



School of Physical Education - Sport Science and Dietetics

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“Investigation of the effect of ball heading in football, on knee neuromuscular control and predispose to injury”

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3. Heading exposure in women footballers using the HEAD COUNT 2 Weeks questionnaire
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ABSTRACT

Soccer, the most popular sport worldwide, may account for the dominant share of sub-concussive exposure in sports, where excess heading (more than 1,000 per year) may be a cause of sub-clinical brain injury. The history of recognized concussions did not explain these effects. Most studies of head injury in other sports have focused on single or repeated concussive injury episodes, now known to cause brain dysfunction, especially in susceptible individuals. Recently, it was suggested that collision-related injuries, not heading, explained persistent CNS effects from soccer in adolescents. However, because heading was not assessed in this study, it was impossible to parse attribution to unintentional vs intentional head impacts or exposures that also occur during practice.

Noncontact knee injuries in soccer frequently occur during dribbling, cutting, or quick direction changes, while contact injuries are caused by knee hyperextension or a valgus motion. For these reasons, the biomechanics of knee joint motion during activities such as landing, running, and cutting maneuvers have been extensively examined in soccer. Injury to the knee ultimately occurs due to knee loads that cannot be supported by bony structures and muscles, thus leading to substantial ligament loads. It is increasingly recognized, however, that extreme knee loading scenarios may be potentiated through abnormal neuromuscular control elsewhere at the lower extremities. Hypotheses related to gender differences in the transverse and frontal plane hip rotations and rear foot pronation have been formulated. However, the data to support these theories could be more detailed. On average, during a 90-minute soccer game, a player has 51 ball contacts, 26 with the foot. In a recent study, soccer kicks accounted for approximately 51% of potential actions that may lead to an injury from 18,000 playing actions in 10 soccer games.

CHAPTER 1

1.1 Introduction

Little is known about the short-term effects of heading or unintentional head impacts on cognitive function. However, effects like this, even if transient, might inform mediation of persistent effects of repetitive head trauma from long-term participation in soccer. At the same time, it is unknown if sub-concussive head impacts contribute to persistent changes in CNS function; evidence that neurophysiology (NP) performance co-varies about heading would be consistent with such a hypothesis. Previous studies have examined the relation of long-term exposure to soccer on variation in NP function in small cohorts. Heading the ball was estimated over a season, year, or lifetime, but these studies did not consider unintentional head impacts. Using a validated questionnaire for heading activity in 2 weeks, the results of this study indicate that variation in NP function is directly related to variation in heading but not to variation in unintentional head impacts or Concussion.

The Congress of Neurologic Surgeons definition states that Sports Related Concussion (SRC) is "a clinical syndrome characterized by the immediate and transient post-traumatic impairment of neural function such as alteration of consciousness, disturbance of vision or equilibrium, etc. due to brainstem involvement."

D Parallel with the term "concussion" has been the term "mild brain injury." Jennet et al. proposed the Glasgow Coma Scale (GCS) as a prospectively validated prognostic scale for assessing traumatic brain injury. This scale distinguished mild, moderate, and severe brain injury based on a standardized score of 6 hours following injury.

Several standard features that incorporate clinical, pathologic, and biomechanical injury constructs that may be used in defining the nature of a concussive head injury include:

1. Concussion may be caused by a direct blow to the head or elsewhere on the body with an "impulsive" force transmitted to the head.
2. Concussion results in an immediate and short-lived impairment of neurologic function.
3. Concussion may result in neuropathologic changes; however, the acute clinical symptoms reflect a functional problem rather than structural injury.
4. Concussion may result in a set of clinical entities that may or may not involve loss of consciousness (LOC). Resolving the clinical and cognitive symptoms follows a sequential course over time.

In summary, this dissertation utilized a targeted approach to identify biomechanical and cognitive mechanisms in concussed athletes that may provide an objective connection for the relationship between SRC and future knee injury risk. Additionally, impaired performance on cognitive working memory and attentional capacity tests indicated a previous SRC history. The present findings suggest that clinical management of an SRC must include specific assessments to monitor motor and cognitive performance in concussed athletes. Researchers should examine pre- and post-SRC biomechanical outcomes with a mental load during sport-specific tasks to expand our understanding of knee injury risk in athletes who sustain an SRC.

1.2 Sports-Related Concussion Injury Incidence

Beyond increasing public awareness, the statistics of SRCs tell an alarming story. Estimates suggest that 3.8 million concussions occur in the United States annually because of sport and recreation, with up to 50% of concussions going unreported. The incidence of Concussion in sports has been steadily increasing over previous decades, with two comprehensive studies of collegiate athletes in North America showing an increase in concussion rates from 1.7 per 10,000 athlete exposures (1 athlete exposure is defined as one athlete taking part in 1 practice or game) in

1988–1989 to 3.4 in 2003–2004⁵ and to 4.47 in the period between 2009 and 2014. Similar incidence trends are also found in high school athletes and school children.⁸ For comparison, the incidence of concussion injuries was almost double that of the seemingly more common anterior cruciate ligament injuries. Exacerbating this is the fact that 35%–62% of concussion injuries in high school and collegiate athletes are not reported. In collegiate athletes, the most significant number of concussion injuries was observed in men's American football. In contrast, the highest rates of Concussion were noted in men's and women's ice hockey and women's soccer. In 2017, approximately 2.5 million American high school students self-reported having at least one physical activity–related or SRC in the preceding 12 months, while 1 million reported two or more.¹ At the elite level, concussions are more common, with an analysis of head injuries during the 2012–2013 and 2013–2014 National Football League (NFL) seasons illustrating a concussion rate of 66.1 (per 10,000 athlete exposures).

1.3 Physiological and Biomechanical Mechanisms of Sports-Related Concussion

Kinematics is the area of mechanics concerned with the motion of an object without reference to the forces that cause the motion. For many years, biomechanical research has focused on understanding the brain's response to head kinematics and how this relates to brain injury. Additionally, more recent metrics utilize finite element (FE) brain models and consider the parts of vector (i.e., directionality), frequency content, and time-pulse rather than just peak values of the kinematic outcome. Many brain injury criteria may be limited by the low validity of biomechanical approaches to develop them. Further limitations include low concussion/brain injury sample cohorts, oversampling of non-independent, non-injurious impacts, as well as issues such as injury underreporting and low diagnostic accuracy. These limitations ask if brain injury criteria are valid or clinically relevant. These limitations are the reason why the majority of studies report

only peak kinematic magnitudes (e.g., linear acceleration, angular acceleration, and angular velocity) of sub concussive impacts in sport, that higher magnitude impacts are more severe even though peak resultant outcomes do not account for significant head kinematic characteristics.

From a biomechanical point of view, injury is comparable to the failure of a machine or structure from an energy transfer to the tissue. The combination and interaction between internal and external risk factors play a role when assessing injury causation in sports. Age, sex, skill level, and physical fitness are examples of internal risk factors. Environment and sports equipment are examples of external risk factors. The mechanical properties of human tissues govern the body's response to physical loads. In injury, micro and macro failure may occur. For biomechanical injury risk factors, it is essential to consider how an injury either resulted in a mechanical load beyond limits under normal biomechanical conditions (Mechanism 1) or could reduce the level of tissue tolerance over time to a stage where an average biomechanical load can no longer be tolerated, or normal function is compromised (Mechanism 2). The process may also satisfy conditions for injury, high loads, and a potential tolerance reduction (acute or long term) through microtrauma (Mechanism 3). An SRC may fall into Mechanism 1 or 3, whereas long-term problems from repetitive impacts may fall into Mechanism 2. More research is required to ascertain the extent to which these ideas hold in practice; examples of evidence for concussion and repetitive head acceleration exposure are given below.

1.4 Neurophysiological Markers of Sports-Related Concussion

NP measures provide the opportunity to quantify the functional disturbances in Concussion, as suggested by McCrory et al., potentially informing the doctor of subtle and prolonged changes in brain health in light of symptom resolution. Lab tests such as electroencephalography (EEG) and

transcranial magnetic stimulation (TMS) have shown altered evoked potentials despite the individuals being asymptomatic. A recent systematic review of 16 studies presented abnormalities in resting state EEG activity following SRC. EEG studies have also been utilized in studies of sports with a high volume of "sub-concussive" trauma, defined as where the brain experiences head impacts such as soccer heading and other injuries (head to head), bumps, or tackles in football, but without the overt signs or symptoms of SRC. The outcomes from studies investigating persistent post-concussion symptoms (beyond three months), showing increased intercortical inhibition, may reflect a form of dysfunctional neuroplasticity in response to the injury. For example, a recent study by Pearce et al. showed impaired reaction time performance and increased fatigue, suggesting that persistent symptoms occur regularly. This hypothesis of increased inhibition has been argued before, and it posits that the increased inhibition seen in the acute phase following a brain injury is a mechanism to protect the brain from spreading further dysfunction. However, unlike the majority of the athletes who recover, in a small minority, this increased inhibition does not resolve.

1.5 Head Impact Biomechanics and Sports-Related Concussion Risk

When the head is impacted, the skull accelerates while the brain lags due to its inertia, resulting in relative motion at the skull-brain interface. This causes strains and pressure gradients within the brain tissue, which can lead to injury if tolerable limits are exceeded. Characterizing the immediate strain response of the brain to impact would help improve understanding of the functional and anatomical changes that result. Still, this response is challenging to quantify during impact, especially in vivo. Several early attempts to observe brain motion during effects have been made using cadaveric and primate specimens. Still, these studies generally only utilized

qualitative measures or involved substantial compromise of the skulls of the specimen, limiting the interpretation of the findings.

The two types of acceleration are thought to result in two different injury mechanisms: linear acceleration is believed to cause transient intracranial pressure gradients resulting in more focal injury, while rotational acceleration is believed to cause shear strain from relative motion at the skull-brain interface resulting in more diffuse injury. Focal brain injuries typically include hematoma and contusion, while diffuse brain injuries include diffuse axonal injuries, Concussion, and swelling. However, most injuries result from both types of acceleration, as real-world head impacts always involve both. The roles of these two variables in producing brain injury have historically been studied independently, as each tends to be associated with different injury mechanisms. Linear acceleration is thought to cause injury via transient intracranial pressure gradients. In contrast, rotational acceleration is thought to cause injury through shear strain in the neural tissue from the brain's motion relative to the skull. Scientists still debate whether the impact is more attributable to linear or rotational head acceleration. This debate is complicated by the complex nature of studying Concussion in a laboratory setting, as concussive injury manifests in a weakly understood physiologic response that many models struggle to reproduce. There are different levels of physiologic response depending on the severity of the brain injury.

1.6 Sports-Related Concussion Symptoms and Reporting Behaviors

Previous literature on SRC knowledge (i.e., essential injury awareness, related signs and symptoms, and potential health repercussions) has been limited to high school and NCAA varsity collegiate athletes. Results from several studies suggested that high school athletes were relatively knowledgeable about the general signs and symptoms of SRC (i.e., headache, confusion, and dizziness); however, a gap persisted regarding less familiar signs and symptoms of SRC. Despite

increasing educational initiatives to promote knowledge and awareness, SRCs at the high school and collegiate levels continue to go unreported as athletes prioritize sports participation over their Health. Although SRC education has increased recently, more than 50% of athletes still need to report their suspected SRC to an authority figure. Increased SRC knowledge would translate into increased SRC-reporting behaviors. However, our results and previous researchers suggest that SRC knowledge is needed to reflect increased recognition and reporting behaviors. Similar reasons indicate that collegiate club-sport athletes did not or would not report their SRC because they did not think it was serious, did not want to let their teammates down, and feared losing playing time.

Although it is essential to consider reporting behaviors in all settings, more research is needed on athletic populations that lack consistent access to on-field medical care (e.g., collegiate club sports and youth sports). As mentioned, the self-governing nature of youth club sports adds another layer of intricacy to the already complicated process of identifying and managing SRCs, as the athletes essentially act as their medical providers. This population needs evaluation by a trained sports medicine professional immediately after an injury, so they must make game-time decisions using their best judgment from their current knowledge and previous experiences.

1.7 Sex Differences in Sports-Related Concussion

Females are at higher risk of sustaining a sports-related concussion. Coincidentally, girls and women are more involved in the National Collegiate Athletic Association than ever. Approximately 43% (~210,000) of all collegiate level-athletes are female. However, notwithstanding this large number of female athletes, they remain understudied in sports-related concussions. Moreover, despite the higher risk of females sustaining a concussion in comparison to males, studies

including both female and male athletes to examine sex-related differences following a concussion are sparse.

Findings from the available literature indicate that females have prolonged recovery trajectories and worse outcomes following Concussion compared to males. This evidence comes primarily from studies that have utilized subjective symptom reporting, neurological evaluations, and computerized neurocognitive test performance, i.e., approaches that offer indirect insight into the brain.

The literature to date has not provided sufficiently conclusive evidence for a modulating effect of sex and gender on outcomes following sports-related concussions. Nonetheless, despite a few studies that found no significant differences between males and females following Concussion, the accumulation of evidence points to sex-related differences across a range of clinical and neurological outcomes. It should be noted, however, that most studies investigating sex-related differences in sports-related Concussion predominantly used subjective assessment tools, such as symptom reports and brief computerized neurocognitive testing, e.g., ImPACT, as the only outcome measure. This was particularly true for the few studies that did not find sex-specific differences. Several subtle patterns emerge in those studies that report significant sex-related differences following Concussion. For example, examining postconcussive symptoms, multiple studies report a more substantial symptom burden in female athletes in conjunction with a more extended recovery period, with some evidence of differences in symptoms in males and females. Several factors may contribute to these differences, including social factors, which make males less likely to report symptoms.

1.8 Sports-Related Concussions in Female Athletes

Sex-based differences regarding the incidence and outcomes of SRC have been reported. Such research has shown that female athletes may be more likely to sustain a concussion while playing sports than their male counterparts. Women's soccer, softball, and basketball have higher incidence rates of Concussion than male-equivalent sports. Even with intentional body-checking prohibited in women's ice hockey and permitted in male ice hockey, female hockey players sustain nearly equivalent rates of Concussion relative to male hockey players. Additionally, female-dominated sports, such as cheerleading, have high rates of Concussion. Further, female athletes have demonstrated higher postconcussive symptom (PCS) scores, have slower reaction times compared with baseline, exhibit more significant cognitive decline, and take longer to RTP after experiencing SRC in comparison with males playing comparable sports. Research also suggests that female athletes have more prolonged concussion-related symptoms than their male counterparts.

Proposed explanations for these sex-based differences include physical and physiologic aspects, hormonal effects of estrogen and progesterone, and gender norms of behavior. Several studies have reported that shorter neck dimensions, less head mass, and narrower neck girth result in less neck strength in females than male athletes, predisposing girls and women to more excellent head-neck acceleration during impacts. Recent research suggests that the menstrual cycle phase and serum progesterone concentration during a concussive injury predict outcomes among women. Additionally, female athletes tend to be more forthcoming in reporting their concussion-related symptoms.

1.9 Recovery Time from Sports-Related Concussion

The most recent consensus statement on Concussion in sports discussed the importance of gradual return-to-school protocols. Importantly, however, few investigations have been designed to assess the nature and length of timelines for athletes returning to academics and sports activities across collegiate sports. Therefore, studies that include additional athlete and injury outcome characteristics (i.e., sex, level of contact, time to return to academics, return to limited sports participation) across sports will be informative from a descriptive standpoint in documenting differences in SRC recovery and prognosis.

Researchers have suggested that female athletes face an increased risk for SRC in sex-comparable sports, report a greater frequency and severity of SRC symptoms, and have protracted recovery patterns (i.e., symptom resolution) compared with male athletes. Additional evidence has indicated sex differences in recovery timelines depending on the sport. For example, among female collegiate soccer and basketball athletes who sustained an SRC in practice and competition, Covassin et al. demonstrated longer recovery times than male athletes in similar activities. These outcomes suggested mixed results for sex differences in SRC recovery and prognosis, although considerations of additional intermediate markers of clinical recovery (i.e., return to academics, return to limited sports participation) were either few or also produced mixed results. Furthermore, many investigations of clinical recovery timelines post-SRC are underpowered to assess the effect of sex.

Overall, student-athletes demonstrated a median of 9 days for full symptom resolution, eight days for return to academics, 12 days to return to limited sports participation, and 16 days to return to full sports participation. Across all time measures, participants in women's sports experienced longer symptom resolution trajectories and returned to academics than men's sports. The median difference of 1 day for symptom resolution between men's and women's sports may not

have been clinically significant; therefore, we point to sex differences within sports (e.g., lacrosse).

1.10 Neuropsychological Evaluation for Sports-Related Concussion

In the injured athlete who is not rendered unconscious, performing the initial screening assessment may be challenging, especially in sports that do not include play stoppages for medical tests. Recently, however, World Rugby and National Collegiate Athletic Association soccer guidelines were changed to allow a team to substitute for the injured player. At the same time, they are being evaluated for Concussion. The initial screening assessment should include questions assessing the athlete's orientation and immediate and remote memory. Asking the athlete what they remember about the game before or after the injury can help the provider determine how the athlete processes memory information. Inquiring about the day, date, month, and year can also be helpful. Asking for the venue name or location, the score, who scored last, the team's last opponent, and the game's outcome can quickly be done on the sideline.

New to the SRC assessment field are tools that evaluate saccadic eye movements in individuals who may be injured. The utility of such tests has been explored in mixed martial arts athletes, youth and collegiate athletes, and professional hockey and football players, and they hold promise in assessing SRC. The King-Devick (KD) test uses numbers placed in a standardized fashion, spaced at varying intervals on three cards. The athlete is timed as they read off the numbers from each card over 1 to 2 minutes. Research on the KD test has demonstrated that visual-scanning ability decreases (i.e., it takes longer) after a concussion. As with other sideline assessment tools, the KD test is also associated with a practice effect in non-concussed controls, whereby they perform better after exposure. This underscores the importance of having individual baseline scores or group-based norms (or both) available for comparison if this test is used on the sideline.

Another novel area of concussion assessment is the measurement of reaction time. Although sideline tests exist, a measuring stick attached to a hockey puck has been used to measure reaction time; performance is based on how quickly and where the athlete grasps the stick when it is dropped, and in a study of youth athletes, reaction time differentiated concussed from non-concussed athletes, with a significant decline in post-injury versus baseline time in the concussed group compared with an outcome toward improvement in the non-concussed group. The sensitivity and specificity of the reaction-time test were 75% and 68%, respectively, with a reliable change index of 65%. The reaction-time test also remained stable during acute exercise and provided acceptable reliability. Future investigations of the sideline reaction-time test to evaluate SRC are needed.

