

THESIS

THE SHOE-SURFACE INTERACTION DURING 180° CHANGE OF DIRECTION WITH  
REDUCED APPROACH STEPS ON TWO DIFFERENT ARTIFICIAL TURF SURFACES

Submitted by

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## ABSTRACT

### IMPACT OF REDUCED APPROACH STEPS ON THE SHOE-SURFACE INTERACTION DURING 180° CHANGE OF DIRECTION ON TWO DIFFERENT SURFACES

Change-of-direction (COD) movements impose high traction and loading demands during early stance at the shoe–surface interface and are commonly associated with elevated lower-extremity injury risk. Third-generation (3G) artificial turf (AT) infill composition and commonly performed reduced approach strategies may influence shoe–surface interaction, yet their combined effects during high-demand COD tasks remain poorly understood. The purpose of this study was twofold: (1) to investigate loading and traction differences between 3G AT systems infilled with crumb rubber (CR) or engineered wood (EW), and (2) to evaluate how a 1-step versus 2-step approach influences shoe–surface interaction during a maximal-effort 180° COD.

Twenty-one physically active athletes completed a minimum of six trials per condition across both surfaces and approach strategies. Three-dimensional kinematic and kinetic data were analyzed to quantify ground reaction forces (GRFs), loading rates, traction metrics, foot and body center-of-mass (COM) kinematics. Statistical analyses were performed using a linear mixed-effects model (LMM) to account for the repeated-measures design and within-subject variability. EW produced greater GRFs and loading rates than CR, accompanied by reduced initial foot displacement and lower horizontal foot velocity at initial contact. In contrast, CR demonstrated greater foot displacement and horizontal foot velocity, consistent with its greater reported compliance. Despite these differences, vertical foot velocity at initial contact and time

to minimum foot velocity did not differ between surfaces, likely reflecting differences in impulse distribution, with higher forces applied over shorter displacement on EW and lower forces applied over longer displacement on CR. Participant perceptions aligned with COM and foot kinematics, with EW generally perceived as providing greater traction, evident by a more aggressive trunk lean angle and lower horizontal COM velocity angle. Despite these perceived differences, no surface-related differences were observed in traction metrics.

The 2-step approach increased horizontal GRFs, vertical and horizontal loading rates, and linear traction coefficient relative to the 1-step approach, resulting in greater foot displacement following initial contact, while vertical GRFs remained unchanged. Participant feedback and COM mechanics indicated that the 2-step approach was more natural and aggressive, likely due to use of a penultimate step to prepare for the COD, whereas the 1-step approach required continued postural adjustment at initial contact. Rotational traction metrics did not differ between surfaces or approach conditions; however, a significant surface  $\times$  approach interaction was observed for vertical free moment (VFM), with greater values during the CR 2-step condition, indicating increased rotational loading at the shoe–surface interface during higher-intensity CODs. Stiffer infill systems may constrain linear foot motion and enhance perceived stability but increase loading magnitude and rates, whereas more compliant infills permit greater foot displacement but may still expose athletes to elevated rotational loading specifically during higher intensity CODs.

The overall results demonstrate that both infill type and reduced approach steps meaningfully influence the shoe–surface interaction during maximal effort 180° COD tasks and reinforce the need for human testing to capture performance and injury-relevant mechanics.

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## 1. INTRODUCTION

Artificial turf (AT, aka synthetic turf) has become widely used as a replacement to natural grass across all levels of sport due to its durability, reduced maintenance costs, and ability to be used indoors (Jastifer et al., 2019). Modern third-generation (3G) AT systems typically consist of a synthetic carpet infilled first with silica sand followed by a performance infill, most commonly crumb rubber (CR). CR is styrene-butadiene rubber (SBR) typically derived from recycled tires; offering benefits of playability, minimal upkeep, and cost effectiveness (Fleming et al., 2023; Jastifer et al., 2019). Despite these advantages, concerns persist regarding increased risk of musculoskeletal injury on AT, particularly from non-contact injuries (Gould et al., 2023; Kushner et al., 2024; Mikhail et al., 2025). These non-contact injuries most frequently occur during rapid deceleration and change of direction (COD) tasks (Yu & Garrett, 2007).

