrix the letters A-H are used.[40,70] Salway et al. used a 5x5 grid and letters from "A" to "I", whereas Martini et al. used the numbers 1-8.[40] The number "1" always started in row two, column two and the researcher read the direction of the sequential letters.[70] The sentences read were constructed as such: "in the next square to the right/left/up/down put a 2" and were read until the location of the letter "8" was identified.[70] The subject was then given a grid and had to place the letters in the correct squares.[70] This test was even done with a simple finger tapping procedure creating a DT paradigm where the subject had to tap their opposite hand to the beat of a metronome while writing letters in the correct areas of the grid.[70] However, the writing portion of the methodology for the BVT cannot be used during a jump-landing task. Luckily Martini et al. modified the BVT so that the individual only had to identify the direction of the next number using the words, "up, down, right, left."[40] For both studies, the numerical order can only be placed in adjacent squares that are straight in line with the previous number and no square could have more than one number in it.[40,70]

Both of the previous studies successfully used the BVT in a DT paradigm.[40,70] Martini et al. used it during a gait DT study with concussed individuals.[40] This study found that the DT condition of walking with obstacles and the BVT was sensitive enough to identify concussed individuals who had a more conservative gait pattern than their healthy counterparts.[40] This study was not interested in the change in cognitive performance, so it is unclear if healthy or concussed individuals had decreased cognitive performance on the BVT due to the DT paradigm presented. The BVT has been used with healthy, young subjects in a multiple DT paradigms as well. Salway et al. used the BVT concurrently with the subject using their finger to tap a switch to the beat of a metronome.[70] In this study individuals were ask to give the position of given sentences in a 5x5 matrix while tapping 4 switches in a clockwise manner to a metronome.[70] Contrary to Martini et al.'s study, this study only looked at the cognitive performance in the DT paradigm.[70] Results found that healthy individuals performed worse on the BVT when it was done concurrently with the finger tapping functional task previously described.[70] These studies demonstrate that, not only is it feasible, but it is also effective to use the BVT in a dual-tasking situation. In both cases, the BVT was cognitively challenging enough to elicit either cognitive or functional changes in subjects. The limitation to these studies is that neither study looked at both functional and cognitive consequences that may occur when using the BVT in a DT paradigm. Therefore, it is possible that pairing the BVT with an even more demanding functional task, jump-landing, may demonstrate greater cognitive and functional interference than previously observed.

Symbol Digit Modalities Test

The SDMT is different from the BVT and SCWT in the fact that the answer key is presented to the individual for the entirety of the test. Additionally, unlike the SCWT, the test was not designed to trick an individual into incorrectly answering. For the SDMT, the subject is present with a grid that has nine shapes/symbols on it, and the nine shapes are all placed above a unique number from one to nine.[8] The subject is then presented with a single shape and the individual must identify the number associated with that shape by referencing the grid.[8] Because of these facts and previous research, the SDMT has been classified as neuropsychological measure of cognitive processing speed.[8] The SDMT is commonly used in studies on multiple sclerosis, fMRI studies and other neurological conditions.[8,72,73] However, the SDMT has been used in a DT setting to evaluate the DT interference that occurs in those with multiple sclerosis.[8] This study administered the SDMT during a walking task and found that step speed and step length decreased during the DT paradigm.[8] Furthermore, when the extent of disability was controlled for, there was still a significant decrease in step speed and step length during the DT.[8] Since severity of disability was controlled for, it is plausible that the SDMT could elicit similar results in healthy individuals. This may not be the case in healthy individual during a walking task, but the jump-landing task may be challenging enough to elicit these same effects in healthy individuals.

Implications in Other Research Areas

DT research has started to become a predominant component of furthering concussion research.[4,5,38-41] The majority of these studies, like most DT studies, focus on gait and balance. The novelty of using the LESS to score biomechanics during a DT paradigm is not only due to a more dynamic task being used, but it also due to another concern that has surfaced in the concussion literature. Recent studies have shown that injury rates after a concussion increase even after proper returned to activity protocols.[44-46,74] One of the first studies to look at injuries occurring after a concussion identified how likely it was for a person to sustain another concussion.[74] Athletes who were returned to activity within 10 days after an initial concussion diagnosis were more likely to sustain a second concussion.[74] It is important to note, that the reoccurring concussion rate found in this study was relatively low, with the risk of suffering a second concussion in a single sports season at 3.78%.[74] But suffering a second concussion is not the only injury that clinicians have to worry about, in fact recent research may have discovered even more alarming findings. Nordstrom et al. found that concussed athletes who safely returned to activity had less games missed when compared to other athletic injuries, yet formally concussed athletes had an increased rate of injury following their concussion.[46] Even after controlling for injury rates in the subjects prior to a concussion incident, subjects who sustained a concussion were still more likely to sustain an injury.[45,46] The injuries suffered after a concussion appeared to be more acute injuries as concussion history did not have a good correlation with chronic injuries.[46] To be more specific about what kind of injuries are being reported after a concussion, Lynall et al. and Brooks et al. specifically looked at acute lower extremity injuries that occur in concussed athletes.[44,45] Similar to Nordstrom et al., these studies found that concussed athletes were more likely to sustain an acute lower extremity injury than their non-concussed counterparts.[45] The most astounding finding was that these increased injury rates were found to be significant in concussed athletes 90 days to a year after a concussion incident.[44-46,75] These studies do not look at the mechanism of the injuries that occurred after a concussion, but it is possible that changes due to a concussion cause an individual's biomechanics to change, especially during a DT paradigm, that is putting them at risk for future lower extremity injuries.