1.11 Balance and Postural Control Considerations in Sports-Related Concussion

Deficits in balance, or postural stability, are common after SRC and could result from direct injury to the vestibular apparatus or poor integration of sensory input. Balance is often assessed with tools such as the Balance Error Scoring System. The Balance Error Scoring System has been extensively researched and is helpful for acute balance assessment (sensitivity 34%; specificity 91%–96%) but can less identify deficits after 3–5 days post-concussion. Postural stability was examined during a single-legged hop from a box and a single-legged squat in subjects with a concussion history and in subjects who served as controls. The time to stabilize after landing from the top of a box was longer for the non-dominant limb in concussed subjects than controls. At the same time, no group differences were found for the dominant limb or in the squat task. Whether balance/postural stability tasks and measures can identify persistent motor control impairments after SRC is unclear.

SRC might affect movement patterns, but how it does is unclear. Gait after SRC has been found to have altered inter-joint coordination and more significant changes in the center of mass position. Leg stiffness during a single-legged jump-landing task decreased post-season in football players who sustained SRC. This could be problematic because insufficient joint stiffness increases the risk of soft tissue injury.

1.12 Balance Error Scoring Systems (BESS)

The Balance Error Scoring System was developed to provide a quick and efficient balance assessment along the sidelines following sports concussions. This tool may add value to the balance assessment of other populations (vestibular/ non-sports related Concussion); however, it has yet to be evaluated in these populations. The mCTSIB has been assessed in the vestibular population. The mCTSIB requires similar training, time to administer, and equipment and is recommended as a superior test to the BESS. A significant learning effect was noted with tandem stance, especially with single-leg stance and foam items (Valovich et al., 2003; Valovich et al., 2004). Exertion adversely affects BESS scores, with the most significant effect on single-leg and tandem stance conditions. (Susco et al., 2004) A distracting environment may negatively impact scores (most noted on single-leg foam conditions, total score, and tandem-leg foam conditions). A revised version of the test has been performed with four conditions: single-leg stance on firm and foam, and tandem stance on firm and foam) (Hunt, TN et al. (2009)) with improved reliability.

1.13 The Relationship between Cognitive Status and LE Injury

A hallmark of SRC is a temporarily compromised cognitive state that may last days or weeks after a concussive event despite athletes reporting no symptoms.³ Interestingly, collegiate athletes'

lower preseason baseline cognitive performance (mental processes related to visual recognition, processing speed, and response initiation) has been prospectively and retrospectively associated with a higher risk for LE injury. However, traditional post-SRC measures of cognitive performance were unable to predict LE injury occurrence in recently concussed male and female collegiate competitors. Nonetheless, there is clinical utility in assessing cognitive performance for the dual purposes of SRC management and LE injury risk in collegiate athletes with and without a recent history of SRC. To further elucidate the relationship between cognitive performance and LE biomechanics associated with injury, recent studies have determined that athletes with slower reaction time and reduced working memory perform landing maneuvers with biomechanical patterns associated with LE injury, such as increased vertical ground reaction force (vGRF), greater knee valgus angle, and decreased landing stability.

There appears to be a complex relationship between cognitive performance, SRC, and LE injury in athletes, which may alter future concussive management strategies. While an increasing number of research studies suggest that previously concussed athletes are at greater risk for knee and ankle injury, there is a need for more multifaceted clinical tests of recovery that emphasize dynamic motor tasks to ensure athlete safety while returning to sports-RTS.

1.14 Risk of Re-Injury Following a Sports-Related Concussion

Recent studies demonstrate that athletes returning to play from a concussion harbor an elevated risk of LE injuries within 90 days and one year of Concussion. As the level of competition increased, there was a concurrent increase in the likelihood of sustaining an LE injury. Additionally, when evaluating the impact of multiple concussions, a more significant number of concussions were found to correlate with an increasing risk of LE injury. Finally, both men and women were shown to be vulnerable to LE injury. However, minimal data exists on the comparison of

men and women. Despite implementing return-to-play protocols after Concussion, the current literature reports an increased risk of LE injuries for collegiate and professional athletes in both the short- and long-term periods.

Traditionally, return-to-play protocols after Concussion focused on neuroprotective measures. In recent years, research has revealed a more global impact of brain injury, including effects on LE and proprioceptive factors, resulting in a greater focus on kinematic metrics.

Multiple theories have suggested that concussions share similar pathophysiology and biological factors with injuries such as altered cerebral blood flow, diffuse axonal injury, and neuroinflammation. The acute effects of concussions can be detrimental to athletic performance, with prior studies demonstrating alterations in reaction time, gait patterns, and postural stability after returning to play. These alterations adversely affect performance and make the athlete more vulnerable to subsequent injury.

With athletes receiving clearance to return to play an average of 16-20 days after a concussion, an emerging trend over the past several years is an increased risk of lower extremity musculoskeletal injury after athletes have returned to sports post-concussion. Beginning in 2014, researchers observed that male soccer players who sustained a concussion were twice as likely to maintain an additional injury in the year following their return to play compared to their counterparts without Concussion.

1.15 Rationales for Lower Extremity Injury Risk After a Sports-Related Concussion

While the tools above provide significant insight into SRC injuries, they are limited in their applicability to biomechanical-related tasks. Given that athletes are exposed to cognitively and physically challenging tasks during sports, researchers and clinicians utilize dual-task movement

analyses within an RTS protocol. Gait analysis in athletes previously concussed has revealed locomotor instabilities that may translate to further instability within more demanding sports environments. During dual-task gait examinations, athletes' post-SRC demonstrated deficits in gait velocity and frontal/sagittal plane core stability. When paired with a cognitive task, deficits in locomotor tasks may persist weeks beyond symptom resolution and a return to NP baseline scores, suggesting variable recovery rates exist amongst SRC assessment types. After clearance for RTS, SRC impairments, including a failure to report symptoms or subtle functional deficits, may place an athlete at greater risk for LE injury. Recent evidence suggests that adolescent and collegiate athletes are at a significantly greater risk for lower body injury following an SRC. This risk has been noted to be present upwards of one year after the concussive event, as collegiate athletes with an SRC history displayed more excellent injury rates (64–67% increase) compared to control groups during this period.

Recent evidence suggests that athletes with a prior SRC history across all sports are at greater risk for joint injury, although the mechanism for this is presently unclear. Multiple theories have been postulated, such as impaired motor planning and coordination, reductions in cortical excitability, and neuromuscular alterations that persist far beyond the resolution of traditional post-SRC measures. Studies have demonstrated that following SRC, most athletes can return to baseline values relating to symptom reporting, NP performance, and balance/sway tasks like BESS within a short period. However, some cognitive and physical deficiencies may persist, only to be revealed during a dynamic sporting environment that tasks performers to complete highly complex maneuvers.

1.16 Introduction and rationale of the present research project/Aims and Significance

The main purpose of this study is to determine if a daily activity in football, such as the head of the ball, can cause knee injury and especially ACL in healthy individuals.

One of the major risk factors for ACL injury is neuromuscular control, muscle weakness around the knee joint, and knee stability.

To examine the above we will use the following evaluation tools:

1. Neuromuscular examination and contractile muscle property for the diagnosis of functional muscle symmetry, either temporal or morphological of the muscles around the knee using the method of tensomyography.
2. The stability of the ACL with digital laximetry.
3. Proprioception with a power platform (force plate) after a drop jump.

The clinical significance of this work is to give clinicians and physiotherapists a new tool for better ACL injury recovery and a re-injury prevention strategy.

It also helps to better understand the subclinical concussion in football and the strategy for the prevention and evaluation of this injury. In connection with the present study, it is important to identify subgroups of patients with different findings in the lower extremity and knee depending on the cause of the problem and how the subclinical micro-concussion may affect.

CHAPTER 2

The effect of ball heading and subclinical concussion in the neuromuscular control of the lower limb: A systematic review

2.1 Abstract

Soccer is unique among sports because it is the only sport that involves the purposeful use of the head to control, pass, or shoot the ball. This action of soccer heading has drawn considerable attention from policymakers, clinicians, researchers, parents, coaches, and athletes for its potential effects on the brain, particularly among younger players. Mild T.B.I. (S.R.C.) is among the most common neurological conditions, with an estimated annual incidence of 500/100,000 in the United States only. Sports Related Concussion (S.R.C.) is considered among the most complex injuries in sports medicine to diagnose, assess, and manage. The following ten databases were searched: MEDLINE (Epub Ahead of Print, In-Process & Other Non-Indexed Citations, Ovid MEDLINE(R) Daily and Ovid MEDLINE(R)), C.I.N.A.H.L. Plus with Fulltext, E.M.B.A.S.E., PsycINFO, Cochrane Database of Systematic Reviews, Cochrane Central Register of Controlled Trials, Scopus, Web of Science, PsycARTICLES, and SPORTDiscus.

The search was limited to English-language and peer-reviewed publications but had no date restriction. The search was conducted on 10–15/12/ 2022. Most S.R.C.s occur without loss of consciousness or frank neurological signs. A few studies examined the possible long-term effects of sub-concussive head impacts. While L.E.L.E. injury risk has been associated with S.R.C. occurrence across multiple collegiate populations, previous investigations failed to control for L.E.L.E. injury history before an S.R.C. This potential confounding variable may influence subsequent injury risk. Significant methodological challenges are associated with the study of sub-concussive impacts. The challenge researchers face at this time is that (i) there is no established

definition of a sub-concussive impact or a sub-concussive injury, (ii) a blow may or may not cause an injury, and it is difficult to understand if an injury has occurred, and (iii) the biomechanical features and thresholds for measuring a blow and identifying an injury have not been agreed upon. Neuroimaging studies show modest evidence of some athletes' macrostructural, microstructural, functional, and near-chemical changes. More research is needed to understand better the prevalence of S.R.C. and other neurological and orthopedic conditions and injuries and the extent to which they are related to concussions and repetitive neurotrauma after a ball heading sustained in Soccer.

2.2 Introduction

Soccer is unique among other sports because it is the only one that involves the purposeful use of the head to control, pass, or shoot the ball. This action of soccer heading has drawn considerable attention from policymakers, clinicians, researchers, parents, coaches, and athletes for its potential effects on the brain, particularly among younger players. (1) These types of preceding match events are likely to cause the most severe header impacts due to the higher velocity the football travels, reaching speeds up to 85 km/h (23.6 m/s). In response to a recent lawsuit and to minimize concussions from heading in youth soccer, U.S. Soccer enacted guidelines restricting heading under age 11 and limiting it for players aged 11 to 13 years. Many more institutions, like the Football Association in the U.K., follow similar guidelines for young footballers, males and females.

Examining research papers that studied the incidence of concussions in Soccer, he found that S.R.C. accounted for 5.8 percent to 8.6 percent of total injuries sustained during games. One study found that 62.7 percent of soccer players had suffered symptoms of a concussion during their playing careers, yet only 19.2 percent will realize it. (2) Another found that 81 percent of

athletes who had suffered a concussion had experienced two or more and that players with a history of concussion had 3.15 times greater odds of sustaining another one than those who had never had a concussion. Concussion/mild T.B.I. can be described as an acute neurophysiological event related to blunt impact or other mechanical event applied to the head, neck, or body (with transmitting forces to the brain), such as from sudden acceleration, deceleration, or rotational forces. (3) Concussion can be sustained from a motor vehicle crash, sport or recreational injury, falls, workplace injury, assault, or incident in the community. (4)

Clinical signs of concussion immediately following the injury include any of the following:

1. Any period of loss of or a decreased level of consciousness less than 30 min.
2. Any memory loss for events immediately before or after the injury (post-traumatic amnesia) less than 24 hours.
3. Any change in mental state at the time of the injury (e.g., confusion, disorientation, slowed thinking, alteration of consciousness/mental state).
4. Physical Symptoms (e.g., vestibular, headache, weakness, loss of balance, change in vision, auditory sensitivity, dizziness).
5. Note: No evidence of intracranial lesion on standard imaging (if present, suggestive of more severe brain injury). (5)

S.R.C. is among the most common neurological conditions, with an estimated annual incidence of 500/100,000 in the United States. (6)

One Canadian study examining hospital-treated cases and those presented to a family physician calculated the incidence of mTBI in Ontario to lie between 493/100,000 and 653/100,000, depending on whether primary care physicians or a secondary reviewer made the diagnosis. (7)

Over the previous five years, various sporting populations have established a newfound relationship between L.E.L.E. (lower extremity) injury and S.R.C. (sports-related concussion). (6) Athletes at the high school, collegiate (Fino et al., 2017; Gilbert et al., 2016; D. Herman et al., 2017; Lynall et al., 2015), and professional (Nordström et al., 2014; Pietrosimone et al., 2015) levels have demonstrated a greater risk for sustaining an L.E.L.E. injury post-SRC. Most studies consist of retrospective injury surveillance data that monitored L.E.L.E. injury incidence in both concussed and non-concussed athletes for a specified time around the initial S.R.C. event (before and after S.R.C.). (8) All athletes diagnosed with S.R.C. in these investigations were clinically cleared to play sports by sports medicine staff (athletic trainer, doctor, physio) and monitored for L.E.L.E. injury rates at various time points after the initial S.R.C. Of course, it is unclear if the individuals responsible for clearing athletes strictly adhered to all components related to the latest S.R.C. consensus (9).

2.3 Definitions

The Berlin expert panel modified the previous CISG (2017 Concussion in Sport Group) definition (10) as follows:

Sport-related concussion (S.R.C.) is a traumatic brain injury caused by biomechanical forces. Several standard features that may be utilized in clinically defining the nature of a concussive head injury include: S.R.C. may be caused by a blow to the head, face, neck, or elsewhere on the body with an impulsive force transmitted to the head.

1. S.R.C. typically results in the rapid onset of short-lived impairment of neurological function that resolves spontaneously. However, signs and symptoms in some patients evolve over minutes to hours.

2. S.R.C. may result in neuropathological changes, but the acute clinical signs and symptoms largely reflect a functional disturbance rather than a structural injury, and, as such, no abnormality is seen in standard structural neuroimaging studies.
3. S.R.C. results in many clinical signs and symptoms that may or may not involve loss of consciousness. Resolution of the clinical and cognitive features typically follows a sequential rehabilitation course. However, in some cases, symptoms may be prolonged for long.
4. In the broadest clinical sense, S.R.C. is often defined as representing the immediate and transient symptoms of traumatic brain injury (T.B.I.). (11) Such definitions, however, do not give any insights into the underlying problems through which the brain is impaired, distinguish different grades of severity, or reflect newer insights into the persistence of symptoms and abnormalities on specific investigational modalities. (12) This issue is clouded by the need for more data and clarity in definition and terminology. Often, the term mild traumatic brain injury (mTBI) is used with the term concussion; however, this term needs to be more specific and based on validated criteria in this context. (13) One key unresolved issue is whether concussion is part of a T.B.I. spectrum associated with lesser degrees of diffuse structural change than severe T.B.I. or whether the S.R.C. results from reversible physiological and structural changes. The term concussion, while helpful, could be more precise, and because disparate author groups define the term differently, comparison between studies is problematic. (14)

S.R.C. is considered among the most complex injuries in sports medicine to diagnose, assess, and manage (rehabilitate). Most S.R.C.s occur without loss of consciousness or frank neurological signs. Currently, clinicians can rely on no perfect diagnostic test or marker to immediately diagnose S.R.C. in the sporting environment. (15)

Great interest has been expressed in the last years in the concept of ‘sub-concussive blows’ (i.e., subconcussive head impacts like heading a ball in football) as an indicator of repetitive neuro-trauma and possible S.R.C. Sub-concussive impacts like ball heading are typically defined as involving the transfer of mechanical force to the head and brain at enough force to impact axonal or neuronal integrity but not be expressed in clinical symptoms and signs. (16) Some researchers have proposed these impacts as a separate variable from concussion history. We reviewed five sub-concussive impact studies that (i) defined the concept or (ii) quantified the criteria (i.e., years of exposure, estimated number of impacts). These studies are discussed, in part, in the sections below. They either addressed the concept of sub-concussive impacts or added the estimated number of sub-concussive impacts to the athletes’ concussion history. (17) Most subjects were American football athletes or soccer players. Most studies identified significant group-level differences between ‘high exposure’ and ‘low/no exposure’ athletes. However, some studies did not support the notion that repetitive sub-concussive impacts have a measurable, detrimental effect. Some studies have drawn inferences about sub-concussive impacts based solely on a person’s participation in specific contact or collision sports. For example, Meehan and colleagues surveyed >3702 college alums between 40 and 70, and 2121 had no reported concussion history. In those with no reported concussions (a proxy for studying sub-concussive impacts), there were no differences in anxiety, depression, emotional problems, sleep issues, or perceived cognitive functioning in those who participated in collision sports versus those who did not. (18)

2.4 Materials and Methods

We followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines in the search strategy and reporting according to the P.R.I.S.M.A. statement (47)

2.5 Search Strategy

Keywords were selected by agreement of all authors and then submitted to a librarian with expertise in systematic reviews who developed a draft MEDLINE search strategy. This was reviewed by a second expert health sciences librarian using the C.A.D.T.H. Peer Review Checklist for Search Strategies according to the PRESS 2015 Guideline Statement. The draft search strategy was revised based on suggestions from the PRESS review and then tested to be sure known critical studies were retrieved. The MEDLINE search was adapted and translated for all other databases. The following ten databases were searched: MEDLINE (Epub Ahead of Print, In-Process & Other Non-Indexed Citations, Ovid MEDLINE(R) Daily and Ovid MEDLINE(R)), C.I.N.A.H.L. Plus with Fulltext, E.M.B.A.S.E., PsycINFO, Cochrane Database of Systematic Reviews, Cochrane Central Register of Controlled Trials, Scopus, Web of Science, PsycARTICLES, and SPORTDiscus. The search was limited to English-language and peer-reviewed publications but had no date restriction. The search was conducted on 10–15/12/ 2022. (fig 1)