The ability to start, stop, and change direction rapidly are critical determinants of success in multidirectional sports. These high intensity CODs allow athletes to evade defenders and respond to gameplay in real time, often determining the outcome of a play (Rhodes et al., 2021; Sheppard et al., 2014; Sweeting et al., 2017; Young et al., 2015). For instance, an English Football Association Premier League soccer player may perform upwards of 700 CODs during a single match (Bloomfield et al., 2007). These maneuvers generate large ground reaction forces (GRFs), high loading rates, and demand substantial linear and rotational traction at the shoe–surface interface (Fox, 2018; Luo & Stefanyshyn, 2011).

The same mechanical requirements that make COD movements critical for performance also place the lower extremities at elevated injury risk. Non-contact ankle sprains and anterior

cruciate ligament (ACL) injuries of the knee frequently occur during COD tasks, particularly during the early stance phase within 100ms of foot contact (Herzog et al., 2019; Koga et al., 2010). During this period, the cleats of the shoe engage with the surface and GRFs rise rapidly, traction is established, and foot motion relative to the surface is constrained (Bates et al., 2020; David et al., 2017).

The shoe-surface interface represents a complex interaction between footwear design, surface construction, and COD strategy, which together influence foot orientation, force application and traction. Linear traction refers to the resistance to translational motion between the shoe and surface, while rotational traction reflects resistance to rotational motion about a vertical axis. While both forms of traction are necessary for effective performance, AT systems infilled with crumb rubber (CR) have been associated with elevated levels of rotational traction when compared to natural grass, which in turn have been linked to increased joint loading at the ankle and knee (Frias Bocanegra & Fong, 2022; Wannop, 2012).

A critical component of the shoe-surface interface in AT systems is the performance infill, which contributes to surface compliance and traction characteristics (Shorten et al., 2003). Multiple concerns have been raised regarding CR infill, including reported risk of musculoskeletal injury risk (Gould et al., 2023; Kushner et al., 2024; Mikhail et al., 2025), chemical exposure (e.g., PFAS and microplastics) (Ryan-Ndegwa et al., 2024), high surface temperatures (G. Singh et al., 2024), and environmental damage (Armada et al., 2022; Bø et al., 2024). As a result, alternative performance infill materials have been introduced. These alternatives, often composed of organically based materials such as processed coconut coir, cork, olive cores, corn cobs, and engineered wood (EW; sized, smoothed, and shaped yellow pine particles), have been developed to address the limitations of CR.

As adoption of alternative infills increases, there is a pressing need to evaluate how these materials influence shoe–surface interaction during COD tasks. Mechanical testing of EW suggests that it may exhibit greater vertical stiffness, higher impact forces, and greater rotational traction than traditional CR systems (McGowan et al., 2024, 2025). However, standard mechanical testing devices do not account for the dynamic and individual factors that influence real COD movements, such as variations in foot orientation, joint kinematics, and loading strategies (Dura et al., 1999; Sterzing et al., 2008). As a result, mechanical assessments alone cannot fully capture how different infill systems influence the shoe–surface interaction during COD tasks. In vivo testing using force plates and motion capture allows these factors to be evaluated concurrently, providing a more ecologically valid assessment of how infill materials affect the shoe-surface interaction.

Among COD tasks, the 180° COD (aka pivot turn) is particularly demanding, requiring rapid deceleration and complete reversal of momentum resulting in substantial linear and rotational traction (Cortes et al., 2011; Dura et al., 1999). Many studies examine this movement using long or unstandardized approach distances, allowing braking forces to be distributed across multiple steps (Dos’Santos, Thomas, Comfort, & Jone, 2018). While these distances may increase approach velocity, it reduces the mechanical demand placed on the final plant step, the step most closely associated with peak GRFs, large traction demands, and non-contact injury mechanisms (Dos’Santos, Thomas, & Jones, 2021).

In contrast, invasion sports such as American football, basketball, and soccer, CODs are primarily unanticipated and executed over short distances with limited approach steps (Young et al., 2021). When the task becomes unanticipated, greater braking and reversal of direction tends to occur during the final plant step (P. Jones et al., 2016; Mulligan et al., 2024). However,

unanticipated COD is likely to have high trial-to-trial variability and might also put the athlete at unwarranted risk for injury. Therefore, shorter 1-step and 2-step, approaches may better isolate loading and traction demands at the final plant step. A 1-step approach eliminates the penultimate step, concentrating deceleration demands on the final plant step, while the 2-step approach may allow a slightly faster and more natural entry into the COD, still limiting the decelerative role of the penultimate step.

Note: Unanticipated COD is often referred to as ‘agility’. Here, and throughout the document COD is used as a general term. Distinctions between anticipated and unanticipated COD are made only when necessary.