Although DT studies are common in concussion research, many of them have limitations in their clinical application.[15] Most gait and postural studies in DT scenarios require a laboratory setting with expensive equipment,[15] whereas a jump-landing task and LESS scoring can be done by properly instructed clinicians. Therefore, a jump-landing DT would not only allow for DT testing to be done in the clinical setting, but, coupled with LESS scores, clinicians would be able to identify poor movers. In the future, this methodology may be able to help clinicians identify biomechanical changes that are due to concussions or other neurological impairments. Before jump-landing DT methodology can be used in concussed individuals, it would be prudent to understand how this DT paradigm affects healthy individuals. If LESS scores in healthy individuals change when placed under a cognitive load, then our proposed DT paradigm may be used in the future to exacerbate concussive impairments that are causing worse movement patterns, which ultimately may be putting formerly concussed individuals at risk for injuries.

Chapter 3: Methods

Participants

All 20 participants (Tables 1.1 and 1.2) were volunteer, male and female students at the University of North Carolina-Chapel Hill. The participants in this study were required to be recreationally active in one of five sports: basketball, football, rugby, soccer or lacrosse. Recreationally active was operationally defined as participating in their reported sport at least once a week for more than one hour. For the participants' safety, and to not bias the data, all participants met the following requirements: had no history of lower extremity surgery, had no lower extremity injury in the last six months or had no known neurological condition, and had been cleared for full return to activity for at least six months after a diagnosed concussion.[24,44,45] This data was self-reported by the participants during the consent process. All participants read and signed an informed consent document approved by the university's institution review board prior to the participants' testing sessions. All testing and informed consent took place in the Sports Medicine Research Laboratory in Fetzer Hall on the campus of the University of North Carolina-Chapel Hill. Height (cm) and weight (kg) were collected in the lab prior to testing and participants self-reported their age in years.

TABLE 1.1 – PARTICIPANT DEMOGRAPHICS

	Mean	SD
AGE (YRS)	21.1	1.45
WEIGHT (KG)	71.9	11.5
HEIGHT (CM)	176.5	9.9

TABLE 1.2 – PARTICIPANT SEX AND SPORT

	Male		Female		
PARTICIPANTS (#)	11		9		
SPORT	Basketball	Soccer	Lacrosse	Football	Rugby
PARTICIPANTS (#)	9	11	0	0	0

Set-up

The participants were positioned on a 30-cm high box for the entirety of the testing session. GoPro HERO3+ Silver edition (GoPro, Inc. (Philadelphia, PA, USA)) cameras were used to capture sagittal and frontal movement for grading the LESS. One camera was placed 11' in front of the participant to capture frontal plane movement and the second camera was placed to the side of the participant to capture sagittal plane movement.[24,30] Both GoPro cameras malfunctioned; therefore, for the last five participants, two iPads were used to record frontal and sagittal movement for the LESS.

An HP Envy 2-in-1 laptop (Hewlett-Packard, Inc. (Palo Alto, CA, USA)) with a 15.5" computer screen was used in conjunction with a remote clicker to administer the cognitive tests for the baseline and DT testing. The computer was placed on a cart 13' in front of the participant and was approximately at eye level with the participant when the participant was standing on the ground. The cognitive tests were created with PowerPoint, for the SCWT and SDMT, and Word, for the BVT, (Microsoft, Inc. (Redmond, Washington, USA)). There were 12 different variations of each test that were randomly used for the baseline and the DT testing. No test was repeated for each participant and each test was saved with its identification number. A high definition video camera (Canon FS30) was set up slightly behind and to the side of the participant on the box. The camera did not face the computer or the participant and was only used for collecting the verbal responses to the cognitive tests of the participants. An answer key was associated with each number and was used to review trials for correct answers to the cognitive tests. This process ensured that there was no research bias in reviewing the data as the reviewer did not see the jump-landing task/lack of jump-landing task.

To measure the RT for each LESS trial, two laser timing gates (Tractronix TF100 (Lenexa, KS, USA)) were placed on either side of the box facing each other in line with the front edge of the box. The participant was given a verbal cue from the researcher to start the jump-landing task and was instructed to jump as soon as he or she heard the cue. The researcher started the timing gate timer with a remote starter at the same time as the researcher gave the verbal cue, “jump.” When the participant’s shank crossed the front edge of the box, the participant passed through the laser timing gate, thus stopping the timer. This measurement of RT illustrated a gross movement RT during the single and DT conditions. The researcher was always in front of the participant, but never in the testing area as to not impede the jumping or cognitive tasks.

Baseline Testing

Each session started with the participant completing baseline tests for the SCWT, SDMT and BVT. The participant stood on the 30cm box for all the baseline testing to keep his or her surroundings the same as during the DT conditions. The participant completed one practice trial for each cognitive task and then performed three recorded trials of the SCWT, BVT and SDMT. The practice trial and three baseline trials were all different variations of each cognitive test and different variations of the tests were used during the DT paradigm.