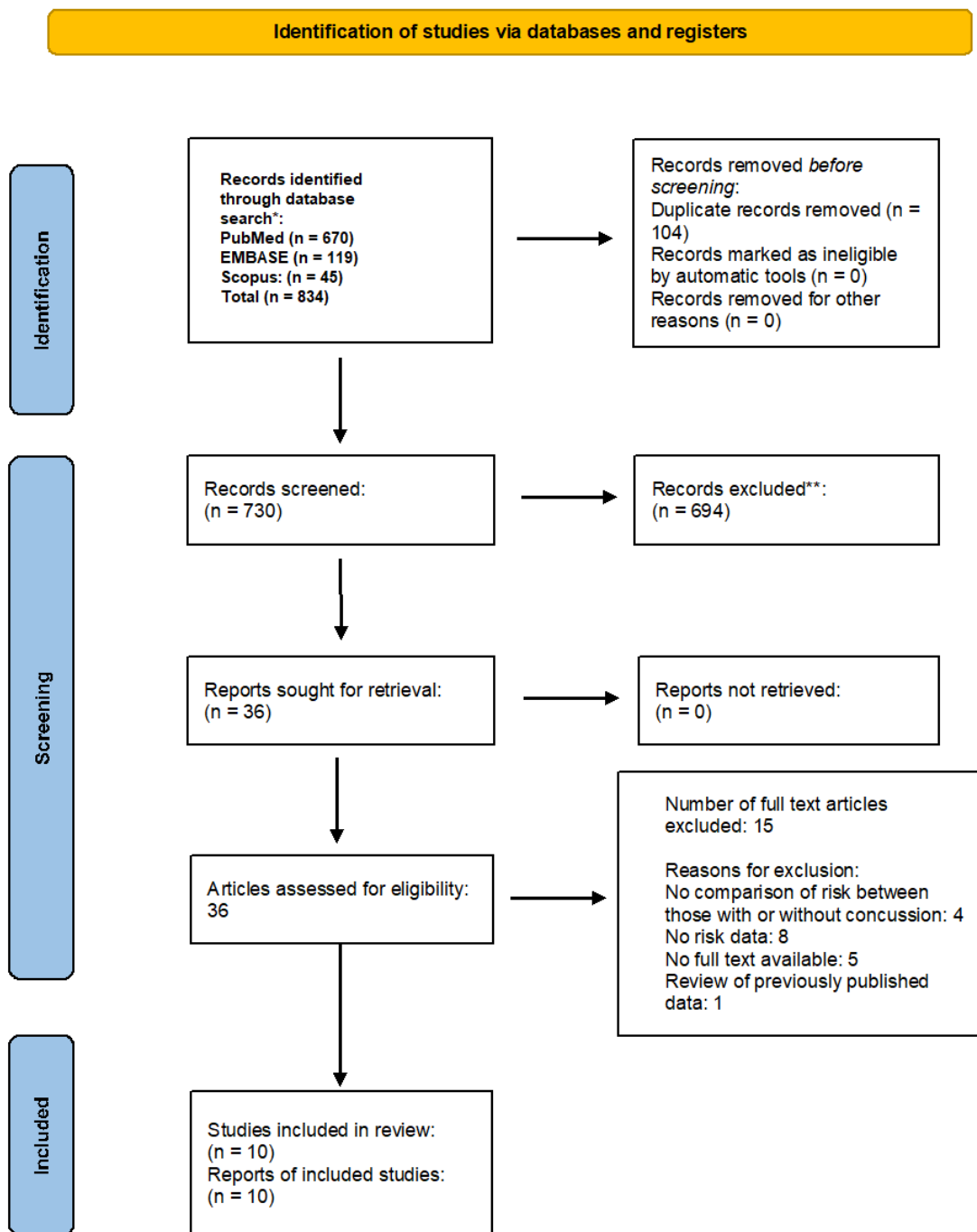


Fig 1: Database search strategy

Risk of bias in studies

Risk of Bias Assessment

The PEDro scale was used for the assessment of the risk of bias among the included studies. PEDro scale is a valid measure of methodological quality of clinical trials in rehabilitation. It consists of 11 items including external validity (item 1), internal validity (items 2–9), statistical reporting (items 10 and 11), and each one of them contributes one point to a total score of 10, except for one dichotomous item (yes/no).

The PEDro scale is considered to meet interval level measurement, allowing score comparisons between studies. Scores of <4 are considered ‘poor’, 4–5 are considered ‘fair’, 6–8 are considered ‘good’, and 9–10 are considered ‘excellent’. Two reviewers assessed the risk of bias in each study independently and a third reviewer was recruited in case of any argument.

	Eligibility Criteria & Source	Random Allocation	Concealed Allocation	Baseline Comparability	Blinding of Participants	Blinding of Therapists	Blinding of Assessors	Adequate Follow Up (>85%)	Intention to Treat Analysis	Between Group Statistical Comparisons	Reporting of point measures & variability	Total Score (0-10)
Brooks (2016)	+	+	+	-	-	-	-	-	+	+	+	6/10
Burman (2016)	+	+	+	-	-	-	-	+	+	+	+	7/10
Cross (2016)	+	+	-	-	-	-	-	-	-	+	+	4/10
Fino (2017)	+	-	+	+	+	-	-	-	-	-	+	5/10
Herman (2017)	+	+	+	+	-	-	-	-	-	-	+	5/10
Lynall (2015)	+	+	-	-	-	-	-	-	-	+	+	4/10
Lynall (2017)	+	+	+	+	+	-	-	-	-	+	+	7/10
Makdissi (2009)	+	+	-	-	-	-	-	-	-	-	+	3/10
Nordstrom (2014)	+	+	+	+	-	-	-	-	+	+	+	7/10
Nyberg (2015)	+	+	+	+	-	-	-	+	+	+	+	8/10

1. Eligibility criteria were specified; 2. subjects were randomly allocated to groups (in a cross-over study, subjects were randomly allocated an order in which treatments were received); 3. allocation was concealed; 4. the groups were similar at baseline regarding the most important prognostic indicators; 5. there was blinding of all subjects; 6. there was blinding of all therapists who administered the therapy; 7. there was blinding of all assessors who measured at least one key outcome; 8. measures of at least one key outcome were obtained from more than 85% of the subjects initially allocated to groups; 9. all subjects for whom outcome measures were available received the treatment or control condition as allocated or, where this was not the case, data for at least one key outcome were analyzed by “intention to treat”; 10. the results of between-group statistical comparisons are reported for at least one key outcome; 11. the study provides both point measures and measures of variability for at least one key outcome; Note: The first item relates to external validity and the remaining 10 items are used to calculate the total score, which ranges from 0 to 10. + Yes - No.

2.6 Study selection criteria and data extraction

Studies were included if they (i) were original research; (ii) evaluated the incidence/prevalence, risk factors, or causation related to neurodegenerative disease; (iii) included individuals who have suffered a sport-related concussion; (iv) evaluated athletes and retired athletes as the study subjects and (v) evaluated possible long-term sequelae defined as ≥ 10 years after sports-related injury. Studies were excluded from this review if published in languages other than English, such as animal studies, review articles, case reports, book chapters, conference abstracts, editorials/commentaries/expert opinion, theses, or dissertations.

Pairs of authors independently screened citations. A third reviewer adjudicated disagreements between authors. Following the initial abstract and title screening process, full-text articles were

Table 2. Data extracted from studies

Lead Author (Year)	Athletes With Concussion, No. and Level of Participation	Sports	Control Athletes	Quality Checklist Score	Time from concussion to Return to Sport	Injuries Tracked	Injury Tracking Time Period
Brooks (2016)	75 (58 male, 17 female) college	Football, soccer, hockey, basketball, volleyball, softball	Non concussed, matched players	8	21 days	Acute, non-contact lower extremity injuries	90 days
Burman (2016)	281 (206 M, 75 F)	Hockey, soccer, handball	Athletes with an ankle sprain, same 3 sports non concussed players	7	Not reported	Not defined	24 months
Cross (2016)	135 (135 M, 0 F) professional	Rugby	Non concussed players	9	11 days	Any injury	2 seasons
Fino (2017)	110 (76 M, 34 F) college	Baseball, basketball, lacrosse, football, tennis, volleyball	Non concussed matched players	9	18±40 days	Acute lower extremity injuries	12 months
Herman (2017)	73 (52 M, 21 F) college	Football, basketball, lacrosse, soccer	Non concussed matched players	9	9±7 days	Acute lower extremity injuries	90 days
Lynall (2015)	44 (28 M, 16 F) college	Hockey, football, lacrosse, soccer, basketball, tennis	Non concussed matched athletes	11	Not reported	Acute lower extremity injuries	12 months
Lynall (2017)	2004 high school	Baseball, basketball, lacrosse, soccer, softball, tennis	Not applicable	6	Not reported	Acute and chronic lower extremity injuries	Undefined
Makdissi (2009)	117 (117M, 0 F) professional	Australian football	Non concussed matched players from same team	10	Not reported	Any injury	Undefined
Nordstrom (2014)	66 (66 M, 0 F) professional	Soccer	Non concussed injured player	9	Not reported	Any injury	12 months
Nyberg (2015)	81 (81 M, 0 F) professional	Hockey	Athletes with Knee injury	9	Not reported	New knee injuries	42 days

retrieved, and data were extracted using a standardized method. Results were extracted by one author and reviewed by a second author to ensure accuracy and completeness.

2.7 Discussion

While lower limb joint injury risk has been associated with S.R.C. occurrence across multiple collegiate populations, previous investigations failed to control for L.E.L.E. injury history before an S.R.C. This potential confounding variable may influence subsequent injury risk. (19) Studies showed that athletes returning from A.C.L. reconstruction are 15 times more likely to re-injure the A.C.L. on the contralateral or ipsilateral limb (20). When accounting for previous L.E.L.E. injuries, Fino et al. found college athletes post-SRC at a 67% greater risk for subsequent L.E.L.E. injury when matched to those of the same team (19). While the exact location of L.E.L.E. injury following S.R.C. was unclear in the studies above, (21) determined significant associations between S.R.C. (reported, unreported, and unrecognized) and lateral ankle sprain, knee injury, and L.E.L.E. muscle strain (22). This investigation comprised 335 athletes (61% female) who completed a questionnaire about their injury history after finishing their collegiate career. Although limitations exist due to self-reporting and an inability to determine the order of injury occurrence, athletes with a stated S.R.C. history were 1.6-2.9 times more likely to report a L.E.L.E. injury (23), findings similar to related retrospective data (23,24). Various studies also suggest that collegiate athletes are at greater risk for L.E.L.E. injury at 90 days (24), 180 days (25), and 365 days (26) post-SRC. Collegiate male and female athletes across seven sports were 2.5 times more likely to sustain an L.E.L.E. musculoskeletal injury than matched counterparts 90 days after sustaining an S.R.C. (27,28). It was found that 17% of post-SRC athletes sustained a non-contact L.E. injury, while the incidence of similar injuries was less (9%) in the matched control group (29). In a related study of collegiate basketball, Soccer, and lacrosse athletes, L.E.L.E. musculoskeletal injury risk was 3.4 times greater in athletes previously concussed when matched

to those of comparable athletic status during a 90-day follow-up period (30). Male football athletes with prior S.R.C. were 3.7 times more likely to injure the knee and ankle. Female sports participants demonstrated a 2.8 times greater risk for L.E.L.E. injury after S.R.C. (31). These findings at 90 days post-SRC were not observed in other collegiate cohorts (32). However, why these findings are equivocal is still being determined. While Lynall et al. did not observe differences at 90 days, athletes were significantly more likely to sustain an L.E. injury at 180 days (2.02 times) and 365 days (1.97 times) post-SRC compared to pre-concussion injury rates (33). In addition to youth and collegiate athletes, professional athletes have demonstrated greater injury risk following S.R.C. Elite male European soccer athletes were at greater risk for subsequent injury (combined lower and upper extremity) following S.R.C. occurrence across three time periods (0–3 months, 3–6 months, and 6–12 months post-SRC), In addition to youth and collegiate athletes, professional athletes have demonstrated greater injury risk and frequencies following S.R.C. Elite male European football players were at greater risk for subsequent injury (combined lower and upper extremity) following S.R.C. occurrence across three time periods (0–3 months, 3–6 months, and 6–12 months post-SRC, with injury risk being most significant at 6–12 months after an S.R.C. (34). A study follows 28 seasons of injury data in professional ice hockey players, researchers has stated that, in comparison to a knee injury, athletes post-SRC are more likely to sustain a subsequent severe L.E. injury (> 28 days recovery) within 21 days of returning to sport (35). However, no differences were reported at the seven and 42-day follow-up, and the reported injury after the S.R.C. or knee injury was not classified by location (36). Furthermore, no differences were observed in the frequency of subsequent injury between athletes who sustained an S.R.C. or knee injury (37). Recent evidence suggests that athletes with a prior S.R.C. history across all sporting populations are at greater risk for L.E.L.E. injury, although the mechanism for this relationship is unclear. Many theories have been postulated, such

as impaired motor control and coordination (37,38), reductions in cortical excitability (39), and neuromuscular alterations that persist far beyond the resolution of traditional post-SRC measures (40). It has been demonstrated through numerous studies that following a concussive event, the majority of athletes can return to baseline values relating to symptom reporting, N.P.P. performance, and balance/sway within a relatively short period. However, subtle cognitive and physical deficiencies may persist, only to be revealed during a dynamic sporting environment that tasks performers to complete highly complex maneuvers (41).

Recent evidence suggests that cognitive deficits, a hallmark of S.R.C., play a severe role in L.E.L.E. injury risk during sports. Examinations between musculoskeletal injury and cognition determined that collegiate athletes currently injured in the upper or lower extremities performed worse on some tasks than healthy controls, and no statistical differences were found between athletes with a musculoskeletal injury or S.R.C. on any neurocognitive metrics (42). Young adults classified as “low performers” on an N.P. test battery displayed biomechanical patterns suggesting a greater risk for A.C.L. injury when performing dual-task drop landings (43). Compared to elite sports athletes, those with a lower score completed landings with greater vertical ground reaction forces, anterior shear forces, knee abduction moment/angle, and decreased trunk flexion angle (44,46). An athlete with deficiencies in processing environmental stimuli and task constraints (such as an athlete post-SRC), along with the problem of preplan correct movement sequences, may not be able to create protective muscular bracing, thus leading to high impact loads on musculoskeletal tissues that result in injury (45)

2.8 Limitations of the study

The present systematic review should be interpreted in light of its limitations. First, restricting our inclusion criteria to only English-language publications may have increased the risk of missing critical information published in other languages and countries. Second, a few well-designed studies in the current field must be more underpopulated.

2.9 Conclusion

Contact sports participation provides unique opportunities to study S.R.C. and mTBI, given the detailed S.R.C. phenotype data typically available in many sports. It is critical to understand that the outcomes derived from non-sporting mTBI research inform the understanding of S.R.C. (and vice versa), and this arbitrary separation of sporting versus non-sporting T.B.I. should not be viewed as a dichotomous or exclusive view of T.B.I. Mounting evidence claims that athletes with a prior S.R.C. history across all sporting populations are at greater risk for L.E.L.E. injury. However, the mechanism for this relationship is presently unclear and needs more evidence and research for the underlying mechanisms. A few studies examined the possible long-term effects of sub-concussive head impacts. Significant methodological challenges are associated with the study of sub-concussive impacts. The challenge researchers face at this time is that (i) there is no established definition of a sub-concussive impact or a sub-concussive injury, (ii) a blow may or may not cause an injury, and it is difficult to determine if an S.R.C. has occurred, and (iii) the biomechanical forces and thresholds for quantifying a blow and identifying an injury have not been agreed upon. Therefore, the hypothesis that sub-concussive impacts cause long-term neurological injury requires more research before more conclusions can be drawn.

CHAPTER 3

PAPER 1

Heading the ball exposure in women footballers using the HEAD COUNT 2 Weeks questionnaire

3.1 Abstract

Over one in 20 humans play football, the only sport where athletes deliberately engage in repeated head impacts, which is part of the game. Growing evidence shows that football is associated with a risk of persistent central nervous system (C.N.S.) impairment and structural changes. We used HeadCount-2 weeks, a self-administered web-based questionnaire to capture heading exposure during the prior two weeks. We previously reported its validation in a cohort of women footballers of the GREEK SUPER LEAGUE 1 and 2. In the present study, we sought to validate HeadCount-2w (HeadCount-2w ©2013 Michael L Lipton) in an adult population, representing a large segment of women soccer players and dispersed among numerous leagues and teams over a wide geographic area. To evaluate the potential effects of heading in this population, it will be essential to have proven scalable, low-cost means available to quantify exposure.

Our study reveals the variation in heading exposure and symptoms in women footballers over four months in training and matches using the 2-week HEAD COUNT self-reporting. We have questions about the temporal relation, magnitude (e.g., frequency, intensity), and nature (i.e., linear versus rotational) of the ball heading required to modify cognitive function, the effect's persistence, and whether the long-term intensity of exposure mediates carryover effects.

3.2 Introduction

More than 1 in 20 humans currently play Soccer, the only sport where athletes deliberately engage in repeated head impacts .¹ Growing evidence indicates that Soccer is associated with the risk of persistent central nervous system (C.N.S.) dysfunction and structural changes. These long-term effects may be mediated by the short-term impact of soccer .² Concussion carries the most comprehensive health risks for players and the most significant litigation risk for organizations. Still, current diagnosis, protocols, and tracking tools must be improved to solve either. Most studies of head injury in sports have focused on single or repeated recognized S.R.C. that are associated with the risk of cognitive impairment and chronic brain pathology, especially in susceptible individuals. ³Years of soccer play are related to neuropsychological (N.P.N.P.) impairment, abnormal white matter microstructure, and structural brain changes. Impairments to memory, attention, and cognitive flexibility are the domains of brain function most commonly associated with soccer ball heading. ⁴However, most previous studies have focused on the long-term effects of the ball heading or S.R.C. Fewer studies have examined the short-term effects of soccer activity on C.N.S. function. In Soccer, purposeful heading is an integral component of play that entails repeated head impacts, often of low intensity. ⁵Although heading has been associated with adverse consequences in players at various levels, the causative role of sub-concussive heading in either short or long-term alteration of brain function and structure remains controversial. Practical and reliable means for quantifying exposure to heading are essential to effectively evaluating potential risks from heading.⁶

Heading can be assessed by direct observation of play or video recordings of the game, wearable miniature accelerometry, and self-reporting. While direct observation is assumed to be the gold standard, it is prone to observer bias, requires careful training and monitoring of observers, and involves substantial labor costs for sideline personnel. Direct observation is not suitable for

large-scale epidemiology studies. Wearable miniature accelerometers are a potential solution for characterizing exposure, but available methods have yet to prove reliable. Player self-reporting is a low-tech, low-cost means to capture exposure, but it is also prone to potential limitations, such as recall bias.⁷

3.3 Methods

We used HeadCount-2 weeks, a self-administered web-based questionnaire to capture heading exposure during the prior two weeks. We previously reported its validation in a cohort of women footballers of SUPER LEAGUE 1 and 2. In the present study, we sought to validate HeadCount-2w(HeadCount-2w ©2013 Michael L Lipton)in an adult population, representing a large segment of women soccer players and dispersed among numerous leagues and teams over a wide geographic area. To evaluate the potential effects of heading in this population, it will be essential to have proven scalable, low-cost means available to quantify exposure. To this end, we evaluated the validity of the HeadCount-2w-based estimate compared to daily reports captured using an electronic diary (HeadCount-daily) over the same 2-week period.