## **1.1 Knowledge Gaps**

Although some research, which will be discussed in more detail in the literature review, has separately examined surface properties, COD biomechanics, approach speed, and anticipation, no studies have examined traction related aspects of limited approach steps during 180° COD. Understanding these interactions is vital for developing ecologically valid shoe-surface interaction testing protocols to enhance the accuracy of COD performance/injury risk and surface testing.

## **1.2 Purpose of the Study**

The purpose of this study is twofold: (1) to investigate loading and traction differences between 3G AT systems infilled with either CR or EW, and (2) to evaluate how a 1-step versus 2-step approach influences shoe-surface interaction during a maximal-effort 180° COD. These

findings will contribute to the ongoing development and evaluation of alternative performance infills for safe and effective use in sport-specific turf environments.

### **1.3 Specific aims and hypotheses**

Aim 1: To assess how turf infill type (CR vs. EW) influences GRFs, loading rates, traction, body COM, and foot kinematics at initial contact and early stance of a 180° COD task with limited approach steps.

Hypothesis 1: While we do not anticipate differences at initial contact, we expect that the EW infill will produce greater vertical and horizontal GRFs, higher rotational and linear traction coefficients, and reduced linear displacement of the toe during early stance.

Aim 2: To assess how approach condition (1-step vs. 2-step) influences GRFs, loading rates, traction, body COM, and foot kinematics at initial contact and early stance of a 180° COD task.

Hypothesis 2: Due to improved momentum and preparatory mechanics, the 2-step approach condition will result in greater body COM and foot horizontal velocities as well as altered foot orientations at initial contact, which will result in larger GRFs, loading rates, higher traction coefficients, and greater linear displacement of the toe during early stance.

## 2. REVIEW OF THE LITERATURE

The literature on AT and the shoe surface interaction during COD highlights a complex interplay between surface properties, movement strategies, and injury risk. AT has evolved considerably over the past five decades, with modern 3G infill systems designed to mimic natural grass while balancing durability, safety, and performance demands (Balazs, 2015; Gould et al., 2023; Ngatuvai et al., 2022; G. Singh et al., 2024). However, concerns remain about AT's role in musculoskeletal injuries, particularly ankle sprains and non-contact ACL tears, which frequently occur during COD tasks (Alentorn-Geli et al., 2009; Boden et al., 2000; Takahashi et al., 2019; Tosarelli et al., 2024). Research in COD biomechanics emphasizes the importance of the penultimate step and the early stance phase of the final plant step and their contribution to both performance and injury risk (Bates et al., 2020; Dempsey et al., 2007; Koga et al., 2010; Krosshaug et al., 2007). The following literature review highlights research across relevant domains and establishes the context for evaluating how surface infill types and approach steps influence 180° COD performance and injury risk.

### **2.1 Artificial Turf**

#### *2.1.1 Purpose and Growth of Artificial Turf*

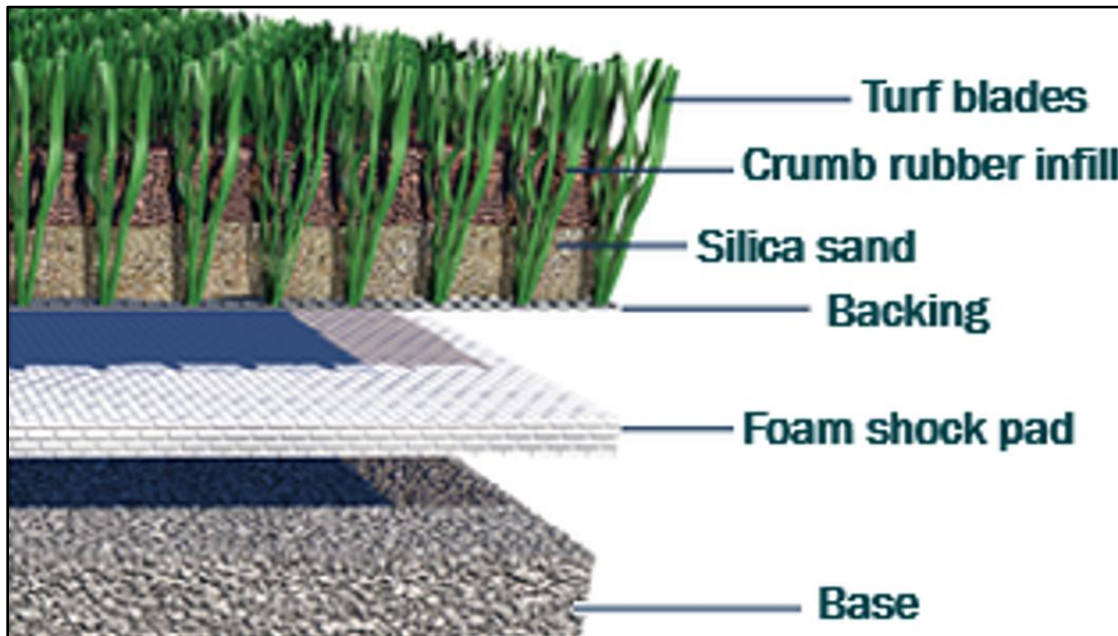
AT was first introduced as a sporting surface in 1966 at the Houston Astrodome, where a short-fiber, dense nylon carpet initially named "Chem Grass" but later dubbed "Astroturf" was installed over a compacted base (Claudio, 2008). The apparent success of this installation prompted many stadiums to adopt synthetic turf in place of natural grass, largely due to its lower maintenance demands, enhanced durability, and versatility (Claudio, 2008; Jastifer et al., 2019). However, early versions of AT quickly drew criticism for their potential contribution to athlete