Stroop Color Word Test

Three variations of the test where randomly chosen out of the twelve possible SCWTs for the baseline test and were not used again during the DT trials. Each PowerPoint consisted of 25 slides and on each slide the word “red,” “blue,” “green,” or “yellow” appeared in 300-point font, except for the word “yellow” which was in 250-point font in order to fit the word on the slide. The words “red,” “blue,” “green,” and “yellow” were ordered randomly throughout the PowerPoint and typed in ink that could be any of the colors listed previously. The participant was instructed to verbalize the color of the color of the font rather than the word.[12] For example, the word “red” may be typed in green ink, in which case the participant would have to verbalize the word “green” to identify that word correctly. The participant was instructed to complete the test as quickly and as accurately as possible. The participant used a remote clicker connected to the laptop to proceed through the test at his or her own speed.

The first three slides of each PowerPoint made up the phrase, “ready, set, go,” with each word on a single slide and each slide automatically proceeded to the next slide after one second. The final slide of this series automatically proceeded to the first word in the SCWT, which signified the start of the cognitive test. The participant was instructed to complete all 25 slides and stop as soon as he or she saw the black slide, which signified the end of the cognitive test. A research assistant used a stopwatch to determine the duration of the test by starting the timer as soon as the first word in the SCWT appeared and stopping the timer as soon as the black slide appeared.

Symbol Digit Modalities Test

Three variations of the test where randomly chosen out of the twelve possible SDMTs for the baseline test and were not used again during the DT trials. The SDMT is a substitution and working memory task that required the participant to look at a reference key with 9 different symbols matched with the numbers 1-9.[8,76,77] The reference key was a laminated piece of white paper that was held above the computer screen for the duration of the test. During the test, the participant was told to verbalize the number that corresponded with the symbol on the reference key.[8,76,77] For example, if the symbol on the slide was a triangle, and the reference key denoted that the number “2” was associated with a triangle, the participant verbalized the number “2.” There were 25 symbols on 25 PowerPoint slides for each trial and the symbol was placed in the center of a single slide large enough for the participant to read it. No participants reported having any issues reading the reference key or the symbols on the PowerPoint. The participant was asked to complete the test as quickly and accurately as possible. The participant used a remote clicker connected to the laptop to proceed through the test at his or her own speed.

The first three slides of each PowerPoint made up the phrase, "ready, set, go," with each word on a single slide and each slide automatically proceeded to the next slide after one second. The final slide of this series automatically proceeded to the first word in the SDMT, which signified the start of the cognitive test. The participant was instructed to complete all 25 slides and stop as soon as he or she saw the black slide which signified the end of the cognitive test. A research assistant used a stopwatch to determine the duration of the test by starting the timer as soon as the first symbol in the SDMT appeared and stopping the timer as soon as the black slide appeared.

Brooks Visuospatial Test

The BVT was created with Microsoft Word and printed on white printing paper. The paper was laminated and displayed 13' in front of the participant on the same cart as the previous two cognitive tests describe. Three variations of the test where randomly chosen out of the twelve possible BVTs for baseline testing and were not used again during the DT trials. The BVT is a visuospatial task that uses the numbers 1 through 8 in a 4x4 grid.[40,70] Starting with the number 1, each proceeding number is either in the square above, below, or to the left or right.[40,70] The participant was presented with the BVT grid and was instructed to memorize the order of the digits 1-8 in the 4x4 grid. The number 1 always started in the second row, second column. The researcher then read the order of the numbers and the direction each number was located, in reference to the previous number, to the participant starting with the number 1. The participant used the directions, “right, left, down, up” to identify the order of the digits. For example, if on the grid the number 2 was placed in the square to the right of the number 1, the participant would have to verbalize the direction, “right.” Subsequently, if the number 3 was located in the square below the number 2, the participant would have to verbalize the direction, “down.” Therefore, the test consisted of seven directions that had to be recited by the participant in the correct order.

Once the researcher finished reading the directions of the numbers, the grid was removed from the sight of the participant and the participant had to repeat the direction of each number as quickly and accurately as possible. Participants were instructed to start the test as soon as the grid was removed and the test ended as soon as the participant verbalized the seventh direction. A research assistant used a stopwatch to determine the duration of the test. The research assistant started the timer as soon as the grid was removed and stopped the timer as soon as the participant verbalized the seventh direction.

LESS procedures

The jump-landing task required a 30cm box and a landing area determined by the height of the participant. The landing area was placed at a distance 50% of the participant’s height in front of the box.[23,24,27,29] Athletic tape was used to mark the landing area and the participant was instructed to get his or her heels to land on the tape. The jump-landing task was considered successful if any part of the participant’s foot hit the tape denoting the landing area. The participant was instructed to jump horizontally with as little vertical movement as possible.[24] Following their initial contact with the ground, the participant must jump vertically as high as possible.[24,27,29,30] In order for it to be considered a successful trial, the participant had to: start with their toes at the edge of the box, land with some part of his foot on the athletic tape denoting the landing area, have as little vertical movement from the box to the floor as possible and complete the task in a fluid motion.[24,27,29,30] Conventionally, two GoPro cameras are placed in front (frontal plane view) and to the side (sagittal plane view) of the landing area in order to capture the 17 movement items.[23,24,30,53] LESS scores were based on 17 movement items where a "0" denotes that no error had occurred and a "1" or "2" was used to denote that a movement error was present and possibly how extreme the error was.[24,27,29,30] Therefore, a high LESS score indicated that the participant performed the jump-landing task with a high amount of movement errors.