We sent out the HEAD COUNT 2-WEEK exposure draft translated to Greek, and we took back almost 195 responses from female footballers who filled out 390 Head Counts between August 2022 and November 2022—the University of Athens Sports Science Department. I.R.B. approved the study. All participants gave written informed consent at the time of enrollment.

HEAD COUNT 2-Week Recall Questionnaire

Details on the development of HeadCount-2w, the 2-week recall questionnaire, are described below. In brief, HeadCount-2w was completed as a web-based questionnaire, organized into four modules focused on heading in outdoor practice, outdoor games, indoor practice, and indoor games. Identical questions are repeated for outdoor and indoor settings and include (1) any practice sessions, (2) several soccer practice days, (3) an average number of ball headings during practice in the past two- weeks, and (4) C.N.S. signs. Participants were asked how often (0 to 5+ episodes) in the past two weeks they experienced heading that was directly followed by C.N.S. symptoms, defined as shallow impact (no pain = 0), mild impact (slight pain = 1), moderate impact (moderate pain, some dizziness = 2), severe impact (felt dazed, stopped play, needed medical attention = 3), and very severe impact (knocked unconscious = 4). For indoor and outdoor competition, questions were asked about the (1) number of competitive soccer games, (2) positions played during games, (3) average number of headings during games, and (4) C.N.S. symptoms (as above). Finally, questions were asked about lifetime head injuries. HeadCount-2w has been previously validated.

Study Population and Data Collection

Details on the study and recruitment methods are described. In brief, adult female soccer players recruited through diverse outreach methods in Athens, Greece, and surrounding areas were directed to an enrollment website for preliminary consent and screening. Inclusion criteria were age 18–35, at least five years of active soccer play, current active soccer play, and 6+ months of soccer play per year. Exclusion criteria were schizophrenia, bipolar disorder, neurological disorder, and pregnancy.

Ethics Statement

This study was carried out according to the recommendations of the UNIVERSITY OF ATHENS Institutional Review Board, with written informed consent from all subjects. All subjects gave written informed consent to the Declaration of Helsinki. The University of Athens-Sports Science Review Board approved the protocol.

3.4 Results

We sent out the HEAD COUNT 2 Weeks exposure draft online via Google Forms, translated into Greek, and we took back almost 195 responses from female footballers who filled out 590 Head Counts. Women soccer players completed baseline and serial online 2-week recall questionnaires (HeadCount). They reported (1) soccer practice and games, (2) heading and unintentional soccer head trauma, and (3) frequency and severity (mild to very severe) of C.N.S. symptoms. For analysis, CNSC.N.S. Symptoms were affirmed if one or more moderate, severe, or severe episodes were reported in 2 weeks. Repeated measures of logistic regression were used to study if 2-week heading exposure was associated with CNSC.N.S. Symptoms. Models were completed with all 741 HeadCounts-2w and then without 14 HeadCounts-2w on which probable concussive symptoms (felt dazed, stopped play, and required medical attention) were reported and another 8 HeadCounts-2w on which concussion was reported. Of 590 HeadCount-2w, 246 reported heading activity and unintentional impacts, 284 reported heading, but no unintentional impacts, 21 reported unintentional impacts, but no heading, and 39 reported no unintentional head impacts or heading.

3.5 Discussion

Our study exams for the first time self-reporting questionnaire about ball heading exposure in women footballers in Greece. Our results are limited by the relatively small sample size and heterogeneity in subject participation in answering the questionnaire. Additionally, we specifically studied heading during competitive gameplay. Although the questionnaire performed very well in this context, it might perform differently to assess heading during practice, including heading drills where a significant burden of heading exposure may occur.⁸ We report on young adult collegiate players. The findings might not be generalized to other soccer populations, such as youth, high school, adult amateurs, and professional players. Rutherford et al. nine also found a correlation between self-reported and observed headings, with a tendency to overestimate based on self-reports. The critical distinction between that study and ours was that the Rutherford questionnaire asked players to provide exact numbers of headers per game. In contrast, our questionnaire asked players to estimate average heading over multiple games. These two approaches may apply to distinct contexts: exact reporting may be more beneficial to capture short-term exposure versus estimated reporting for cumulative mid- to longer-term exposure.^{10 11}

Other self-report instruments, such as those developed by Kerr et al.¹² or Montenegro¹³, utilize a structured interview approach that may provide increased accuracy but is less easily scaled to large populations or remote (online) participation. Additionally, although these two studies resembled our study most closely in their technique for estimation of cumulative heading, they both relied on differences in player position to augment exposure estimation.^{14 15}

HeadCount is brief, inexpensive, and easy to administer. Although it may not precisely quantify the absolute number of headers a player performs, it does index heading exposure in a consistent, reliable, and valid way, which ranks players concerning each other in terms of heading exposure.^{16 17}

Overall, our sample is diverse in terms of the season of activity. Participants typically report playing Soccer throughout the year because they are semi-professional women footballers in the GREEK SUPER LEAGUE. We cannot generalize to college or amateur competitions or to the entire year of soccer experience to estimate the proportion of players at risk of C.N.S. symptoms from different sources of exposure.¹⁸

Data on heading, unintentional head impacts, and outcomes are self-reported and subject to recall error, raising the question of whether the significant associations in this study are explained by reporting bias.¹⁹

For example, reverse causation (i.e., reporting more symptoms could motivate reporting more heading and unintentional head impacts) could explain the study results. However, this explanation is unlikely for headings as participants answered the symptom questions after answering the heading questions, and responses could not be changed.^{20,21} In addition, the estimate of 2-week heading exposure was the product of a formula that included soccer practice and competition activity and separate data about heading during these activities.^{22,23}

3.6 Conclusion

Our study reveals the variation in heading and symptoms in women footballers in 4 months in training and matches using the 2-week HEAD COUNT self-reporting. Questions remain about the temporal relation, magnitude (e.g., frequency, intensity), and nature (i.e., linear versus rotational) of heading required to modify cognitive function, the persistence of the effect, and whether the long-term intensity of exposure mediates carryover effects. Answers to these questions may be necessary to manage the risk of long-term effects from heading and underscore the need for long-term follow-up. Prevention efforts like neck strengthening and minimizing unintentional head impacts are Soccer's most common cause/risk factors of recognized concussive

injury. The current toolkits keep information scattered. With no central information reservoir, practitioners must stitch it together from different threads – on the field, during rehabilitation and training, and through return to play. Concussive head impacts, however, may not represent the entire span of risks for brain injury. Repeated transient changes due to the ball heading create long-term underlying pathophysiologic changes. In that case, current prevention practices will be insufficient to mitigate the risk of cumulative brain damage due to soccer play.

CHAPTER 4

PAPER 2

Mechanical and Contractile Properties of Knee Joint Muscles after Sports-Related Concussion in Women Footballers

4.1 Abstract

Background

Many studies on neuromuscular control of the L.E. after concussion and epidemiological studies suggest that concussion may increase the loss of the neuromuscular control of the knee joint. Tensiomyography measures the radial displacement of a muscle during an electrically evoked twitch contraction. The rate of muscle displacement is increasingly reported to assess contractile properties.

Objective

This study aimed to determine if women footballers have an increased lack of neuromuscular control of the knee joint after a concussion compared to a healthy cohort.

Methods

Forty-one (41) female collegiate footballers were enrolled in the study, 20 with a history of S.R.C. and 21 control subjects. The athletes were recruited from the Greek Women's Super League teams using the HEAD COUNT 2-week recall questionnaire. The single-testing TMG procedure was explained to all subjects, and they were asked to provide informed consent before the TMG measurements took place. The subjects recruited in both groups were in the same age

range (18-22). Specifically, the mean age of the S.R.C. group was 19.35 ± 1.18 years and 20.10 ± 1.18 years in the control group, respectively.

Results

- In the case of the Rectus Femoris muscle response, the S.R.C. group had significantly higher Tc (ms) ($z=-5.478$, $p=0.000$) and substantially lower Dm (mm) ($z=-3.835$, $p=0.000$) than the Control group.
- In the case of the Vastus Medialis muscle response
- , the S.R.C. group had significantly higher Tc (ms) ($z=-2.348$, $p=0.016$) and substantially lower Dm (mm) ($z=-4.776$, $p=0.000$) than the Control group.
- In the case of the Vastus Lateralis muscle response
- , the S.R.C. group had significantly higher Tc (ms) ($z=-5.400$, $p=0.000$) and substantially lower Dm (mm) ($z=-4.971$, $p=0.000$) than the Control group.
- Regarding the biceps femoris muscle response
- , the S.R.C. group had significantly higher Tc (ms) ($z=-5.349$, $p=0.000$) than the Control group. In contrast, no significant difference was found in Dm (mm) ($z=-0.198$, $p=0.853$) between the groups.

Conclusions

The outcomes of this study demonstrate a relationship between concussion and contractile properties of the knee joint muscles. They may affect current medical practice standards regarding evaluating and managing concussion injuries.

4.2 Introduction

Concerns are present about the potential adverse effects of purposeful heading on cognitive function, postural control, and symptoms. Recently was reported that heading cause 25-30% of concussions in football, and 62–78% of concussions were from incidental head-to-head contact.³ Increased popularity and accessibility for female athletes have led to an increased incidence of sports-related injuries, and S.R.C. Concussions make up a severe proportion of athletic injuries and are associated with immediate and long-term symptoms for athletes.⁴ However, despite the increasing participation in female contact sports, there is relatively little research on gender-specific characteristics in S.R.C. and their consequences. Female soccer players are at an increased risk of concussion when compared to their male counterparts.⁵ While there is consensus in the sports medicine literature about the increased incidence, there is a lack of evidence as to why this is the case. The sex disparity in concussion rates in soccer players is cause for concern with the growing population of females playing Soccer and the evidence suggesting poorer outcomes following a concussion in the female sex.⁶ A Sports-related concussion (S.R.C.) is a traumatic brain injury (mTBI) induced by mechanical forces resulting in the onset of temporary impairments of neurological function. While many S.R.C.s follow a gradual recovery without long-term effects, some cases can be prolonged and complex.⁷ There is a growing body of evidence that post-concussion neuromuscular control impairments are present during simple gait-related tasks such as obstacle navigation, obstacle clearance, gait initiation, and gait termination. These neuromuscular control impairments extend well beyond symptomatic recovery and fulfillment of return to play criteria.^{8,9} Given the limited challenge posed by these gait tasks, neuromuscular control impairments are likely to be accentuated during high-demand athletic tasks. Tensiomyography used in this study measures the radial displacement of a muscle during an electrically evoked twitch

contraction. The rate of muscle displacement is increasingly reported to assess contractile properties.¹⁰ A muscle cramp is the contractile response to a single electrochemical signal of the nervous system or artificial electrical stimulation of the muscle. As such, a twitch provides information on muscle contractile properties and the functioning of the excitation-contraction coupling process. Tensiomyography.¹¹(TMG) measures the radial displacement of the muscle belly during an electrically stimulated isometric twitch response. From the radial displacement curve, spatial and temporal parameters are derived. The most frequently reported parameters are the maximum displacement (Dm) and the contraction time (Tc). D.M.D.M. provides information on skeletal muscle stiffness and morphological and structural changes. Tc is the interval between 10% and 90% of D.M.D.M. and is correlated to the proportion of slow-twitch fibers. Therefore, a shorter Tc is commonly associated with a higher contraction velocity.¹²

4.3 Methods and materials

Subjects

Forty-one (41) female collegiate footballers were enrolled in the study, 20 with a history of S.R.C. and 21 control subjects. The athletes were recruited from the Greek Women's Super League teams using the HEAD COUNT 2-week recall questionnaire.¹³

The Institutional Review and Bioethics Board of the University of Athens, Department of Physical Education and Sports Science, approved the study. Before the TMG measurements, all subjects were explained the single-testing TMG procedure and asked to provide informed consent.

The subjects recruited in both groups were in the same age range (18-22). Specifically, the mean age of the S.R.C. group was 19.35 ± 1.18 years and 20.10 ± 1.18 years in the control group, respectively (Table 1). Additionally, B.M.I. was not statistically significantly different between the experimental (S.R.C.) and control group ($U=175.500$, $p=0.369 > 0.05$).

Table 1. Sample characteristics.

	Sample		SRC Group		Control Group	
	Mean	SD	Mean	SD	Mean	SD
<i>n</i>	(<i>n</i> =41)		(<i>n</i> =20)		(<i>n</i> =21)	
Age	19.73	1.23	19.35	1.18	20.10	1.18
Weight (Kg)	61.95	7.62	59.15	8.22	64.62	6.05
Height (cm)	166.76	7.54	163.45	7.44	169.90	6.32
BMI	22.21	1.67	22.07	2.03	22.35	1.27

n, number; SD, standard deviation; BMI, Body mass index.

4.4 Instrumentation and Procedures - Measurement procedure

TMG measurements were performed by a health professional who needed to be informed about the subject's S.R.C. history. TMG works by using a small device called my tonometer to measure the electrical activity of the muscles. This device sends a small electrical impulse into the muscle, causing the fibers to contract. My tonometer then measures the muscle's rate of contraction and degree of stiffness, providing valuable information about the muscle's functional state.

Data processing and statistical tests were carried out with S.P.S.S. 25. Initially, all the primary data and characteristics of the sample of athletes were analyzed with descriptive statistics (central tendency, variance, distribution, and ranking indices).

Testing for normality of the sample distribution was performed using the Kolmogorov-Smirnov and Shapiro-Wilk statistical criteria with a confidence interval set at 95%. Testing for normality of distribution was performed before each inferential statistical test of comparisons between the S.R.C. and the control group. In most cases, the results showed a non-normal distribution, so non-parametric statistical tests were performed. Specifically, the Mann-Whitney statistical test was used to compare continuous variables between 2 independent groups (S.R.C. and control group). A 95% confidence interval ($\alpha=0.05$) was set in all statistical tests, and the significance probability values were calculated using the Monte-Carlo simulation method.

4.5 Results

3.1. TMG Parameters

The descriptive analysis of the TMG parameters of the muscular response for both SRC and control group are presented in Table 2.

Table 2. TMG descriptive parameters of muscles' response in groups.

				Values			
Muscle	Variable	N	Group	Mean	SD	Median	Mean Rank
Rectus Femoris	Tc (ms)	20	SRC	18.20	0.09	18.21	31.50
		21	Control	15.88	0.61	15.88	11.00
	Dm (mm)	20	SRC	4.07	0.78	4.10	13.65
		21	Control	5.13	0.77	5.10	28.00
Vastus Medialis	Tc (ms)	20	SRC	14.20	0.06	14.20	25.50

		21	Control	13.49	0.76	13.34	16.71
Vastus Lateralis	Dm (mm)	20	SRC	4.11	0.45	4.10	11.85
		21	Control	5.05	0.38	4.99	29.71
	Tc (ms)	20	SRC	16.29	0.58	16.31	31.35
		21	Control	13.66	0.87	13.70	11.14
Biceps Femoris	Dm (mm)	20	SRC	4.19	0.39	4.12	11.48
		21	Control	5.15	0.42	5.19	30.07
	Tc (ms)	20	SRC	15.48	0.32	15.55	31.25
		21	Control	13.63	0.75	13.76	11.24
	Dm (mm)	20	SRC	5.07	0.15	5.17	21.38
		21	Control	5.15	0.51	5.15	20.64

N, number; SD, standard deviation; Tc, contraction time; Dm, maximal displacement.

3.2. Mann-Whitney U Test

The results indicated the following: The SRC group had significantly higher Tc (ms) ($z=-5.478$, $p=0.000$) and significantly lower Dm (mm) ($z=-3.835$, $p=0.000$) than

the Control group in the case of Rectus Femoris muscle response (Figure 1)

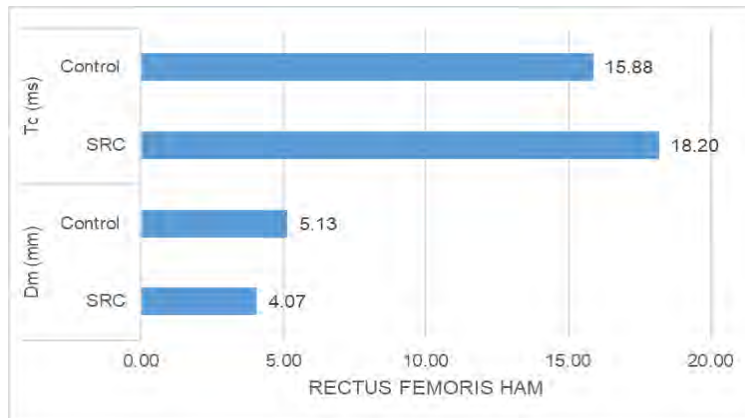


Figure 1. Rectus Femoris response.

The SRC group had significantly higher Tc (ms) ($z=-2.348$, $p=0.016$) and significantly lower Dm (mm) ($z=-4.776$, $p=0.000$) than the Control group in the case of Vastus Medialis muscle response (Figure 2)

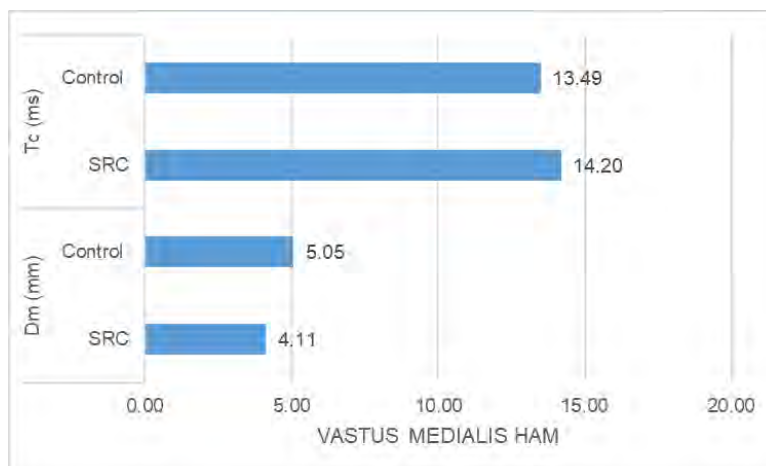


Figure 2. Vastus Medialis response.

The SRC group had significantly higher Tc (ms) ($z=-5.400$, $p=0.000$) and significantly lower Dm (mm) ($z=-4.971$, $p=0.000$) than the Control group in the case of Vastus Lateralis muscle response (Graph. 3).