injuries, particularly due to their surface stiffness and lack of shock absorption (Sivasundaram et al., 2021).

To address these concerns, second-generation turf systems were developed and introduced in 1976. These newer surfaces incorporated longer fibers, a shock-absorbing pad beneath the carpet, and a silica sand infill designed to help keep the fibers upright (Jastifer et al., 2019). Continued innovation led to the creation of third generation (3G) turf. Modern 3G turf systems consist of a layered structure including a compacted sub-base, often composed of gravel or asphalt, an optional shock pad, and a carpet made from slit film, monofilament, or hybrid blades. The carpet is typically partially filled with silica sand and topped with a performance infill layer, most commonly crumb rubber (Jastifer et al., 2019; Zuccaro et al., 2022). While some companies have begun installing fourth generation (4G) turf, a new turf designed to be used with no or little infill, 3G turf remains the industry standard today. A sectional view of standard 3G turf can be found in Figure 2.1.

As of 2024, the global AT market was valued at approximately 6.87 billion USD and is projected to reach 9.97 billion USD by 2030, (*Artificial Grass Market Size & Forecast Report, 2033, 2025*). This rapid growth reflects the widespread adoption of AT across professional and recreational sports environments, highlighting the scale at which athletes regularly interact with these surfaces. Given AT's prevalence, AT is not merely a cosmetic or convenient alternative to natural grass, it is a complex, biomechanically active system whose components, material composition, installation, maintenance, and aging all influence athletic performance and injury

risk. Understanding these factors is therefore critical for optimizing safety and performance on these widely used playing surfaces.



**Figure 2.1: Artificial Turf Field System Components (Motz, 2019). The base layer is covered by an optional foam shock pad followed by the bladed carpet layer, infilled with an optional stabilizing layer of sand and followed by the performance infill.**

### *2.1.2 Components and Mechanical Properties*

3G AT systems are designed to replicate the performance of natural grass while offering consistency and durability. Several key components influence the mechanical properties of these surfaces, including shock padding, infill, fiber characteristics, and surface age.

Shock pads are a critical layer, serving to absorb impact forces and enhance energy dissipation during landings, but are not always included. The quality of this padding can influence the safety and performance of the playing surface. Well-designed shock pads have been shown to improve impact attenuation, and reduce surface stiffness (Qu et al., 2022).

Because higher mechanical loads are associated with greater external knee moments and

increased ACL loading, (Dai et al., 2014; Weinhandl & O'Connor, 2017; Yu & Garrett, 2007), reducing surface stiffness may help limit the magnitude of forces transmitted to the lower limbs. The shock pad not only aids in dissipating energy but also contributes to the overall resilience of the turf, providing athletes with a stable, more uniform surface to perform on (Allgeuer et al., 2008). However, much of the supporting evidence is derived from mechanical testing rather than athlete-based studies, leaving uncertainty about their true effect in sport contexts.