Dual-Task Procedures

After the cognitive baseline testing, the participants performed twelve jump-landing tasks, nine jump-landing tasks with a concurrent cognitive test (three SCWT, three BVT, three SDMT) and three jump-landing tasks with no concurrent cognitive test. The twelve trials were randomly ordered; this was done by using a verified random numbers generator online. The random number generator website used was: http://stattrek.com/statistics/random-number-generator.aspx. The numbers one through three were assigned with the condition of jump-landing with the SCWT, the numbers four through six were assigned with the condition of jump-landing with the SDMT, the numbers seven through nine were assigned with the condition of jump-landing with the BVT and the number ten through twelve were assigned with the condition of just the jump-landing task. When the numbers were generated, no numbers were repeated. Each participant had a different order generated so that no participant had the same order as another.

The participants held onto the remote clicker during all jump-landing tasks, even during the BVT dual-tasks and jump-landing tasks. This ensured that any changes in the LESS score are due to the actual cognitive task and not due to participants holding on to the clicker during the jump-landing tasks.

The procedures for the jump-landing task and the cognitive tests were the same as previously described. The participant was not instructed on which task required more of the attention. The participant was only instructed to complete the cognitive task as quickly and accurately as possible and to jump as high as possible after initial contact with the floor during the jump-landing. Starting on the box, the participant started the cognitive task first. Once the participant has completed two answers of the cognitive test, regardless of accuracy, the researcher gave the verbal cue, “jump” at any time during the test which signaled to the participant to start the jump-landing task. The participant must continue with the cognitive task even during the jump-landing task. Continuing the cognitive test was operationally defined as completing two or more answers (colors, numbers or directions) during the jump-landing task. If the participant did not complete two answers during the jump-landing task, the trial did not count and was redone. If a trial was redone, the participant was given a different version of the given cognitive task that was not used before. Similarly, all the criteria for the jump-landing task previously described had to be met for a successful trial. Again, if a participant did not meet these criteria, the trial was redone and a different version of the given cognitive test was used. When the participant completed the jump-landing task, he or she had to stand on the floor and complete the rest of the cognitive test. Measuring the cognitive variables and the jump-landing variables was done the same as previously mentioned.

Statistical analysis

Sample Size

Twenty-one participants (Table 1) were enrolled in the study; however, one participant was excluded from our final data analysis due to data corruption. A statistical power analysis was conducted to determine the appropriate sample size needed for this study. The power analysis was calculated from published data by Broglio et al.[78] This study reported on how postural control changed with and without a cognitive task. The cognitive task used in this study is a visual processing task similar to the 3 cognitive tasks we will be using. Postural control is different from a dynamic task; however, a DT has never been used in healthy participants with a jump-landing task. Therefore, we believed that the study by Broglio et al. had similar enough procedures and outcome measures to justify the use of this study to determine our sample size. This is also the most conservative effect size (0.80) found in DT studies that looked at a healthy population. With the effect size= 0.80, alpha= 0.05 and power=.80, the projected sample size needed was approximately N=16. Thus, our sample size of N=20 is more than enough to meet the main objective of this study.

LESS Scores

We used a four way (task: DT SCWT, DT SDMT, DT BVT, single task) repeated measures ANOVA to examine the difference in LESS scores between the four different tests: LESS without a cognitive task, LESS with SCWT, LESS with SDMT and LESS with BVT. Statistical significance was set *a priori* at $\alpha < 0.05$. post-hoc analysis was done using a Bonferroni's correction and three paired samples T-test to compare the DT scenarios with the jump-landing task.

Reaction Time

We used a four way (task: DT SCWT, DT SDMT, DT BVT, single task) repeated measures ANOVA to examine the difference in LESS scores between the four different tests: LESS without a cognitive task, LESS with SCWT, LESS with SDMT and LESS with BVT.

Statistical significance was set *a priori* at $\alpha < 0.05$ and post-hoc analysis was done using a Bonferroni's correction and three paired samples T-test to compare the DT scenarios with the jump-landing task.

Cognitive Test Efficiency

For cognitive variables, a paired samples t-test to compare the difference in percent correctness and the speed of test completion (sec) between each separate (SCWT, SDMT, BVT) baseline cognitive tests and DT cognitive tests. Statistical significance was set *a priori* at $\alpha < 0.05$ for all analysis.

Chapter 4: Manuscript

Introduction

It is rare in sports for an athletic movement to occur where the individual can focus solely on his or her movement. Therefore, most athletic movements occur under a multi-task situation, which means that the athlete must complete two or more tasks at once. Despite the relevance to athletics, most dual-task (DT) research has focused on gait and postural control in elderly or impaired cohorts.[1-15] Some of these studies found gait and postural control changes in individuals during a DT paradigm; some of these findings were even in young, healthy individuals.[13,16-20] However, some research has found that a DT paradigm decreased postural sway or had no effect on postural sway.[31-34] It is also possible that the functional tasks, walking or standing still, are too simple of a task for a cognitive load to create noticeable changes,[34] which may be why DT research on young, healthy individuals has been inconclusive. Therefore, research has begun to look at more dynamic tasks under a DT paradigm like a single leg squat and jump-landing.[33,65] However, the biomechanics of the single leg squat or the jump-landing have not been the focus of former DT research.[33,65]

A jump-landing task is a sport-specific movement and can be scored with the Landing Error Scoring System (LESS) in order for clinicians to objectively quantify an individual's biomechanics.[29] The LESS is a reliable and valid movement assessment and has been applied to the study of movement quality in multiple sports.[23,24,27,29,30,51] Specific movement patterns, such as decrease in knee, hip and trunk flexion with an increase in knee valgus, lateral trunk displacement and leg rotation during a jump landing task have all been associated with ACL injuries and other knee ligamentous injuries.[25,28,55] These movements are all incorporated in the 17 errors evaluated during the LESS.[23,24,30] To our knowledge, no study to-date has identified the effects of a DT paradigm on cognition and biomechanics during a sport-specific movement; Therefore, a graded jump-landing task paired with a well-established cognitive test would give insight to how biomechanics change during a jump-landing task.