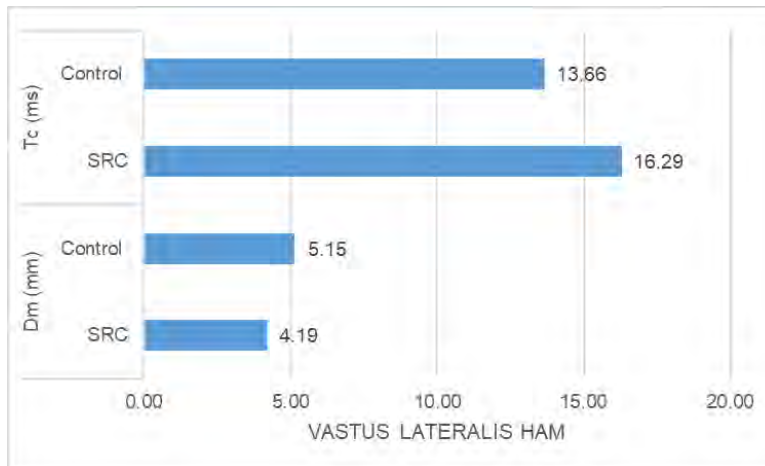


Figure 3 .Vastus Lateralis response.

The SRC group had significantly higher Tc (ms) ($z=-5.349$, $p=0.000$) than the Control group in the case of Biceps Femoris muscle response whereas no significant difference was found in Dm (mm) ($z=-0.198$, $p=0.853$) between the groups (Figure.4).

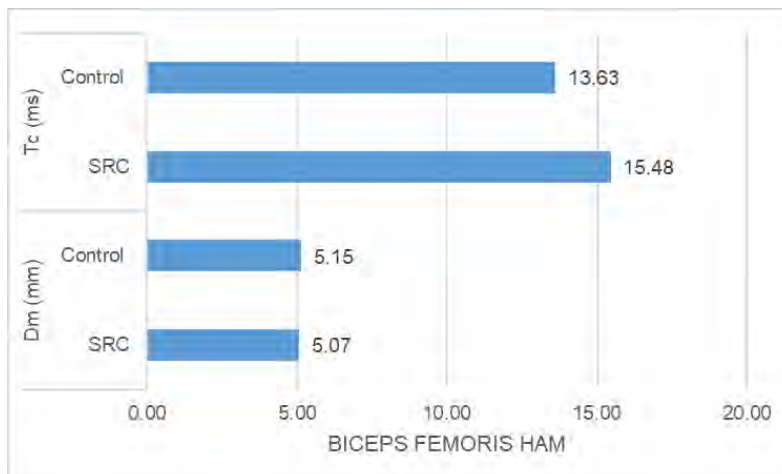


Figure 4. Biceps Femoris response.

Table 3 shows the results of the Mann-Whitney U Test performed in the case of all four muscles assessed.

Table 3. Mann-Whitney U Test analysis values between groups.

Muscle	Variable	z	p value
RECTUS FEMORIS HAM	Tc (ms)	-5.478	.000
	Dm (mm)	-3.835	.000
VASTUS MEDIALIS HAM	Tc (ms)	-2.348	.016
	Dm (mm)	-4.776	.000
VASTUS LATERALIS HAM	Tc (ms)	-5.400	.000
	Dm (mm)	-4.971	.000 ^b
BICEPS FEMORIS HAM	Tc (ms)	-5.349	.00
	Dm (mm)	-0.198	.853

Tc, contraction time; Dm, maximal displacement.

4.5 Discussion

Our study confirms that the muscles that control and move the knee joint are compromised after concussion. Our overall findings suggest that repetitive ball heading and S.R.C. in women footballers may be associated with knee abnormal biomechanical patterns related to a higher risk for future L.E.L.E. injuries in women footballers with a history of SRC.¹⁴ Repetitive head impacts are expected in football due to the sport's unique feature of purposeful heading of the ball with

the unprotected head. This game element remains controversial, as the potential associations between proprioception-processing components involved in maintaining functional joint stability during body movements.^{16,17} Inadequate functioning of this system may predispose joint damage, commonly occurring after a ligament injury. Poor neuromuscular control has been demonstrated to be a risk factor for musculoskeletal injury. An emerging area of research has identified that an increased risk of musculoskeletal injury may exist upon returning to sports after a sport-related concussion (S.R.C.).¹⁸ The mechanisms underlying this phenomenon, however, remain unknown. One theorized reason for this increased injury risk includes residual neuromuscular control deficits that remain impaired despite clinical recovery from the S.R.C. For example, abnormal movement patterns in the lower extremity and trunk differ between high and low-risk groups for anterior cruciate ligament injury; in particular, frontal plane motion at the knee and dysfunctional trunk control are predictive of injury.^{19,20}

The potential for such an increased risk of musculoskeletal injury after concussion has been observed in recently published studies in professional athletes. Nordstrom et al. examined an injury registry comprised of 46 elite male professional soccer clubs from the 2001/02 to 2011/12 seasons.²¹ Sixty-six cases of concussion were examined and were found to have a hazard ratio of 1.70 for sustaining an acute-onset musculoskeletal injury in the year after concussion compared to the year before concussion. The hazard ratios for acute-onset injury in comparison to non-concussed players ranged from 1.76 to 3.69, depending on the duration of time from the concussion injury.²² Cross et al. noted similar findings among professional rugby players, with the incidence of any injury for players who returned to sports in the same season following a diagnosed S.R.C. being 60% higher than non-concussed players. Finally, Pietrosimone et al. employed a survey of 2429 retired professional football players and demonstrated an association of multiple injury types in players who also reported a history of concussion.²³ The number of injuries experienced

was also found to increase with increasing number of concussions. However, there are limitations to this data. In particular, some of the above studies lack controls for relative amounts of participation; hence, the relationship between concussion and musculoskeletal injury may have been a function of higher exposure rates (e.g., starters versus reserve players). Notably, more is needed to know which factors influence head impact exposure in youth. on a study on female suggested that also sex may play a significant role.²⁵ Both studies, however, were careful to emphasize the limited generalizability of their conclusions, mainly due to small sample sizes and potential differences in playing styles between countries might further limit the external validity of their findings. Providing more accurate data on heading exposure and how this may be influenced by age and sex is critical to assessing risk.

youth players, Harriss et al. found that purposeful headers increased with age.²⁴ Chrisman et al. homogenous populations. In addition, these studies were conducted in North America, and po4.6

4.6 Limitations of the study

The current study has its limitations. The data was collected at a single institution, which may limit the overall generalizability of the results. The study utilized historical data in a prospective design with a relatively small sample size. As such, comparisons of subsequent L.E.L.E. injury risk based on injury type or comparisons by sport or position were not feasible. The current analysis did not include any effects of a history of prior lower extremity injury. This decision was made due to multiple factors. First, we lacked needed more reliable information on the pre-injury history. Given our limited sample size and the number of reported injuries, there also needed to be more consensus on what would qualify as meaningful prior injury history in terms of the injury experienced and the historical timeframe for inclusion.

4.7 Conclusion and Future Directions

The results of the current study may have implications for current practice standards regarding the evaluation and management of concussions. These neurocognitive and neuromuscular issues are likely subtle and not easily detected with current assessment tools. However, they may have a significant clinical impact on subsequent injury risk as such deficits are likely to be magnified with more challenging athletic tasks. Hence, these deficits may create a “window of susceptibility” to musculoskeletal injury following a return to play after a concussion. The duration of this “window of susceptibility” to musculoskeletal injury is poorly understood. The presence of this “window of susceptibility” to musculoskeletal injury following concussion implies that current return-to-play guidelines may not be sufficient as currently designed to protect athletes from potential significant post-concussion sequelae. Musculoskeletal injury risk may need to be an item of consideration in the development of future guidelines and rehabilitation strategies. Current clinical tools may also be insensitive to detecting meaningful post-concussion deficits or provide insufficient coverage of possible domains of effect (such as neuromuscular function). Continued development of clinical tests, including novel testing paradigms incorporating measures of neuromuscular control, may be required to adequately assess athletes for suitability for return to play after S.R.C. Finally, post-concussion rehabilitation strategies may also need to be altered to account for this relationship. This may include incorporating aspects of neuromuscular-based injury prevention strategies that have been used with evidence of success for reducing the risk of injuries such as ankle sprains and A.C.L. ruptures.

CHAPTER 5

PAPER 3

An Evaluation of BESS in Female Soccer Players Following Soccer Heading: A Pilot Study

5.1 Abstract

Background: Soccer is a contact sport, and therefore, the participants risk injury, including concussion. Interestingly, the task most frequently associated with concussions is the act of heading the ball.

Our study seeks to answer the following research question: Does an acute playing of purposeful Soccer heading in female football players lead to changes in BESS normative outcomes and balance? Additionally, we want to explore the relationship between a gold-standard BESS Test and a Balance Test performed on a force plate. By addressing these questions, we hope to provide meaningful information to assess heading thresholds in female Soccer and contribute to understanding the effects of purposeful Soccer heading on balance in female players.

Methods: A total of 28 elite-level female soccer players (age = 19.6 ± 2.96 years, mass = 60.4 ± 5.3 kg, and height = 163.6 ± 6.4 cm) participated in this project. This pilot study, meticulously

designed, aims to check the feasibility of measuring BESS to evaluate balance pre and post-soccer heading. Twenty-eight female participants underwent BESS monitoring on a force plate during heading and footing training. In this study, we used Standard 450 g soccer balls. Participants performed ten headers for the header condition and ten footers for the footer condition. We calculated the resultant sway velocity and BESS error outcomes.

Results:

Table 2 shows the descriptive analysis of the BESS scores pre- and post-heading condition and the Wilcoxon Signed Ranks Test results for the 28 female athletes.

Statistically significant changes after the heading condition were revealed in the following cases:

- Single Leg Stance (COP PATH) score rise ($Z = -3.986, p = 0.000$)
- BESS score foam score rise ($Z = -2.511, p = 0.012$)
- BESS score firm score rise ($Z = -2.353, p = 0.019$)

Statistically significant changes after the footer condition were revealed in the following cases:

- Tandem Stance (mm2) score rise ($Z = -2.900, p = 0.004$)

The post-BESS score foam difference was statistically significant between the group conditions ($U = 268.500, p = 0.042$). The BESS score foam mean increase was 1.93 after the heading condition and 0.21 after the footer condition.

Conclusion

This pilot study not only tests the feasibility of using force plates to measure BESS outcomes after heading in female Soccer but also highlights the effectiveness of using BESS parameters to

evaluate changes in balance function following heading compared to control footer conditions. These results could revolutionize our understanding of the effects of Soccer on balance in female soccer players.

5.2 Introduction

Repetitive head impacts (R.H.I.), such as purposeful Soccer heading, in females and the short- and long-term effects of those impacts on overall physical and mental health pose significant public health concerns. (1) Concussion is a brain injury characterized by an alteration in brain function caused by a direct acceleration or deceleration force transmitted to the head of the female player. Epidemiology shows that between 1.6 and 3.8 million sports-related concussions occur every year in the U.S.A. (2) It is a common injury in contact sports like Soccer and American football. Consensus guidelines recommend removing any player exhibiting signs or symptoms of a concussion for evaluation. Making the diagnosis of a concussion is not always easy, as players can deny symptoms, and neurocognitive testing may be similar or only slightly different from baseline. The physical and neurological examinations are often regular. The Balance Error Scoring System (BESS) is developed as an objective test to assess concussed athletes. (3,4) The Balance Error Scoring System (BESS) test was created as an outcome measure of postural stability. The tool is used in the population of athletes with S.R.C. (Sports Related Concussion). The new American Academy of Neurology concussion guidelines [5] view the BESS assessment tool as likely to identify concussion with only low to moderate diagnostic accuracy with a low specificity of 34 to 64% (meaning a false positive rate for concussion of 34 to 64%), but a high degree of specificity of 91% (meaning that the test will only miss one out of ten concussions). (6,7) This game element remains controversial, as the potential associations with long-term neurological consequences remain controversial. Nevertheless, even though heading is usually asymptomatic

and rarely causes concussion, there is evidence to suggest that cumulative heading exposure may lead to brain alterations in adults and affect cognitive function in adolescents. As a result, U.S.U.S. Soccer has implemented rule changes to restrict heading behavior in youth football, aiming to prevent head injuries. Female soccer players are vulnerable to the risk of injury from Soccer as their brains are still developing. (8) Female youths seem to be particularly vulnerable based on their increased rates of concussion. No studies have evaluated the feasibility of assessing BESS outcomes with force plates in female Soccer till today.

Balance-related symptoms (i.e., dizziness and vertigo) are commonly reported in the context of S.R.C. (sports-related concussion).(9,10,11) These symptoms may correlate with neurological findings (i.e., signs of postural instability). However, subtle impairments may be missed during a physical. (12) On the one hand, such minor impairments may increase the risk of falls or accidents, particularly in situations of shared attention (i.e., during sports or conversations) [13,14,15]. On the other hand, balance impairments in the acute period after mTBI have been associated with the persistence of postconcussive symptoms [16]. Therefore, sensitive point-of-care measures may be a reasonable addition to the routine physical examination after mTBI to assess for acute balance impairments and the trajectory of recovery and help guide rehabilitation [17].

Regarding sports, the Balance Error Scoring System (BESS) is recommended as a sideline tool to support return-to-play decisions after a suspected head injury during training or competition. Testing like this measures healthy athletes' neurological functions, establishing a “normal” baseline—a score revisited following an S.R.C. Athletes should not return to play until their scores on the test return to their baseline. (18)

5.3 Study design

The subjects recruited in both groups were in the same age range (18-22). Specifically, the mean age of the S.R.C. group was 19.35 ± 1.18 years and 20.10 ± 1.18 years in the control group, respectively. In this cross-sectional study, two observers assessed BESS performances in female players with concussion and a healthy control group cohort. We used KINVENT DELTAS force plates for static and dynamic balance M-BESS tests.

These force platforms are dedicated to advanced sportive performance analysis and provide detailed data and metrics.

Before testing, the force plate was calibrated using the integrated calibration application and leveled to account for potential uneven ground. Manual taring of the force plate setup was performed to compensate for weight variations among the participants, initially and following the incorporation of the foam pad into the assessment. Utilizing the force distribution data from its four sensors, the effective center of pressure (CoP) was computed for each sample point.

Inclusion and exclusion criteria

All participants were actively engaged in their soccer season during testing. Over their 20-week soccer season, they played approximately one game and five practices per week. Participants were excluded if they had neurological, cardiac, or psychiatric conditions. Three participants suffered a concussion more than two years earlier and were both medically cleared by a physician.

Instrumented BESS/Posturography

The most famous low-technology balance assessment tool for those with sports-related concussions is the Balance Error Scoring System (BESS). BESS is an observer-rated clinical tool susceptible to rating bias; more advanced tools for assessing postural stability may be more appropriate and sensitive in the clinical context. In neurology and sports medicine, the instrumented

assessment by force plates is broadly used. The BESS combined with an instrumented posturographic assessment may also offer a more comprehensive evaluation of postural stability in female athletes. However, to date, no standardized protocols for instrumented posturography in the female Soccer point-of-care setting are available, even though an association between concussion-like symptoms and instrumented balance performance in a large sample of female athletes has been previously reported.

The BESS consists of 3 tests lasting 20 seconds each, performed on a force plate with the eyes closed, and scored based on the number of errors across trials:

The player first stands with the feet together, the hands on the hips, and the eyes closed (double leg stance). The player holds this stance for 20 seconds while the number of balance errors (opening the eyes, hands coming off hips, a step, stumble or fall, moving the hips more than 30 degrees, lifting the forefoot or heel, or remaining off of testing position for more than 5 seconds) are evaluated as errors.

The task is then repeated with a single-leg stance using the non-dominant foot, and a third time, a heel-toe stance with the non-dominant foot in the rear (tandem stance) is performed. The BESS is easy to administer and quick (5-7 minutes).

Each twenty-second trial is scored by counting the errors, or deviations from the proper stance, made by the subject. The examiner counts errors only after the individual has the appropriate testing position.

Errors: An error is calculated to the subject when any of the following occurs:

- -moving the hands off of the iliac crests
- -opening the eyes
- -step, stumble, or fall
- -abduction or flexion of the hip beyond 30°

- -lifting the forefoot or heel off of the testing surface
- -remaining out of the proper testing position for more than 5 seconds
- -The maximum total number of errors for any condition is 10.

Test protocol:

Twenty-eight female participants underwent BESS testing on a force plate during and after a heading and footing condition. Standard 450 g soccer balls were used in this project. Participants performed ten headers for the header condition and ten footers for the footer condition. The BESS for resting supine trials and pre- and post-header and footer conditions were assessed for both time and frequency domains. Balance testing was performed using a KINVENT DELTAS system. The testing procedure consisted of each subject performing a series of 4 single-leg balance trials (2 on each leg) and four double-leg balance trials with eyes closed for 20-second trials on a force plate. During single-leg balance trials, non-dominant legs were tested according to the BESS test procedures, with a proctor counting touches to the ground as the force plate collected data. During double-leg balance trials, both legs were tested according to the BESS test procedures, with a proctor counting any stumbles or extra touches as the force plate collected data. The balance test variable of interest is the resultant sway velocity. The BESS test variable of interest is several errors during a trial.

In all tasks, standard 450 g soccer balls (inflated to 8 psi) are thrown at participants at six m/s from a distance of 10 m by a trainer who kicks the ball toward the athletes. Each participant performs ten headers for the header condition, separated by 10-second intervals. For the footer (control) condition, each participant uses their foot to volley the ball ten times, separated by 10-second intervals (to match the header condition).

The resultant sway velocity pre- and post-heading and footing, as well as several BESS errors, were matched by the trial.

We instructed the subjects to perform the following tests barefoot, hands on hips, eyes closed, for twenty seconds each.

1. Double leg stance with feet together
2. Single leg stance on non-dominant foot
3. Tandem stance (one foot in front of the other, dominant foot in back)

Participants completed two testing conditions separated by two weeks. All participants performed the header condition first and the footer (control) condition second. Testing occurred at noon, starting the teams' outdoor training. Participants did not perform physical exercise 24 hours before testing due to its influence on balance modulation.