Pile also plays a critical role in turf mechanics. In the context of AT, the term “pile” describes the vertical fibers that stand upright to form the surface. These fibers are the visible elements that mimic the appearance of natural grass blades. Modern configurations typically use slit-film, monofilament, or hybrid dual-fiber configurations, each having their own distinct mechanical properties (Jastifer et al., 2019). The different fiber types can vary in height, texture, and density, depending on the specific sport requirements. Turf density refers to the number of synthetic fibers per unit area in a synthetic turf system. Wannop et al. (2019) reported that increased fiber density and surface infill compaction elevated rotational traction by up to 8%. Some manufacturers have attempted to solely rely on fiber density to generate the required mechanical properties and eliminate the need for infill material (Hufenus et al., 2013). This evidence highlights that the pile is not merely cosmetic but a biomechanically active layer.

Exposed fiber height, defined as the portion of turf fibers extending above the infill layer, plays a critical role in surface traction. While total pile height refers to the full length of the fibers from the backing to the tip, the exposed portion is the part that directly interacts with athletic footwear. Exposed fiber height has been shown to affect rotational traction. Ruschkowski et al. (2024) reported a significant correlation between exposed fiber height and rotational traction, noting that lengths greater than 18–20 mm substantially increased rotational traction. In

contrast, fiber height below approximately 12–18 mm appeared to have minimal additional effect. These observations suggest that both material selection and installation have direct consequences for athlete safety.

Surface degradation over time also further complicates turf performance and safety as fibers compress and mat down with age, effective pile height decreases, reducing cleat penetration and altering traction (Fujitaka et al., 2017; Meyers, 2017; Schrier et al., 2022). Schrier et al. (2022) demonstrated that aged turf increased knee joint risk factors during high-risk movements, emphasizing the role of surface age in non-contact injury mechanisms. Since re-layering the carpet to refurbish the pile height is costly, facilities often replenish infill to extend field life. Added infill can help reduce incident of injury, but cannot fully restore fiber structure, leaving athletes exposed to higher injury rates on aging fields (Fujitaka et al., 2017). Despite the degradation of AT over time, well maintained AT fields older than 8 years may be able to have a lower number of injuries compared to natural grass in some settings (Meyers, 2017). These findings indicate that turf aging alters biomechanical loading and injury trends, and that while infill replenishment can mitigate some risks, it cannot reverse the underlying degradation of pile structure.

The performance infill material is one of the most influential elements of 3G turf systems, because it directly affects surface stiffness, energy dissipation, and shoe-surface interaction. CR, the most common infill material, typically installed at a depth of 25–40 mm depending on fiber length, is composed of styrene-butadiene rubber (SBR) particles that deform readily under load and dissipate energy through viscoelastic compression (Jastifer et al., 2019). CR is often layered with silica sand to stabilize fibers and provide traction. Growing concern over the environmental and health impacts of CR have accelerated exploration of organic

alternatives such as coconut coir, cork, olive cores, corn cobs, and EW (Edenius et al., 2025). These materials differ fundamentally from CR in both structure and mechanical behavior. Organic infills are composed of fibrous or granular organic particles that exhibit reduced thermal conductivity, resulting in substantially lower surface temperatures compared to CR. Standard CR infilled systems often remain 10–33 °C hotter than natural grass fields, which may elevate heat stress risk (G. Singh et al., 2024) and new cork-based infills are reported by the manufacturer to reduce surface temperatures by up to 30% compared to CR (Amorim Cork Solutions, 2025; G. Singh et al., 2024). EW infill also demonstrates lower surface temperatures compared to CR (Evans, 2021), but mechanical testing indicates a trade-off. Mechanical testing has shown that EW infill generated significantly greater rotational traction than both natural grass and rubber (McGowan et al., 2024, 2025). This increased rotational resistance may arise from a combination of greater vertical and rotational stiffness and reduced particle deformation. Because excessive rotational traction is associated as an ACL injury mechanisms, there is potential for performance–safety conflicts when selecting alternative infills.

Importantly, EW is designed as a complete system with specifications from the manufacturer on the ratio of sand to EW infill and a required high-quality shock pad. CR installations can be highly variable, not always including sand or a shock pad. As such, reliance on isolated mechanical testing comparisons of EW and CR are limiting.

Beyond material type, the morphology and depth of the infill strongly influences its mechanical properties. Alcántara et al. (2009) showed that CR infill granule size and shape affect shock absorption, vertical deformation, and ball rebound characteristics, while Dickson et al. (2022) reported that larger, more heterogeneous particles improved surface uniformity and reduced impact forces that contribute to lower extremity injuries. Sujae et al. (2022)

unexpectedly observed that increasing infill depth was associated with greater surface hardness, which may elevate lower-limb loading. One plausible contributing mechanism is the elastic “push-back” behavior of rubber granules: under load, rubber particles can rebound or resist compression. However, this mechanism is not supported by empirical testing. Most studies indicate that shallower infill depths are associated with higher surface hardness and lower impact attenuation (Dickson et al., 2022). In addition, increased compaction and higher rubber infill density also raise surface hardness and reduce force attenuation (Fleming et al., 2015).