The Stroop Color Word test (SCWT), Symbol Digits Modalities test (SDMT) and Brooks Visiospatial task (BVT) have all be used as cognitive tests in the DT literature.[8,9,11,33,40] These three tests all load slightly different areas of the brain,[8,67,70] yet have all been shown to elicit decreased performances in functional or cognitive tests when used in a DT paradigm.[8,9,12,33,69] The SCWT is one of the most commonly used cognitive tests in the DT literature and similarly the BVT has been used more frequently in recent studies.[33,40,69] Unlike the previous two tests, the SDMT is commonly used in studies on multiple sclerosis, fMRI studies and other neurological conditions.[8,72,73] One study administered the SDMT during a walking task and found that step speed and step length decreased during the DT paradigm.[8] Furthermore, when the extent of disability was controlled for, there was still a significant decrease in step speed and step length during the DT.[8] Since severity of disability was controlled for, it is plausible that the SDMT could elicit similar results in healthy individuals. All three tests are simple to create, easy to administer and can give an objective test score either by speed of completion or number of errors. Furthermore, the test stimulus for all three are visual, which adds to their external validity as most environmental stimuli in sport are visual stimuli.

DT research has started to become a predominant component of furthering concussion research.[4,5,38-41] The majority of these studies, like most DT studies, focus on gait and balance and their translation to clinical use is difficult due to the equipment and training needed.[15]

Concussion research is also interested in understanding why concussed athletes appear to be sustaining more lower extremity injuries even after using appropriate return-to-play protocols.[44-46] A DT protocol that incorporates the LESS may be the next step in clinical evaluation of concussed athletes and their lower extremity biomechanics.

The novelty of a DT paradigm using a jump-landing task and a valid and reliable movement quality assessment may improve the future utility of DT paradigms in the clinic, which is an opportunity for dual-tasking to be used more in the clinic.[15] Therefore, the purpose of this study was to evaluate the effects of a DT (cognition and jump-landing) paradigm on lower extremity movement quality in healthy, college-aged athletes. The clinical impact of this study could help improve knowledge of the effects of a DT condition during a jump-landing task that is regular used to evaluate lower extremity movement quality. We hypothesized that a jump-landing task combined with a cognitive test would increase LESS scores and reaction time (RT) in healthy, college aged athletes. Additionally, we hypothesized that the SCWT would elicit the greatest increase in LESS scores and RT compared to the SDMT and BVT. Finally, we hypothesized that cognitive test performance would not change between baseline testing and the DT paradigm.

Methods

Participants

Twenty participants (male = 11, female = 9; age = 21.1 $\pm$ 1.45 years, height = 176.5 $\pm$ 9.9 cm, weight = 71.9 $\pm$ 11.5 kg) volunteered for this study. The participants in this study were all recreationally active, defined as participating in his or her reported sport at least once a week for more than one hour, in one of five sports: basketball, football, rugby, soccer or lacrosse. All participants met the following inclusion criteria: no history of lower extremity surgery, no lower extremity injury in the last six months, no known neurological condition, and had been cleared for full return to activity for at least six months after a diagnosed concussion.[24,44,45] This data was self-reported by the participants during the consent process. All participants read and signed an informed consent document approved by the university's Institution Review Board prior to the participants' testing sessions. All testing and informed consent took place in the Sports Medicine Research Laboratory in Fetzer Hall on the campus of the University of North Carolina-Chapel Hill.

Experimental Set-up

Participants on a 30-cm high box for the entirety of the testing session. GoPro HERO3+ Silver edition (GoPro, Inc. (Philadelphia, PA, USA)) cameras were used to capture simultaneous sagittal and frontal movement during the jump-landing task, and captured data at 48 Hz.[24,30]

An HP Envy 2-in-1 laptop (Hewlett-Packard, Inc. (Palo Alto, CA, USA)) with a 15.5" computer screen was used in conjunction with a remote clicker to administer the cognitive tests for the baseline and DT testing. The computer was placed on a cart thirteen feet in front of the participant and was approximately at eye level with the participant when the participant was standing on the ground. We did not test visual acuity, however no participant reported having issues viewing any of the cognitive tests. The cognitive tests were created with PowerPoint, (SCWT and SDMT) and Word, (BVT) (Microsoft, Inc. (Redmond, Washington, USA)). There were 12 different variations of each cognitive test that were randomly assigned for use for the baseline and the DT condition; no cognitive test variations were used more than once for a given participant. A high definition video camera (Canon FS30) was set-up slightly behind and to the side of the participant on the box. This camera was only used for collecting the verbal responses to the cognitive tests of the participants; it did not face the computer or the participant.