5.4 Methods and materials

The study was conducted in the Sports Medicine clinic at Fysiotek Spine and Sports Lab, Athens, Attiki, Greece, and the University of Athens Sports Science dept. Campus during the 2022-2023 soccer season. Therapists/trainers and a supervising attending physician from the Department of Neurology of the Medical School of the University of Athens follow each team. Ethics approval was obtained from the Research Ethics Board of the University of Athens Sports Science dept. Head injuries are more likely to occur in girls versus boys and during games because of contact with another player. Clinical outcome measures of concussion are often utilized to study the effects of Soccer heading in both field and laboratory environments. Immediately following Soccer heading, youth players frequently report headaches and demonstrate some balance-outs deficits. Modifying factors that may benefit soccer players participating in purposeful heading activities include stronger neck musculature, wearing headgear, and using mouthguards

Subjects

Table 1. Subjects Characteristics	
Characteristic	Soccer players (n=28)
Age (years)	
mean (SD)	()
Weight (Kg)	
mean (SD)	59.14 (4.29)
Height (m)	
mean (SD)	1.65 (0.07)
BMI	
mean (SD)	21.79 (1.48)

n, number; SD, standard deviation; BMI, Body mass index

++ Inclusion criteria - Exclusion criteria

Statistical analysis

Wilcoxon Signed Ranks Test was used to identify statistically significant paired differences in the six BESS variables assessed (Double et al. R, Double Leg Stance L, Tandem Stance, Single Leg Stance, BESS score foam, and BESS score firm) before and after the heading and before and after the footer.

The mean change of all BESS variables was calculated by subtracting the pre-heading and footer scores (initial indicators) from the post-heading and footer scores (final indicators). The Mann-Whitney U was used to test statistically significant differences between the two independent conditions (groups), heading and footer, regarding the mean change of all BESS variables.

In all cases, the confidence level was 95% ($\alpha=0.05$). S.P.S.S. statistical software was used for data entry, processing, and analysis in combination with Microsoft Excel spreadsheets.

The use of force plate systems to collect balance sway issues is widely used and shown to be reliable and valid across studies. A force-plate-collected balance test still needs to be validated against the BESS test. Research recommends expanding baseline testing, routinely performed at the elite level and, increasingly, at the high school level, to include a balanced assessment like BESS.

5.5 Results

BESS Parameters/scores pre and post the heading condition

The descriptive analysis of the BESS scores pre and post the heading condition and the results of the Wilcoxon Signed Ranks Test for the 28 female athletes are shown in Table 2.

Statistically significant changes after the heading condition were revealed in the following cases:

- Single Leg Stance (COP PATH) score rise ($Z = -3.986$, $p = 0.000$)
- BESS score foam score rise ($Z = -2.511$, $p = 0.012$)
- BESS score firm score rise ($Z = -2.353$, $p = 0.019$)

Table 2. pre & post heading condition BESS descriptive parameters (n=28)

Variable	Time	Mean	SD	Median	Mean Rank	Z value ^a	p value ^a
Double Leg Stance R (mm ²)	pre	66.32	5.96	66.00	12.21	-1.601 ^b	0.109
	post	64.82	7.41	64.50			
Double Leg Stance L (mm ²)	pre	61.00	5.98	61.00	12.39	-1.863 ^c	0.062
	post	64.71	11.02	63.50			

Tandem Stance (mm2)	pre	61.64	10.87	59.50	10.18	-1.851 ^c	0.064
	post	65.68	7.46	63.50			
Single Leg Stance (COP PATH)	pre	2040.86	323.23	2064.50	28.00	-3.986 ^c	0.000
	post	2107.71	423.62	2098.00			
BESS score foam	pre	17.32	2.51	17.00	12.50	-2.511 ^c	0.012
	post	19.25	3.58	19.00			
BESS score firm	pre	13.39	2.51	13.00	6.00	-2.353 ^c	0.019
	post	15.46	4.08	15.00			

n, number; SD, standard deviation; a, Wilcoxon Signed Ranks Test; b, Based on positive ranks; c, Based on negative ranks

-
-

BESS Parameters/scores pre and post the footer condition

The descriptive analysis of the BESS scores pre and post the footer condition and the results of the Wilcoxon Signed Ranks Test for the 28 female athletes are shown in Table 3.

Statistically significant changes after the footer condition were revealed in the following case:

- Tandem Stance (mm2) score rise ($Z = -2.900$, $p = 0.004$)

Table 3. pre & post footer condition BESS descriptive parameters (n=28)

Variable	Time	Mean	SD	Median	Mean Rank	Z value ^a	p value ^a
Double Leg Stance R (mm2)	pre	66.50	5.71	66.00	11.71	-1.448 ^b	0.148
	post	65.18	6.94	64.50			

Double Leg Stance L (mm2)	pre	61.00	5.98	61.00	14.75	-.289 ^b	0.773
	post	60.71	11.66	59.00			
Tandem Stance (mm2)	pre	57.86	10.24	56.50	13.70	-2.900 ^c	0.004
	post	66.04	7.12	64.00			
Single Leg Stance (COP PATH)	pre	1962.57	354.72	2050.00	11.89	-.229 ^b	0.819
	post	1977.14	340.03	1952.00			
BESS score foam	pre	17.11	3.51	17.00	10.50	-.016 ^c	0.987
	post	17.32	2.78	17.50			
BESS score firm	pre	14.43	3.57	13.50	4.75	-.401 ^b	0.688
	post	14.04	2.67	14.00			

n, number; SD, standard deviation; a, Wilcoxon Signed Ranks Test; b, Based on positive ranks; c, Based on negative ranks

Mann-Whitney U Test

Table 4 shows the results of the Mann-Whitney U Test performed to identify possible statistically significant mean differences in mean BESS score change between the post-heading and the post-footer condition.

A statistically significant difference between the group conditions was found in the case of post BESS score foam difference ($U = 268.500$, $p = 0.042$). BESS score foam mean increase was 1.93 after the heading condition and 0.21 after the footer condition.

Table 4. post header & footer condition mean BESS scores' changes (n=28)

Variable	Condition	Mean	SD	Mean Rank	U value ^a	p value ^a
----------	-----------	------	----	-----------	----------------------	----------------------

pre-post Double Leg Stance R difference (mm2)	Post-Header	-1.50	4.57	28.13	381.500	0.863
	Post-Footer	-1.32	4.53	28.88		
pre-post Double Leg Stance L difference (mm2)	Post-Header	3.71	10.07	31.82	299.000	0.127
	Post-Footer	-0.29	12.33	25.18		
pre-post Tandem Stance difference (mm2)	Post-Header	4.04	10.74	25.63	311.500	0.187
	Post-Footer	8.18	12.39	31.38		
pre-post Single Leg Stance (COP PATH) difference	Post-Header	66.86	174.74	31.91	296.500	0.118
	Post-Footer	14.57	307.61	25.09		
pre-post BESS score foam difference	Post-Header	1.93	3.79	32.91	268.500	0.042
	Post-Footer	0.21	3.64	24.09		
pre-post BESS score firm difference	Post-Header	2.07	4.09	32.16	289.500	0.062
	Post-Footer	-0.39	4.31	24.84		

n, number; SD, standard deviation; a, Mann-Whitney U Test

5.6 Discussion

This pilot study not only tests the feasibility of using force plates to measure BESS outcomes after heading in female Soccer but also highlights the effectiveness of using BESS parameters to evaluate changes in balance function following heading compared to control footer conditions. These findings could potentially revolutionize our understanding of the effects of Soccer heading on balance and neuromotor performance in female soccer players.

Our results suggest that BESS is a feasible testing tool that may provide meaningful information to assess heading thresholds in female Soccer. The new American Academy of Neurology S.R.C. guidelines approved the BESS assessment tool to identify concussion with only low to moderate

diagnostic accuracy with a low specificity of 34 to 64% but a high degree of specificity of 91% (meaning that the test will only miss one out of ten concussions). (19)

A recent study [20] likewise concluded that the BESS is a valuable test for assessing balance in high school-aged athletes. It found that a total BESS score of 21 or more errors optimally identified patients in the acute concussion group versus healthy participants with 60% sensitivity and 82% specificity. It also stated that the BESS could discriminate between healthy and concussed high school-aged athletes beyond three days, at odds with an earlier study [21,35], which found that the BESS returned to baseline three days after concussion.

Postural control is maintaining one's center of mass within its support base and maintaining an upright stance in response to internal and external perturbations. This dynamic act primarily involves three primary sensory systems: the visual, vestibular, and somatosensory systems. (22)

A recent study likewise concluded that the BESS is a valuable test for assessing balance in high school athletes, finding that a total BESS score of 21 or more errors identified patients in the acute S.R.C. group versus healthy participants with 60% sensitivity and 82% specificity. It also studied that the BESS could discriminate between healthy and concussed high school-aged persons for three days, at odds with an earlier study [23] which found that the BESS returned to baseline three days after concussion.

Sensory information from these three systems determines the body's upright position in space and relative movements made from internal or external forces. In turn, the central nervous system uses this information to react to or plan for muscular adjustments to maintain the upright body position via feedback and feedforward strategies. (24)

The clinical analog of postural control is commonly denoted as balance, the state of an upright stance. Both constructs (postural control and balance) can indirectly assess the impact on the nervous system because of the interplay between sensory and action systems (motor). (25)

Postural control deficits are a cardinal sign of concussion regardless of mechanism (i.e., sports activity, car accidents, falls, and the like). In recent years, the acute and long-term effects of concussion, specifically sport-related concussion, on postural sway have been well documented with clinical resolution at 2 to 5 days post-injury but with potential lingering issues beyond six months. (26)

Three studies examined the BESS and sports-related concussions. Initially, concussed ($n = 16$) and healthy ($n = 16$) individuals were compared 1, 3, 5, and 10 days after injury on the BESS and Sensory Organization Test. Concussed persons had more errors on day one post-injury ($P = 0.03$) but returned to baseline within 3 (firm) to 5 (foam) days post-injury. Compared with controls, the concussed group had more errors on the double-leg ($P = 0.01$), single-leg ($P = 0.01$), and tandem ($P = 0.00$) stances on foam. (27,34)

The average BESS score was 17 errors one day after the injury, compared with approximately 8 for healthy control. Guskiewicz et al. validated the BESS against the Sensory Organization Test in a concussed population and included a baseline measure. Thirty-six Division I college athletes with concussions were compared with matched controls. The concussed group had worse balance on days 1, 3, and 5 post-injury but returned to baseline levels by day 3. (28, 33)

All participants used the same ball trajectory and speed for heading testing and conditions. The relatively low variability between header impact accelerations suggests that the head impacts measured from the seven instrumented players reflect the heading exposures for the entire cohort. While the present study shows evidence of balance changes following five headers, impairments are related to the severity of head injury. (29, 35)

The number of headings performed in this study simulated the heading exposure and head accelerations in female Soccer. However, we do not know whether a more significant number of

headers or larger head impact accelerations would show transient changes in the balance function. (30)

Finally, using a prospective design, McCrea et al. examined the recovery of postural stability following concussion: 1631 football players had baseline BESS scores preseason, 94 of whom went on to sustain a concussion, and were compared to 56 controls. BESS scores were similar at baseline, but the concussed group had worse postural stability immediately after injury, which returned to baseline 3 to 5 days after concussion (day five mean difference = -0.31 , 95% confidence interval = $-3.02, 2.40$ errors). (31)

Instrumented balance-testing measures were not used in this study. However, those suffering from concussion exhibited the same recovery profile on the BESS as in previous studies using instrumented balance-testing devices. (32)

5.7 Limitations of the study

Experts believe that the BESS is best used when a baseline BESS score is obtained before the start of the season when a player is healthy. Then, repeated scores after a concussion can be used to monitor recovery. One limitation of this study is that we only evaluate female players; however, investigating female football players is significantly relevant as females are more prone to concussions than males. In addition, due to the pilot study design and small sample size, we cannot assess whether athletes' head impacts over the study period negatively influenced balance or nervous system functioning.

5.8 Conclusion

The heading is a crucial part of Soccer and is unlikely to be discontinued; thus, ensuring proper technique, neck strength training, and regulation awareness is the only way to minimize the risk.

This pilot study identified the instrumented BESS with force plates as a reliable and valid diagnostic tool in a point-of-care setting and provides insights into possibly helpful age-appropriate adoptions in the explanation and procedure of testing.

By combining the clinical BESS testing with instrumented posturography, this work adds valuable information regarding the magnitude, responsiveness, and trajectory of body sway in several testing positions. Instrumented posturography may complement clinical assessment in investigating postural control in children and adolescents. While the BESS score only allows for considering a total score approximating postural control, instrumented posturography gives several parameters representing the responsiveness and magnitude of body sway and a more differentiated analysis of movement trajectory.

Accordingly, future work should explore the importance of BESS measures and the potential impact of cumulative headers on brain health.

Medical professionals should educate coaches, players, parents, and other stakeholders about the signs and symptoms of concussion and the return to sports strategies to ensure players are safe and treated correctly.

CHAPTER 6-Overall conclusions and future perspectives

Increased risk of lower extremity musculoskeletal injuries after a concussion has previously been established in specific groups of athletes.

Neuroscience will continue to help uncover how the nervous system influences and determines motor control, and the mechanistic errors in motor control resulting in non-contact ACL injury.

Poor baseline neurocognitive performance or impairments in neurocognitive performance via sleep deprivation, psychological stress, or concussion injury can increase the risk for subsequent musculoskeletal injury. Knowledge of the relationship between neurocognitive performance and musculoskeletal injury risk could supplement the current neuromuscular-focused paradigm of injury risk screening, rehabilitation, and prevention. Clinicians should incorporate neuromuscular assessments as part of return-to-activity from a concussion for all patients, not just athletes.

CHAPTER 7 Appendix

Appendix 7.1 Internal Ethics Committee approval

Appendix 7.2 Questionnaires used for baseline characteristics of the SRC athletes

Appendix 7.3 Figures and Tables

Appendix 1: Example questionnaire

Head Count 2 Weeks

The following questions ask about various aspects of organized competitive soccer in which you have participated over the past 2 weeks. Please note that the various sections and questions ask separately about competitive soccer GAMES versus soccer PRACTICE and about INDOOR versus OUTDOOR play. For this reason, it may seem that same questions are asked more than once. This is not an error, but is because we want to learn about aspects of your soccer play in different contexts. Please pay careful attention to the instructions in order to be sure you are answering the specific question that is asked.

For GAMES, consider competitive games between your team and another team.

For PRACTICE, consider any sessions of organized team practice, including practice games (e.g., scrimmages).

1. Have you played any soccer over the past 2 weeks?

- ☐ Yes
- ☐ No [\[skip to question 47\]](#)

2. Did the past 2 weeks coincide with the active season of your soccer team/club/group?
- ☐ Yes
 - ☐ No

OUTDOOR GAMES

3. Did you play any GAMES OUTDOORS over the past 2 weeks? (For OUTDOOR GAMES, consider any competitive games between your team and another team played outdoors.)
- ☐ Yes
 - ☐ No [\[skip to question 12\]](#)

OUTDOOR GAMES

4. **[dropdown; 1 to 14]** How many GAMES did you play OUTDOORS during the past 2 weeks?
5. During OUTDOOR GAMES, what was your MAIN POSITION, the position you played most often in the past 2 weeks?
- ☐ Forward
 - ☐ Midfield
 - ☐ Defense
 - ☐ Goaltender

6. When you were not playing in your MAIN POSITION, what ALTERNATE POSITION did you play most often in the past 2 weeks in OUTDOOR GAMES? (Select 'None' if you did not play in an ALTERNATE POSITION.)

- ☐ None
- ☐ Forward
- ☐ Midfield
- ☐ Defense
- ☐ Goaltender

7. [dropdown; 1 to 50+] On average, how many times did you head the ball per OUTDOOR GAME played during the past 2 weeks?

Usually heading is unremarkable. Sometimes, though, heading is not quite right and may cause dizziness, confusion or other feelings. Referring to the scale and examples below, please indicate how often you experience different severities of heading.

Best Heading > > > > > > > > > > > > > Worst														
Very Low Im- pact	Mild Impact				Moderate Im- pact				Severe Impact				Very Severe Im- pact	

Did not notice No pain Headed it just right	Noticed it Slight pain Did not head it quite right	Stopped playing a few seconds Moderate pain / some dizziness Definitely headed it wrong	Needed medical attention Stopped playing Felt dazed or injured	Knocked out unconscious
--	---	--	---	--------------------------------

8. How often did MILD IMPACT happen in the past 2 weeks during OUTDOOR GAMES?

- ☐ 0
- ☐ 1
- ☐ 2
- ☐ 3
- ☐ 4
- ☐ 5+

9. How often did MODERATE IMPACT happen in the past 2 weeks during OUTDOOR GAMES?

- ☐ 0
- ☐ 1
- ☐ 2
- ☐ 3
- ☐ 4
- ☐ 5+

10. How often did SEVERE IMPACT happen in the past 2 weeks during OUTDOOR GAMES?

- ☐ 0
- ☐ 1
- ☐ 2
- ☐ 3
- ☐ 4
- ☐ 5+
- ☐ 0

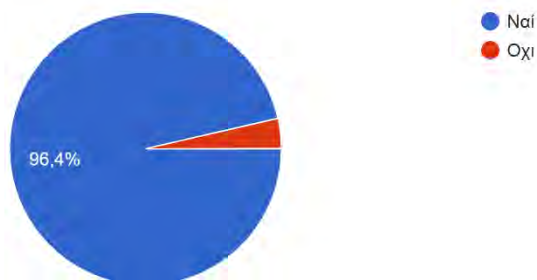
Appendix 2: Head Count 2 weeks questioner results

1. Have you played any soccer over the past 2 weeks?

- ☒ Yes
- ☐ No [skip to question 47]

1. Έχετε παίξει ποδόσφαιρο τις τελευταίες 2 εβδομάδες; (εάν όχι, μεταβείτε στο τέλος και υποβάλλετε τη φόρμα)

195 απαντήσεις

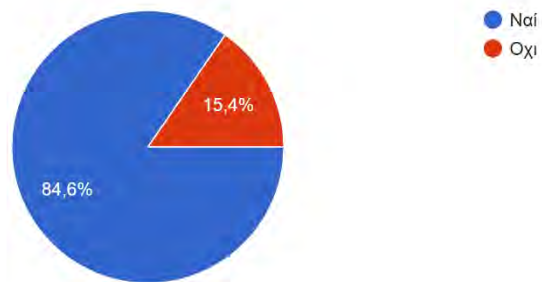


2. Did the past 2 weeks coincide with the active season of your soccer team/club/group?

- ☒ Yes

☐ No

2. Συμπίπτουν οι τελευταίες 2 εβδομάδες με την ενεργή σεζόν της ποδοσφαιρικής ομάδας σας;
195 απαντήσεις



3. During match and training, what was your MAIN POSITION, the position you played most often in the past 2 weeks?

☐ Forward

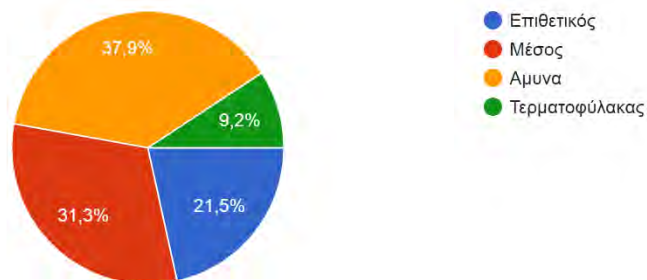
☐ Midfield

☐ Defense

☐ Goaltender

3. Κατά τη διάρκεια των ματς, ποια ήταν η ΚΥΡΙΑ ΘΕΣΗ σας, η θέση που παίζατε πιο συχνά τις τελευταίες 2 εβδομάδες;

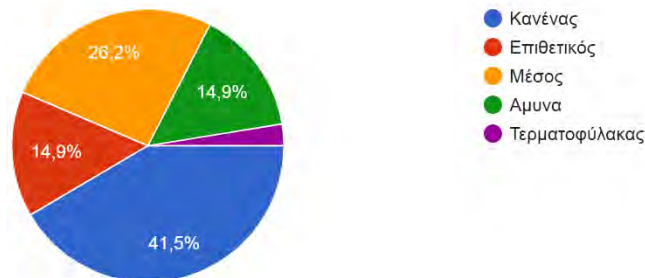
195 απαντήσεις



4. When you were not playing in your MAIN POSITION, what ALTERNATE POSITION did you play most often in the past 2 weeks in OUTDOOR GAMES? (Select 'None' if you did not play in an ALTERNATE POSITION.)