### *2.1.3 Reported ACL Injury Trends on Artificial Turf*

As AT becomes more prevalent in both recreational and professional sports, concerns about its potential impact on athlete injury risk, particularly ACL injuries, have intensified. The rapid adoption of AT underscores the importance of large-scale epidemiological and biomechanical research to understand how playing surface, AT and natural grass may influence injury risk across athlete populations. Note: While upper extremity, and head/neck injuries are important to consider, the frequency and burden of lower extremity injuries are the focus of this paper.

ACL injuries most frequently occur through a combined valgus and internal rotation mechanism, where the tibia rotates inward relative to the femur while the knee collapses inward, often during rapid deceleration, pivoting, or cutting movements in sport (Domnick et al., 2016). This combined valgus and internal rotation places high tensile and shear forces on the ACL, which is functioning to resist anterior tibial translation and internal tibial rotation. Surface characteristics may influence ACL injury risk by altering the shoe–surface interaction. AT systems often provide elevated rotational and linear traction when compared to natural grass, which restricts foot rotation and translation effectively fixing the foot to the surface during COD.

When rotation or translation of the foot is constrained, the ability to dissipate energy through controlled slip may be reduced, resulting in greater internal rotation and valgus loads being transferred to the knee and increasing ACL strain during COD.

Several studies have reported elevated injury risks on AT compared to natural grass, particularly for non-contact lower extremity injuries. For example, a 12-year national surveillance study reported higher ACL injury rates on AT for high school football and girls' soccer, though no significant differences were observed in boys' soccer or overall football injury rates (Ngatuvai et al., 2022). Similarly, Xiao et al. (2022) reported increased ACL injury risk for female soccer players during matches on AT. In American football, Balazs et al. (2015) found elevated ACL injury risks associated with AT, though this study included older turf technologies that may have exaggerated the findings. In a systematic review of 53 studies, Gould et al. (2023) found that foot and ankle injuries were more frequently reported on AT. Laboratory testing supports this epidemiological overall trend of greater injuries on AT, with Villwock et al. (2009a) reporting that AT configurations produced significantly higher peak rotational torques than natural grass, values that align with thresholds implicated in injury risk.

Conversely, several studies have found no significant difference in ACL injury rates between AT and natural grass. For instance, McCormick et al. (2024) analyzed NFL data from 2020-2023 and reported no statistical difference in ligament tear rates after adjusting for surface exposure. Likewise, Howard et al. (2020) found no surface-based differences in NCAA soccer match injuries, though they reported a notable 8.67-fold increase in ACL injuries during practice on natural grass. Kushner et al. (2024), in a scoping review, found mixed results across nine comparative studies: three reported higher injury risk on AT, three found no difference, and one found higher risk on natural grass.

Some evidence even suggests AT may reduce injury risk in specific contexts. A six-year NCAA soccer study showed a slightly lower ACL injury rate on AT during games when compared to natural grass and a significantly higher risk during practices on natural grass for female athletes, suggesting possible surface and sex specific interactions (Meyers, 2017). Similarly, Kuitunen et al. (2023) reported lower overall injury incidence on AT in football, including non-contact knee injuries. Kushner et al. (2024) and Maniar et al. (2023) also found higher rates of hamstring, pelvis, and thigh injuries on natural grass, suggesting that AT does not universally increase injury risk.

Regardless of objective risk, athletes perceive AT as a more dangerous surface. Poulos et al. (2014) reported that Major League Soccer players reported that playing surface type and quality influenced the likelihood of sustaining an injury. Specifically, 94% of players selected AT as the surface they would most likely sustain an injury on, and the majority of players believed that injury would be a non-contact injury. Athletes also frequently report greater “wear-and-tear” (e.g., muscle soreness and joint pain) after playing on AT. In a review focused on AT, elite Rugby Union players reported post-match muscle soreness was consistently higher for several days after competition on AT compared with natural grass (Williams et al., 2016). One possible explanation for the increased soreness may be greater physical output. Modern AT has been shown to support faster sprinting and agility performance compared with natural grass (Ravi & Harish, 2025). If athletes can sprint and change direction faster on AT, the cumulative mechanical and metabolic demands may contribute to both greater post-match soreness and an elevated perception of sustaining an injury.