To measure the RT for each LESS trial, two laser timing gates (Tractronix TF100 (Lenexa, KS, USA)) were placed on either side of the box facing each other in line with the front edge of the box. The participant was given a verbal cue from the principle researcher to start the jump-landing task and was instructed to jump as soon as he or she heard the cue. The principle researcher started the timing gate timer with a remote, digital starter at the same time as the principle researcher gave the verbal cue "jump". When the participant's shank crossed the front edge of the box, the participant passed through the laser timing gate, thus stopping the timer. The principle researcher was always in front of the participant, but never in the testing area as to not impede the jump-landing or cognitive tasks.

Baseline testing

Each session began with the participant completing baseline tests, in the following order, SCWT, SDMT and BVT. The participants completed one practice trial for each cognitive test and then performed three recorded trials of the SCWT, BVT and SDMT. All answers were verbalized by the participant. An incongruent SCWT was used, meaning the participant had to identify the color of the ink (red, blue, green, yellow) and not the word (red, blue, green, yellow).[12,67] The SDMT required the participant to identify the number (1-9) that was associated with a different symbol presented on a 2x9 grid (Appendix A) that was present for the entire test.

The PowerPoint design was the same for all SCWT and the SDMT. The first three slides of each PowerPoint made up the phrase, "ready, set, go," with each word on a single slide and each slide automatically proceeded to the next slide after one second. The final slide of this series automatically proceeded to the first word or symbol in the test, which signified the start of the cognitive test. The participant was instructed to complete 25 slides, with one word or symbol on each slide, and stop as soon as he or she saw the black slide, which signified the end of the cognitive test. A research assistant used a stopwatch to determine the duration of the test by starting the timer as soon as the first word or symbol appeared and stopping the timer as soon as the black slide appeared. For the SDMT, the answer grid was printed on laminated printing paper and held above the computer screen for the duration of the test; no participant reported difficulty reading the SCWT, SDMT or BVT. The BVT was the only non-computer based test. The participant was present with a 4x4 grid, on laminated printing paper, that had the numbers 1-8 numerically assorted in the grid in a unique pattern. Starting with the number 1, each proceeding number is either in the square above, below, or to the left or right and no square was used more than once.[40,70] The participant was read the location and direction of the next number at a pace of about 3 seconds per line (Appendix B).[70] Once all the directions were read to the participant, the grid was removed and the participant had to repeat the order of the directions (up, down, left, right) that fit the numerical pattern on the grid. A stopwatch was used and was started as soon as the grid was removed from sight and stopped as soon as the participant verbalized the last direction in the sequence, regardless of accuracy.

LESS procedure

For the jump-landing task, participants stood atop the 30-cm box, and a landing area was marked with a straight line of athletic tape at a distance 50% of the participant's height in front of the 30-cm box.[23,24,27,29] The participant was instructed to jump horizontally with as little vertical movement as possible.[24] Following their initial contact with the ground, the participant must jump vertically as high as possible.[24,27,29,30] In order for it to be considered a successful trial, the participant had to: start with their toes at the edge of the box, leave the box with both feet at the same time, land with some part of his foot on the athletic tape denoting the landing area, have as little vertical movement from the box to the floor as possible and complete the task in a fluid motion.[24,27,29,30]

Dual-Task Procedures

After the cognitive baseline testing, the participants performed twelve jump-landing tasks, nine jump-landing tasks with a concurrent cognitive test (three SCWT, three BVT, three SDMT) and three jump-landing tasks with no concurrent cognitive test. The twelve trials were randomly ordered; this was done using a verified online random numbers generator (http://stattrek.com/statistics/random-number-generator.aspx. Each participant had a different order generated so that no participant had the same order of twelve trials. The procedures for the jump-landing task and the cognitive tests were the same as previously described. The participant started the cognitive task first. After the participant completed two answers of the cognitive test, regardless of accuracy, the researcher gave the verbal cue, "jump" at any time during the remainder of the test, which signaled to the participant to start the jump-landing task. To be considered a successful trial, participant was required to continue with the cognitive test even during the jump-landing task, which was operationally defined as, "completing two or more answers (colors, numbers or directions) during the jump-landing task". If the participant did not complete two answers during the jump-landing task, the trial was deemed unsuccessful and was repeated, during which the participant was given a different version of the cognitive test that had not been used before. Additionally, all the criteria for the jump-landing task previously described had to be met for a successful trial. When the participant completed the jump-landing task, he or she had to stand on the floor and complete the rest of the cognitive test. Measuring the cognitive variables and the jump-landing variables was done the same as previously mentioned.

Data Processing

An answer key was associated with each cognitive test and was used by a trained research assistant to review auditory trials for correct answers to the cognitive tests following data collection. This blinded procedure ensured that there was no investigatory bias in reviewing and scoring the cognitive performance results, as the research assistant was blinded to the single- or DT condition.

Each participant had one practice jump without a cognitive test that was not graded. LESS scoring was done using QuickTime Player (version 7.7.9; Apple Inc, Cupertino, CA) to advance the frontal and sagittal views frame by frame. All videos were graded by the chief investigator and the two time frames of interested where in initial contact and peak knee flexion.[30] foot symmetry, knee, hip and trunk movement were all assessed as well as overall sagittal and frontal plane movement creating the 17 point grading scale.[30] The chief investigator was blinded as to which videos belonged to which trial type as to not bias the LESS grading.