- ☐ None
- ☐ Forward
- ☐ Midfield
- ☐ Defense
- ☐ Goaltender

4. Όταν δεν παίζατε στην ΚΥΡΙΑ ΘΕΣΗ σας, ποια ΕΝΑΛΛΑΚΤΙΚΗ ΘΕΣΗ παίζατε πιο συχνά τις τελευταίες 2 εβδομάδες στα επίσημα ή φιλικά μ...ανένα" εάν δεν παίζατε σε ΕΝΑΛΛΑΚΤΙΚΗ ΘΕΣΗ.)
195 απαντήσεις

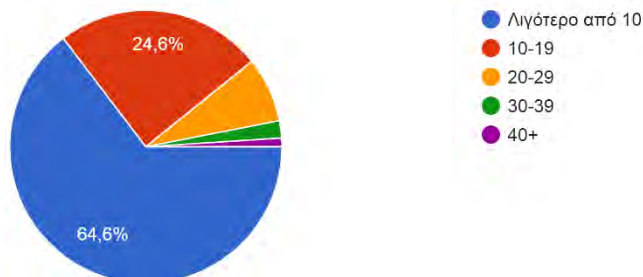


5. On average, how many times did you head the ball per match played during the past 2 weeks?

- ☐ Less than ten
- ☐ 10-19
- ☐ 20-29
- ☐ 30-39

- +40

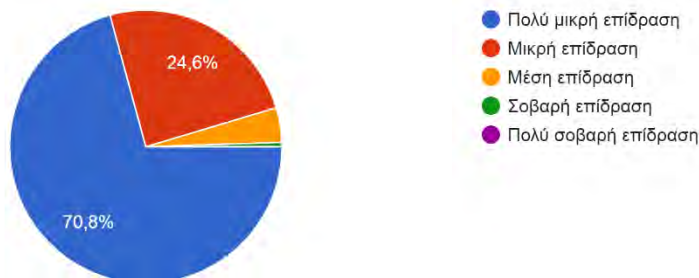
5. Κατά μέσο όρο, πόσες φορές είχατε τη μπάλα ανά παιχνίδι με το κεφάλι τις τελευταίες 2 εβδομάδες;
195 απαντήσεις



6. Usually heading is unremarkable. Sometimes, though, heading is not quite right and may cause dizziness, confusion or other feelings. Referring to the scale and examples below, please indicate how often you experience different severities of heading.

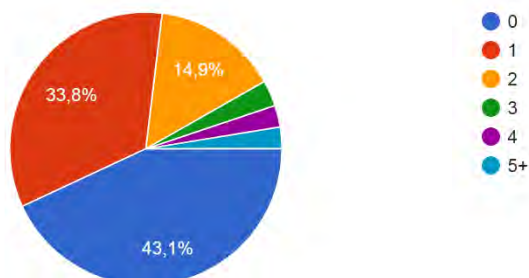
- Very Low Impact(Did not notice)
- **Mild Impact(Noticed it/Slight pain)**
- Moderate Impact(Moderate pain / some dizziness)
- Severe Impact(Needed medical attention/Stopped playing)
- Very Severe Impact(Knocked out unconscious)

6. Συνήθως η διάσειση είναι αξιοσημείωτη. Μερικές φορές, ωστόσο η υποκλινική διάσειση μπορεί να προκαλέσει ζάλη, σύγχυση ή άλλα συν...δρασαν οι κεφαλιές που μπορείτε να θυμηθείτε :
195 απαντήσεις



7. How often did MILD IMPACT happen in the past 2 weeks during match play?

9. Πόσο συχνά συνέβη το ΜΙΚΡΗ ΕΠΙΔΡΑΣΗ τις τελευταίες 2 εβδομάδες κατά τη διάρκεια των ΜΑΤΣ;
195 απαντήσεις

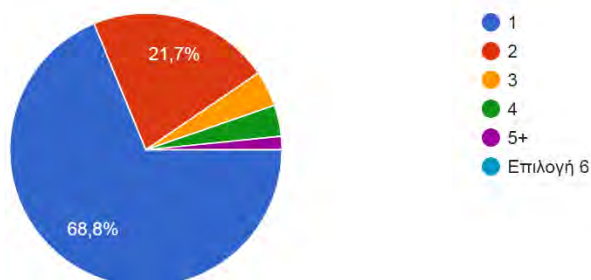


8. Usually heading is unremarkable. Sometimes, though, heading is not quite right and may cause dizziness, confusion or other feelings. Referring to the scale and examples below, please indicate how often you experience different severities of heading.

- **Very Low Impact/Did not notice**
- **Mild Impact/Noticed it**
- **Moderate Impact/Moderate pain / some dizziness**
- **Severe Impact/Needed medical attention**

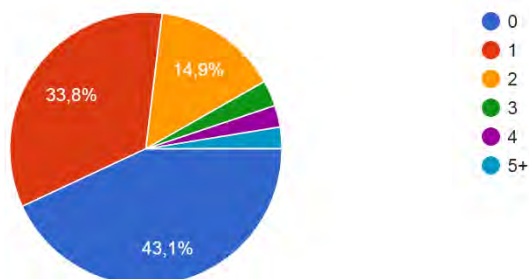
- **Very Severe Impact**

8.Μερικές φορές, η κατεύθυνση ΤΗΣ ΜΠΑΛΑΣ δεν ήταν απόλυτα σωστή ή μια δυνατή μπαλιά μπορεί να προκαλέσει πόνο, ζάλη, σύγχυση ή άλλ...υταίες 2 εβδομάδες κατά τη διάρκεια των ματς?
189 απαντήσεις



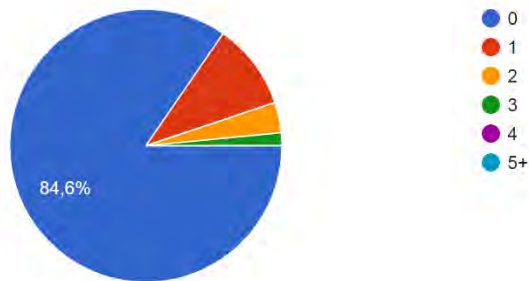
9. How often did MILD IMPACT happen in the past 2 weeks during match play and training?

9.Πόσο συχνά συνέβη το ΜΙΚΡΗ ΕΠΙΔΡΑΣΗ τις τελευταίες 2 εβδομάδες κατά τη διάρκεια των ΜΑΤΣ;
195 απαντήσεις



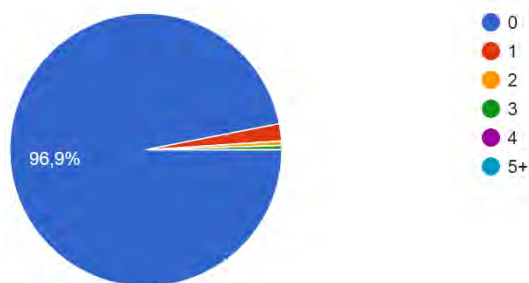
10. How often did MODERATE IMPACT happen in the past 2 weeks during match play and training?

10.Πόσο συχνά συνέβη το ΜΕΤΡΙΑ ΕΠΙΔΡΑΣΗ τις τελευταίες 2 εβδομάδες κατά τη διάρκεια των ΜΑΤΣ;
195 απαντήσεις



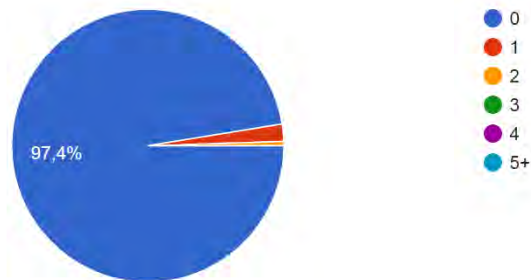
11. How often did SEVERE IMPACT happen in the past 2 weeks during match play and training?

11.Πόσο συχνά συνέβη ΣΟΒΑΡΗ ΕΠΙΔΡΑΣΗ τις τελευταίες 2 εβδομάδες κατά τη διάρκεια των ΜΑΤΣ;
195 απαντήσεις



12. How often did VERY SEVERE IMPACT happen in the past 2 weeks during training and match play?

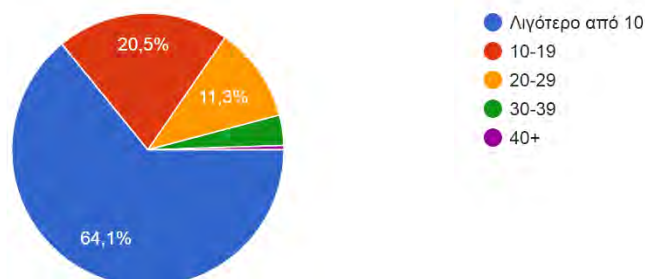
12.Πόσο συχνά συνέβη ΠΟΛΥ ΣΟΒΑΡΗ ΕΠΙΔΡΑΣΗ τις τελευταίες 2 εβδομάδες κατά τη διάρκεια των ΜΑΤΣ;
195 απαντήσεις



13. On average, how many sets of heading drills did you do per training during the past 2 weeks?

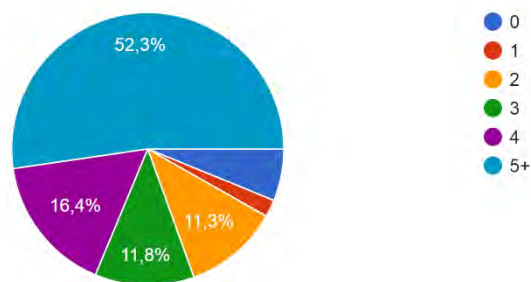
- Less than 10
- 10-19
- 20-29
- 30-39
- +40

15.Περίπου πόσες φορές χτυπήσατε την μπάλα με το κεφάλι κατά τη διάρκεια της ΠΡΟΠΟΝΗΣΗΣ τις τελευταίες 2 εβδομάδες;
195 απαντήσεις



14. How many days did you practice during the past 2 weeks?

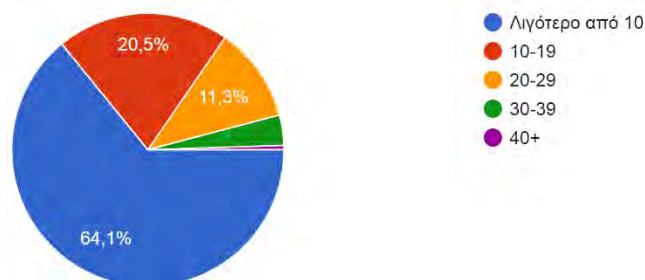
14.Πόσες ημέρες ΠΡΟΠΟΝΗΣΗ ΣΤΟ ΓΗΠΕΔΟ τις τελευταίες 2 εβδομάδες;
195 απαντήσεις



15. On average, how many times did you head the ball ("reps") in each "set" during INDOOR PRACTICE over the past 2 weeks?

- Less than 10
- 10-19
- 20-29
- 30-39
- +40

15.Περίπου πόσες φορές χτυπήσατε την μπάλα με το κεφάλι κατά τη διάρκεια της ΠΡΟΠΟΝΗΣΗΣ τις τελευταίες 2 εβδομάδες;
195 απαντήσεις

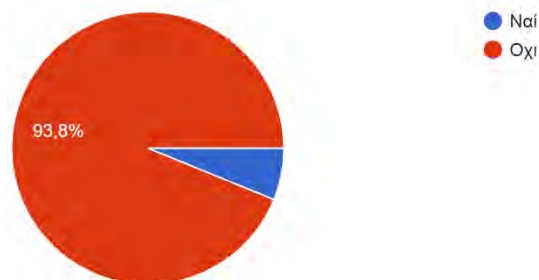


16. Did you experience any symptoms (headache, nausea, confusion, dizziness) related to heading drills during INDOOR PRACTICE over the past 2 weeks?

- yes

- no

16. Συνήθως η ΔΙΑΣΕΙΣΗ είναι αξιοσημείωτη. Μερικές φορές, ωστόσο η υποκλινική διάσειση μπορεί να προκαλέσει ζάλη, σύγχυση ή άλλα συν... της ΠΡΟΠΟΝΗΣΗΣ τις τελευταίες 2 εβδομάδες;
195 απαντήσεις

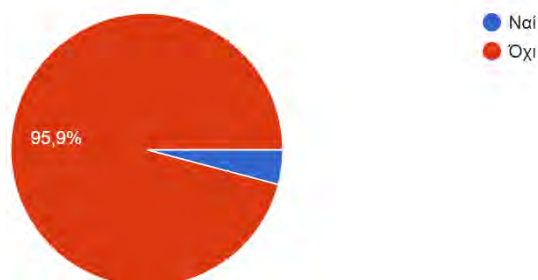


17. Other than from soccer, were you dazed or knocked unconscious from a head injury in the past 2 weeks?

- yes

- no

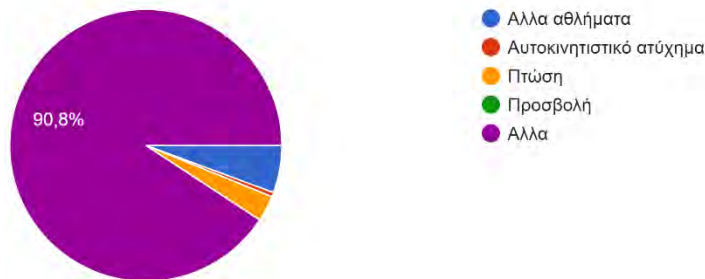
22. Εκτός από το ποδόσφαιρο, ζαλιστήκατε ή χτυπήσατε ασυνείδητα από τραυματισμό στο κεφάλι τις τελευταίες 2 εβδομάδες;
195 απαντήσεις



18.What was the cause of the injury?

- ☐ Other Sports
- ☒ Car Accident
- ☐ Fall
- ☐ Assault
- ☐ Other

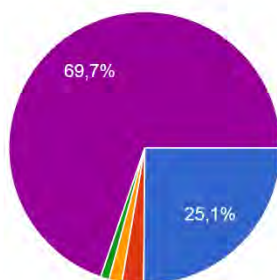
23.Ποιά ήταν η αιτία του τραυματισμού;
195 απαντήσεις



19. Check the one that best describes what happened?

- ☐ I was dazed but not unconscious
- ☒ I was knocked out for less than 1 minute
- ☐ I was knocked out for more than 5 minutes
- ☐ I was hospitalized
- ☐ I do not remember

Ελέγξτε αυτό που περιγράφει καλύτερα τι συνέβη;
195 απαντήσεις



- Ήμουν ζαλισμένος, αλλά δεν είμαι ανασταθής
- Ήμουν νοκ άουτ για λιγότερο από 1 λεπτό
- Ήμουν νοκ άουτ για περισσότερο από 5 λεπτά
- Νοσηλεύτηκα
- Δεν θυμάμαι