In summary, ACL injury risk on AT varies by sport, athlete demographic and context. Data for elite American football players in the NFL remains inconclusive while trends indicate

higher risk for NCAA football players and female soccer athletes on AT. Conversely, there is generally no surface dependent difference in ACL injury rates for male soccer players (Mikhail et al., 2025). An explanation for the inconsistencies in the literature may be due to researchers grouping contact and non-contact injuries when reporting injury incidence. Combining these two injury mechanisms may obscure surface-specific mechanisms and contribute to inconsistent findings. While this may be a plausible explanation, Loughran et al. (2019) reported that the mechanism of ACL injury (contact vs. non-contact) did not differ significantly between surfaces in American football, further complicating the surface story. Furthermore, other factors such as primary playing surface, seasonal weather conditions, sport specific cleat design, and different styles of play are all factors into the inconsistencies in ACL injury rates.

#### *2.1.4 Ankle Injury*

Ankle sprains are the most common injury in sport (Huurnink et al., 2014), with an estimated 23,000 ankle injuries occurring daily in the United States (Kannus & Renström, 1991). They occur frequently across a wide range of athletic populations, particularly in court-based sports such as volleyball and netball (Doherty et al., 2014; Herzog et al., 2019). Although typically associated with shorter acute time-loss than ACL injuries, ankle sprains carry substantial long-term consequences (Ekstrand et al., 2020). Beyond acute impairment, 70% of individuals develop long-term issues, including chronic ankle instability, posttraumatic osteoarthritis, and an approximately 3.5 times greater risk of sustaining another ankle sprain compared with those who have no history of ankle sprains (Anandacoomarasamy & Barnsley, 2005; Herzog et al., 2019), highlighting the considerable long-term burden despite shorter acute time-loss compared to ACL tears.

Evidence regarding ankle sprain incidence to AT is mixed. A systematic review of 53 studies, reported that foot and ankle injuries were more frequently observed on AT compared to natural grass, whereas knee and hip injury rates were largely comparable (Gould et al., 2023). Similarly, Williams et al. (2011) examined rugby union, soccer, and American football on 3rd- and 4G AT and found increased ankle injury risk on AT. In contrast, Steffen et al. (2007) reported no difference in acute ankle injury incidence between AT and natural grass. Although epidemiological findings remain inconclusive, Frias Bocanegra & Fong, (2022) reported futsal athletes performing a sidestep cutting task on AT demonstrated higher utilized friction, resulting in higher peak ankle inversion velocity and higher peak internal rotation moment, which are contributing mechanisms to ankle sprains.

The majority of indirect-contact and non-contact ankle injuries typically occur during rapid COD or when stopping abruptly (Medina McKeon & Hoch, 2019). COD, tasks require athletes to rapidly absorb and reverse their momentum. While the body is rapidly shifting from absorption to propulsion, the use of inappropriate force absorption strategies may lead to musculoskeletal injury in the form of a non-contact ankle-sprain. A component of the typical strategy used to decelerate the body is the heel rocker plantar-flexion arc, landing heel first followed by the forefoot. When this plantar-flexion arc is combined with the laterally directed force of a COD, ankle sprains can occur (Hubbard & Wikstrom, 2010). Individuals with chronic ankle instability exhibit altered ankle joint kinetics and demonstrate greater plantar flexor moments during COD tasks, further suggesting a relationship between plantar flexor moments and increase sprain susceptibility (Simpson et al., 2019).

Although ankle injuries have occurred without plantar flexion, ligamentous ankle sprains are mostly caused by abrupt and forceful plantar flexion and inversion of the ankle often

resulting from a large medially directed GRF (Hubbard & Wikstrom, 2010). The injury causing motion often occurs at the subtalar joint and tears the anterior talofibular ligament which has the lowest ultimate load of the lateral ligaments in the ankle (Fong et al., 2009). The rate of inversion also matters in ankle injuries. Chu et al. (2010) simulated ankle sprains suggested an inversion velocity threshold of 300°/s to identify an ankle sprain. However this threshold is lower than recorded ankle inversion velocities during recorded ankle sprains (Kristianslund et al., 2011). While these mechanical factors explain the injury mechanism, intrinsic factors can modify the chance of sustaining an ankle sprain. Females have a higher risk of suffering an ankle sprain compared to males and children compared to teenagers and adults (Doherty et al., 2014). Intrinsic roles such as high body mass index, slow eccentric inversion strength, fast concentric plantar flexion strength, passive inversion joint position sense, and a slower reaction time of the ankle evertors are associated with an increased risk of ankle sprains (Kobayashi et al., 2016).