Statistical Analysis

A statistical power analysis was conducted *a priori* to determine the appropriate sample size needed for this study. The power analysis was calculated from published data by Broglio et al.[78] This study reported on changes in postural control with and without a cognitive task. The cognitive task used in this study was a visual processing task similar to the 3 cognitive tasks used in the current study. Postural control is different from a dynamic task; however, a DT has never been used in healthy participants with a jump-landing task. Therefore, we believed that the study by Broglio et al. had similar procedures and outcome measures to justify the use of this study to determine our sample size. This is also the most conservative effect size (0.80) found in DT studies that looked at a healthy population. With the effect size= 0.80, alpha= 0.05 and power=

0.80, the projected sample size needed was approximately N=16. Thus, our sample size of N=20 was determined to be appropriate to meet the main objective of this study.

A one way repeated measures ANOVA to examine the difference in LESS scores and RTs between the four different tasks: jump-landing without a cognitive task, jump-landing with SCWT, jump-landing with SDMT and jump-landing with BVT. Post-hoc analysis was used for the significate ANOVAs. Post-hoc analysis was done using a Bonferroni's correction and three paired samples T-test to compare the DT scenarios with the jump-landing task. For cognitive variables, a paired samples t-test to compare the difference in percent correctness and the speed of test completion (sec) between each separate (SCWT, SDMT, BVT) baseline cognitive tests and DT cognitive tests. Statistical significance was set *a priori* at $\alpha < 0.05$ for all analysis.

Results

Cognitive data is presented in Table 2. There was no significant difference in test accuracy for baseline SCWT and DT SCWT (T_{19}= 1.58, p= 0.132). However, both test correctness for BVT (T_{19}= 2.57, p= 0.019) and SDMT (T_{19}= 2.93, p= 0.009) were significantly decreased during the DT condition when compared to their baseline accuracy. Test completion speed was significantly different between the DT and the baseline testing for the SCWT (T_{19}= 6.37, p< .001) and SDMT (T_{19}= 6.20, p< 0.001), indicating that participants completed the tests faster under the DT condition. On average, participants completed the SCWT 11.5% and SDMT 7.5% faster during the DT condition compared to the baseline testing. Test completion speed was not significantly different for the BVT between the baseline and DT testing (T_{19}= 1.64, p= 0.117).

TABLE 2 – COGNITIVE MEASURES

	Baseline			Dual-task			
	Mean	SD	95% CI	Mean	SD	95% CI	p-value
SCWT ERROR (% CORRECT)	98.9	1.96	92.0 – 100	97.8	2.81	90.6 – 100	0.132
SCWT TIME (SECONDS)	24.58	3.81	17.1 – 32.2	21.70	3.33	15.3 – 27.9	< .001*
SDMT ERROR (% CORRECT)	99.5	0.78	97.3 - 100	98.1	2.31	90.7 – 100	0.009*
SDMT TIME (SECONDS)	33.81	4.05	27.4 – 41.6	31.24	3.15	24.9 – 36.1	< .001*
BVT ERROR (% CORRECT)	99.8	1.04	95.3 - 100	96.4	5.97	81.0 – 100	0.019*
BVT TIME (SECONDS)	4.53	1.49	2.5 – 7.7	4.98	1.73	2.3 – 7.7	0.117

LESS score data is presented in Table 3 and RT data is presented in Table 4. No task effect or cognitive effect was observed for LESS scores ($F_{3,17}$=1.767, p= 0.164). However, there was a significant task effect ($F_{3,17}$= 3.298, p= 0.027) for RT. Further analysis was done using a Bonferroni's correction (p= 0.017) and using paired sample t-tests to compare each of the 3 DT conditions (SCWT, SDMT and BVT) to the single-task condition (jump-landing only). There was a significant difference between the SCWT (T_{19}= 5.064, p< 0.001) and SDMT (T_{19}= 2.993, p= 0.007) DT conditions compared to the single-task condition, where participants reacted slower during the DT situation. RT means were also compared between tests using the same methods. There was no significant difference between the changes in RT between the cognitive tests (SCWT vs SDMT [T_{19}= 1.34, p= 0.20], SCWT vs BVT [T_{19}= 1.25, p= 0.23], SDMT vs BVT [T_{19}= 1.72, p= 0.10]). On average, participants reacted 10% slower during the SCWT DT and 15% slower during the SDMT DT when compared to the single task. RT was not affected by the dual-task situation during the BVT (T_{19}= 0.402, p= 0.692) when compared to the single task.

TABLE 3 – LESS

	Mean	SD	95% CI
DT SCWT LESS SCORE	5.4	2.03	4.5 – 6.4
DT SDMT LESS SCORE	5.2	1.89	4.5 – 6.2
DT BVT LESS SCORE	5.9	1.92	5.0 – 6.8
SINGLE TASK LESS SCORE	5.5	1.66	4.7 – 6.3

TABLE 4 – REACTION TIME

	Mean	SD	95% CI
DT SCWT RT (SECONDS)	1.21	0.167	1.13 – 1.29
DT SDMT RT (SECONDS)	1.27	0.315	1.12 – 1.41
DT BVT RT (SECONDS)	1.13	0.327	0.98 – 1.28
SINGLE TASK RT (SECONDS)	1.10	0.129	1.04 – 1.16