Appendix 3: Figures and tables

PAPER 1 Literature review

Table 1.1: Database search strategy

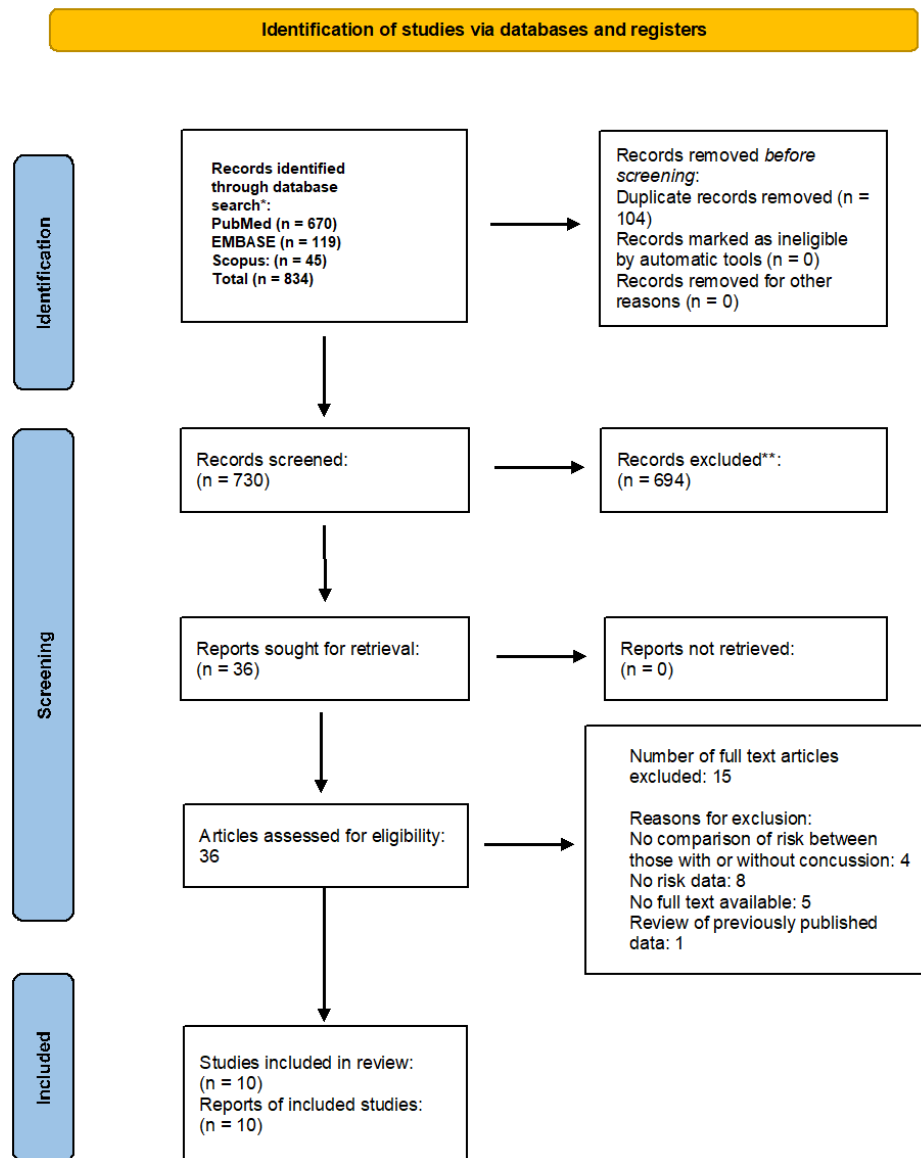


Table 1.2 Bias of studies selected

	Eligibility Criteria & Source	Random Allocation	Concealed Allocation	Baseline Comparability	Blinding of Participants	Blinding of Therapists	Blinding of Assessors	Adequate Follow Up (>85%)	Intention to Treat Analysis	Between Group Statistical Comparisons	Reporting of point measures & variability	Total Score (0-10)
Brooks (2016)	+	+	+	-	-	-	-	-	+	+	+	6/10
Burman (2016)	+	+	+	-	-	-	-	+	+	+	+	7/10
Cross (2016)	+	+	-	-	-	-	-	-	-	+	+	4/10
Fino (2017)	+	-	+	+	+	-	-	-	-	-	+	5/10
Herman (2017)	+	+	+	+	-	-	-	-	-	-	+	5/10
Lynall (2015)	+	+	-	-	-	-	-	-	-	+	+	4/10
Lynall (2017)	+	+	+	+	+	-	-	-	-	+	+	7/10
Makdissi (2009)	+	+	-	-	-	-	-	-	-	-	+	3/10
Nordstrom (2014)	+	+	+	+	-	-	-	-	+	+	+	7/10
Nyberg (2015)	+	+	+	+	-	-	-	+	+	+	+	8/10

1. Eligibility criteria were specified; 2. subjects were randomly allocated to groups (in a cross-over study, subjects were randomly allocated an order in which treatments were received); 3. allocation was concealed; 4. the groups were similar at baseline regarding the most important prognostic indicators; 5. there was blinding of all subjects; 6. there was blinding of all therapists who administered the therapy; 7. there was blinding of all assessors who measured at least one key outcome; 8. measures of at least one key outcome were obtained from more than 85% of the subjects initially allocated to groups; 9. all subjects for whom outcome measures were available received the treatment or control condition as allocated or, where this was not the case, data for at least one key outcome were analyzed by "intention to treat"; 10. the results of between-group statistical comparisons are reported for at least one key outcome; 11. the study provides both point measures and measures of variability for at least one key outcome; Note: The first item relates to external validity and the remaining 10 items are used to calculate the total score, which ranges from 0 to 10. + Yes - No.

Table 1.3 Search results

Lead Author (Year)	Athletes With Concussion, No. and Level of Participation	Sports	Control Athletes	Quality Checklist Score	Time from concussion to Return to Sport	Injuries Tracked	Injury Tracking Time Period
Brooks (2016)	75 (58 male, 17 female) college	Football, soccer, hockey, basketball, volleyball, softball	Non concussed, matched players	8	21 days	Acute, non-contact lower extremity injuries	90 days

Burman (2016)	281 (206 M, 75 F)	Hockey, soccer, handball	Athletes with an ankle sprain, same 3 sports non concussed players	7	Not reported	Not defined	24 months
Cross (2016)	135 (135 M, 0 F) professional	Rugby	Non concussed players	9	11 days	Any injury	2 seasons
Fino (2017)	110 (76 M, 34 F) college	Baseball, basketball, lacrosse, football, tennis, volleyball	Non concussed matched players	9	18±40 days	Acute lower extremity injuries	12 months
Herman (2017)	73 (52 M, 21 F) college	Football, basketball, lacrosse, soccer	Non concussed matched players	9	9±7 days	Acute lower extremity injuries	90 days
Lynall (2015)	44 (28 M, 16 F) college	Hockey, football, lacrosse, soccer, basketball, tennis	Non concussed matched athletes	11	Not reported	Acute lower extremity injuries	12 months
Lynall (2017)	2004 high school	Baseball, basketball, lacrosse, soccer, softball, tennis	Not applicable	6	Not reported	Acute and chronic lower extremity injuries	Undefined

Makdissi (2009)	117 (117M, 0 F) professional	Australian football	Non concussed matched players from same team	10	Not reported	Any injury	Undefined
Nordstrom (2014)	66 (66 M, 0 F) professional	Soccer	Non concussed injured player	9	Not reported	Any injury	12 months
Nyberg (2015)	81 (81 M, 0 F) professional	Hockey	Athletes with Knee injury	9	Not reported	New knee injuries	42 days

Paper 2

2.1 Table 1. Sample characteristics.

	Sample		SRC Group		Control Group	
	Mean	SD	Mean	SD	Mean	SD
<i>n</i>	(<i>n</i> =41)		(<i>n</i> =20)		(<i>n</i> =21)	
Age	19.73	1.23	19.35	1.18	20.10	1.18
Weight (Kg)	61.95	7.62	59.15	8.22	64.62	6.05
Height (cm)	166.76	7.54	163.45	7.44	169.90	6.32

BMI	22.21	1.67	22.07	2.03	22.35	1.27
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n, number; SD, standard deviation; BMI, Body mass index.

2.2 TMG Parameters

Table 2. TMG descriptive parameters of muscles' response in groups.

				Values			
Muscle	Variable	N	Group	Mean	SD	Median	Mean Rank
Rectus Femoris	Tc (ms)	20	SRC	18.20	0.09	18.21	31.50
		21	Control	15.88	0.61	15.88	11.00
	Dm (mm)	20	SRC	4.07	0.78	4.10	13.65
		21	Control	5.13	0.77	5.10	28.00
Vastus Medialis	Tc (ms)	20	SRC	14.20	0.06	14.20	25.50
		21	Control	13.49	0.76	13.34	16.71
	Dm (mm)	20	SRC	4.11	0.45	4.10	11.85
		21	Control	5.05	0.38	4.99	29.71
Vastus Lateralis	Tc (ms)	20	SRC	16.29	0.58	16.31	31.35
		21	Control	13.66	0.87	13.70	11.14
	Dm (mm)	20	SRC	4.19	0.39	4.12	11.48
		21	Control	5.15	0.42	5.19	30.07
Biceps Femoris	Tc (ms)	20	SRC	15.48	0.32	15.55	31.25

		21	Control	13.63	0.75	13.76	11.24
	Dm (mm)	20	SRC	5.07	0.15	5.17	21.38
		21	Control	5.15	0.51	5.15	20.64

N, number; SD, standard deviation; Tc, contraction time; Dm, maximal displacement.

2.3. Mann-Whitney U Test figures

The results indicated the following:

The SRC group had significantly higher Tc (ms) ($z=-5.478$, $p=0.000$) and significantly lower Dm (mm) ($z=-3.835$, $p=0.000$) than the Control group in the case of Rectus Femoris

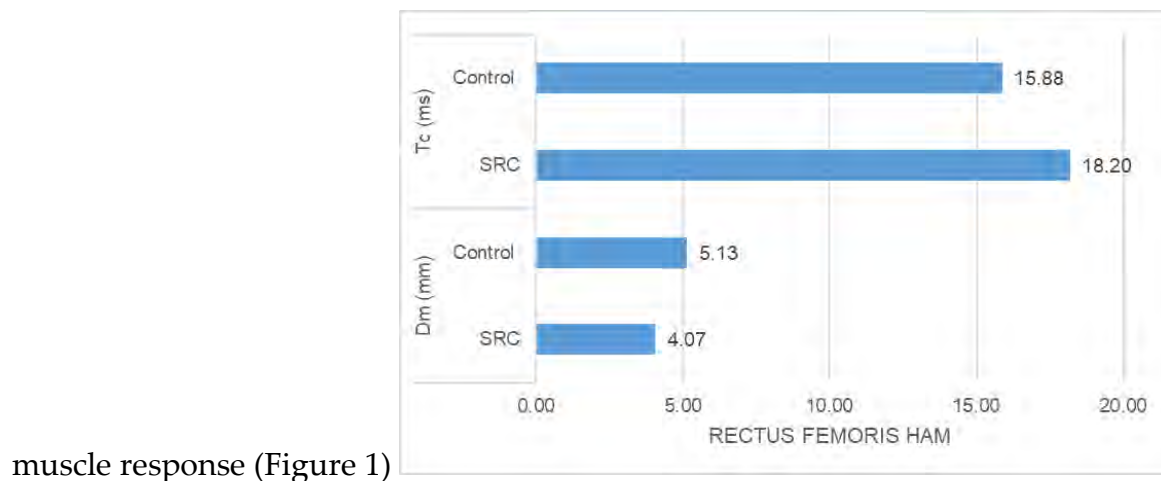


Figure 1. Rectus Femoris response.

The SRC group had significantly higher Tc (ms) ($z=-2.348$, $p=0.016$) and significantly lower Dm (mm) ($z=-4.776$, $p=0.000$) than the Control group in the case of Vastus Medialis muscle response (Figure 2)

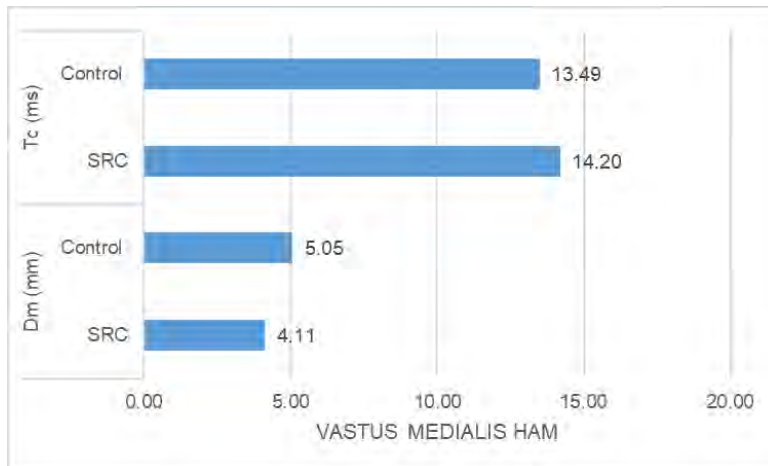


Figure 2. Vastus Medialis response.

The SRC group had significantly higher Tc (ms) ($z=-5.400$, $p=0.000$) and significantly lower Dm (mm) ($z=-4.971$, $p=0.000$) than the Control group in the case of Vastus Lateralis muscle response (Graph. 3).

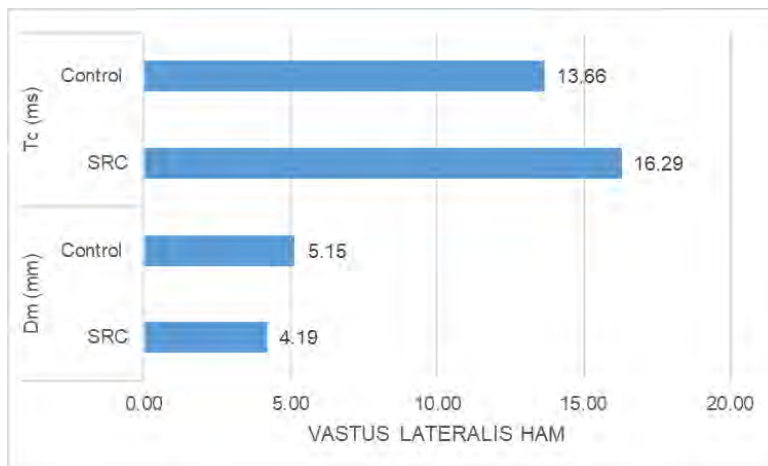


Figure 3 .Vastus Lateralis response.

The SRC group had significantly higher Tc (ms) ($z=-5.349$, $p=0.000$) than the Control group in the case of Biceps Femoris muscle response whereas no significant difference was found in Dm (mm) ($z=-0.198$, $p=0.853$) between the groups (Figure.4).

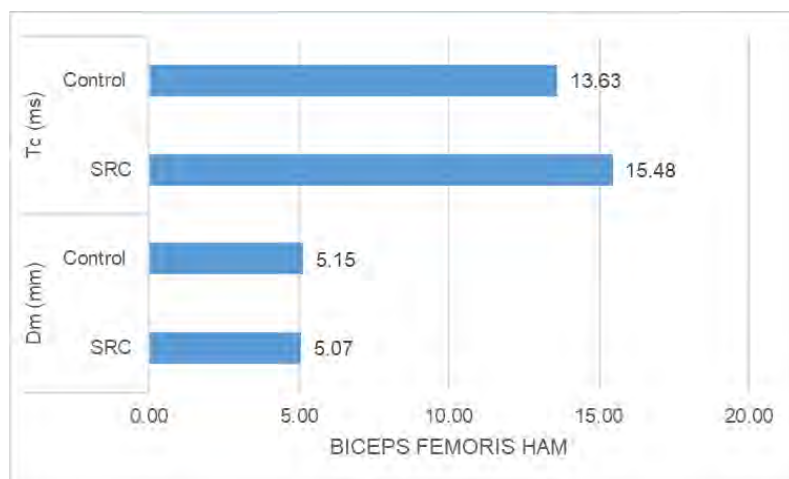


Figure 4. Biceps Femoris response.

Table 3 shows the results of the Mann-Whitney U Test performed in the case of all four muscles assessed.

2.4 Table 3. Mann-Whitney U Test analysis values between groups.

Muscle	Variable	z	p value
RECTUS FEMORIS HAM	Tc (ms)	-5.478	.000
	Dm (mm)	-3.835	.000
VASTUS MEDIALIS HAM	Tc (ms)	-2.348	.016
	Dm (mm)	-4.776	.000
VASTUS LATERALIS HAM	Tc (ms)	-5.400	.000
	Dm (mm)	-4.971	.000 ^b

BICEPS FEMORIS HAM	Tc (ms)	-5.349	.00
	Dm (mm)	-0.198	.853

Tc, contraction time; Dm, maximal displacement.

Paper 3

3.1 Subjects characteristics

Table 1. Subjects Characteristics	
Characteristic	Soccer players (n=28)
Age (years)	
mean (SD)	()
Weight (Kg)	
mean (SD)	59.14 (4.29)
Height (m)	
mean (SD)	1.65 (0.07)
BMI	
mean (SD)	21.79 (1.48)

n, number; SD, standard deviation; BMI, Body mass index

3.2 Pre and post BESS headers

Table 2. pre & post heading condition BESS descriptive parameters (n=28)

Variable	Time	Mean	SD	Median	Mean Rank	Z value ^a	p value ^a
Double Leg Stance R (mm2)	pre	66.32	5.96	66.00	12.21	-1.601 ^b	0.109
	post	64.82	7.41	64.50			
Double Leg Stance L (mm2)	pre	61.00	5.98	61.00	12.39	-1.863 ^c	0.062
	post	64.71	11.02	63.50			
Tandem Stance (mm2)	pre	61.64	10.87	59.50	10.18	-1.851 ^c	0.064
	post	65.68	7.46	63.50			
Single Leg Stance (COP PATH)	pre	2040.86	323.23	2064.50	28.00	-3.986 ^c	0.000
	post	2107.71	423.62	2098.00			
BESS score foam	pre	17.32	2.51	17.00	12.50	-2.511 ^c	0.012
	post	19.25	3.58	19.00			
BESS score firm	pre	13.39	2.51	13.00	6.00	-2.353 ^c	0.019
	post	15.46	4.08	15.00			

n, number; SD, standard deviation; a, Wilcoxon Signed Ranks Test; b, Based on positive ranks; c, Based on negative ranks

3.3 Pre and post footers

Table 3. pre & post footer condition BESS descriptive parameters (n=28)

Variable	Time	Mean	SD	Median	Mean Rank	Z value ^a	p value ^a
Double Leg Stance R (mm2)	pre	66.50	5.71	66.00	11.71	-1.448 ^b	0.148
	post	65.18	6.94	64.50			
Double Leg Stance L (mm2)	pre	61.00	5.98	61.00	14.75	-.289 ^b	0.773
	post	60.71	11.66	59.00			
Tandem Stance (mm2)	pre	57.86	10.24	56.50	13.70	-2.900 ^c	0.004
	post	66.04	7.12	64.00			
Single Leg Stance (COP PATH)	pre	1962.57	354.72	2050.00	11.89	-.229 ^b	0.819
	post	1977.14	340.03	1952.00			
BESS score foam	pre	17.11	3.51	17.00	10.50	-.016 ^c	0.987
	post	17.32	2.78	17.50			
BESS score firm	pre	14.43	3.57	13.50	4.75	-.401 ^b	0.688
	post	14.04	2.67	14.00			

n, number; SD, standard deviation; a, Wilcoxon Signed Ranks Test; b, Based on positive ranks; c, Based on negative ranks

3.4 Man-Whitney BESS scores

Table 4. post header & footer condition mean BESS scores' changes (n=28)

Variable	Condition	Mean	SD	Mean Rank	U value ^a	p value ^a
pre-post Double Leg Stance R difference (mm2)	Post-Header	-1.50	4.57	28.13	381.500	0.863
	Post-Footer	-1.32	4.53	28.88		
pre-post Double Leg Stance L difference (mm2)	Post-Header	3.71	10.07	31.82	299.000	0.127
	Post-Footer	-0.29	12.33	25.18		
pre-post Tandem Stance difference (mm2)	Post-Header	4.04	10.74	25.63	311.500	0.187
	Post-Footer	8.18	12.39	31.38		
pre-post Single Leg Stance (COP PATH) difference	Post-Header	66.86	174.74	31.91	296.500	0.118
	Post-Footer	14.57	307.61	25.09		
pre-post BESS score foam difference	Post-Header	1.93	3.79	32.91	268.500	0.042
	Post-Footer	0.21	3.64	24.09		
pre-post BESS score firm difference	Post-Header	2.07	4.09	32.16	289.500	0.062
	Post-Footer	-0.39	4.31	24.84		

n, number; SD, standard deviation; a, Mann-Whitney U Test

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