Discussion

This study examined the effect of a DT condition on jump-landing performance. The primary findings of this study demonstrated that 1) movement quality did not change during the DT paradigm, 2) jump-landing reaction time significantly increased during the DT paradigm, 3) cognitive speed increased during the DT while test accuracy decreased for various cognitive tests. There was a significant 10% to 15% difference in RT during the SCWT DT and SDMT DT scenarios respectively. Our methodology for measuring RT in this study is unique, in that our RT illustrated a gross movement RT. We believe this measurement of RT is more appropriate for understanding how RT exists in sport because the movement off the box is similar to jumping or cutting in sport. To our knowledge, ours is the first study to look at a gross RT during a DT and to incorporate any sort of RT measurement in a study using the LESS. RT has been hypothesized to be a key component for avoiding injuries, as the first association between RT and increased risk for injury was found in soccer players.[57,58] Similarly, a study using visual-motor RT found that those who had slower visual-motor RTs had sustained more injuries the previous football season.[59] Our findings illustrate the importance of attention during a simple jump-landing task. The verbal cue, although an auditory stimulus, could represent any stimuli during a sporting event that would require the individual to react. Since slower RTs are linked to an increased risk of injury, a DT paradigm could increase the risk of injury; which may help explain why injury rates are higher during competition as compared to practice.[48]

Our findings showed that a DT did not have any effects on jump-landing biomechanics. We hypothesize two theories for this particular finding. First, individuals were willing to sacrifice RT in order to maintain similar jump-landing biomechanics. This trade-off would appear to strengthen the "posture fist" theory coined by Shumway-Cook et al., which states that individuals develop a strategy to keep from falling while performing a functional task.[63] This strategy for a jump-landing task is intriguing, since a decrease in RT would also increase an individual's risk for injury. Therefore, incorporating RT, regardless of a DT scenario, in LESS procedures may improve the injury risk assessment ability of the LESS. More research would be needed to strengthen this claim. The second possible theory for why LESS scores were not affected by DT is that their LESS scores may have been too high at baseline for major changes to occur. Participants in this study were reportedly recreationally active in one of the listed sports. This cohort's LESS scores under a single jump-landing task averaged around a 5.5. This is a high average as scores higher than a 5 or 6 has been identified in individuals with high risk movement patterns.[23,24] Therefore, participant did not have many more errors that could be made during the DT. It is possible that more elite athletes, who presumably have lower baseline LESS scores, would exhibit more biomechanical errors during a DT.

There was a significant decrease in cognitive test correctness for BVT and SDMT where individuals performed worse on the BVT and SDMT during the DT trials. However, we do not believe that these findings are clinically significant as the difference between the means were less than a 2% difference. The mean for the DT BVT is slightly skewed as well as one participant had an extremely poor performance on one of his trials for the BVT causing his average to be significantly lower than the rest of the cohort. Using percentages to quantify the accuracy is a common method, however future research may want to use longer versions of the

SCWT and SDMT for the percent correctness to better correlate with clinical significance. A surprising finding was that individuals performed quicker on the SDMT and SCWT during the DT trials. Participants performed 4 variations of each test prior to the DT trials, therefore it is unlikely that this increase is due to a learning effect. It is possible that individuals were more focused during the DT trials because he or she was anticipating the verbal cue. Completing the tests faster decreased the overall period in which the verbal cue could be given, therefore faster test taking may be a mechanism enacted by the individual to reduce the surprise of the verbal cue. This finding could also be explained by the jump-landing task itself because gait and postural control are continuing movements, whereas the jump-landing task only requires a few seconds of to complete. Regardless of the theory, our findings illustrate that it may not be important to measure neurocognitive data when using a jump-landing task as the functional movement in a DT paradigm.

Limitations

Even though we ran power analysis to determine the size of our cohort, it was still relatively small. To better understand the effects of such a novel DT paradigm, future studies should use a larger cohort of participants.

Our methodology for measuring RT was a gross movement, whereas most RTs studies use more intricate equipment. There was a possibility for human error in manual starting the timing gates as the chief investigator gave the verbal cue. To help limit this error the chief investigator was the only individual to use the remote timing gate controller. More sophisticated methods may produce more accurate differences in RT and would need further investigation.

Although the LESS is a valid and reliable clinical tool, it does not evaluate jump-landing kinetics or kinematics. More advanced kinematic and kinetic assessments used during this novel

DT testing paradigm may reveal aberrant movement patterns that cannot be detected by the LESS, such as small changes in joint angles or kinetic loading variables. Future research should use more advanced measurements of kinematics, like 3D motion capture techniques, and integrated force plates, to better quantify biomechanical changes that may occur during a DT.

Because of the novelty of the experimental design, it was prudent to recruit a healthy, young-adult population. Future research should explore the effects of this DT paradigm on other populations, such as elite athletes or individuals following concussion. Concussed individuals may be more affected by this DT paradigm, thereby revealing larger effects under DT conditions. Using a DT paradigm during movement assessments may help both clinicians and researchers better understand recovery following concussion and improve current return-to-play protocols.

Conclusion

Our findings revealed that individuals' reaction time during a jump-landing task was negatively affected (slower reaction time) by a DT paradigm. These results suggest that individuals may sacrifice RT to create an effective motor plan to complete a jump-landing task with acceptable movement patterns. The novelty of the methodology utilized in this study supports the utility of using DT paradigms in clinical setting with athletes during either pre-season physical evaluations or during return-to-sport decision-making following injury.

Appendix A: SDMT Answer Grid Example

#	@	!	/	?	;	*	+	$
1	2	3	4	5	6	7	8	9

Appendix B: BVT Example

8	1	2	
7	6	3	
	5	4	

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