In summary, ankle injury risk on AT remains inconclusive and is likely multifactorial. While some large-scale reviews and multi-sport comparisons report higher rates of ankle injuries on AT (Gould et al., 2023; Williams et al., 2011), whereas other prospective studies show no surface-related differences (Steffen et al., 2007). Current evidence suggests that ankle sprains cannot be fully explained by surface characteristics, but rather an interaction between surface characteristics, demands of rapid CODs, and intrinsic factors. Elevated surface friction combined with poor COD mechanics which result in a rapidly plantar-flexed and inverted foot posture, and intrinsic factors may increase sprain risk.

## **2.2 Change of Direction (COD)**

As the previous discussion of ACL and ankle sprains revealed, surface type alone cannot fully explain lower limb injury risk. Instead, biomechanical factors, particularly those related to the movement performed may play a more critical role. Non-contact ACL injuries and ankle sprains most commonly occur during high-risk movements such as changes in direction and landing, often under rapid deceleration without external contact (Boden et al., 2000; Takahashi et al., 2019; Tosarelli et al., 2024). COD movements are recognized as a primary mechanism of non-contact ACL injury, accounting for approximately 70% of all ACL injuries in sports (Boden et al., 2000). COD, being a frequent injury mechanism, has fueled extensive research into its biomechanics. For example, Fox (2018) synthesized COD strategies to reduce ACL strain while preserving performance, such as forefoot landings and trunk rotation toward the intended direction of the COD. Although it is not within the scope of this paper, readers interested in this application are directed to the work of Thomas Dos'Santos, which provides a review of cutting techniques and applications (Dos'Santos, McBurnie, et al., 2019).

### *2.2.1 Distinction Between Change of Direction (COD) and Agility*

Although often used interchangeably, COD and agility describe distinct performance qualities. While they are intimately linked, COD is the ability to decelerate, reverse or change movement direction, and accelerate again in a pre-planned movement, without the need to respond to an external stimulus (Dos'Santos, Thomas, Comfort, & Jone, 2018). In contrast, agility incorporates this physical component of COD but adds a perceptual-cognitive element, requiring athletes to rapidly change direction in response to an unpredictable cue or opponent (Sheppard et al., 2014; Young et al., 2015, 2021). For example, a 90° COD in a set direction at a set distance is a COD task, whereas reacting to a defender's movement before deciding when and

in which direction to move is an agility task. This distinction is critical for both training and testing, as COD drills isolate mechanical demands such as strength, braking, and coordination, while agility drills reflect sport-specific perceptual-cognitive challenges.

### *2.2.2 Importance of COD in Sport*

COD movements are fundamental to success in multidirectional sports, where athletes frequently execute sharp CODs at varying speeds and angles (Bloomfield et al., 2007; Karcher & Buchheit, 2014; Nimphius et al., 2016; Sheppard et al., 2014; Taylor et al., 2017; Young et al., 2015). Many field-based and court-based sports such as football, soccer, basketball, tennis, and rugby require athletes to perform frequent high-intensity CODs in response to changing game scenarios (Harper et al., 2019). In the English Football Association, Premier League soccer players perform  $726 \pm 203$  CODs per match (Bloomfield et al., 2007). Likewise, Sweeting et al. (2017) reported that the  $180^\circ$  COD is one of the most common movements performed in professional handball. These movement patterns are frequent and critical to athletic performance and can directly influence competitive outcomes. In soccer, for instance, actions like sprinting, decelerating, and COD have been closely linked to goal-scoring opportunities in both women's and men's matches (Martínez-Hernández et al., 2023, 2024). Similarly, in rugby, side-stepping maneuvers are associated with successful tackle breaks and scoring events (Zahidi & Ismail, 2018). Research has also shown that winning soccer teams tend to exhibit a higher frequency of deceleration actions compared to losing teams (Rhodes et al., 2021). In racket sports, athletes routinely perform CODs after each shot to return to the center of the court for a better defensive position (Giles et al., 2024). Because COD is required and often a key determinant of success in field and court sports, performance of COD tasks are even used for talent identification,

particularly in youth athletes (Gil et al., 2007; Riley et al., 2000). These examples underscore the importance of COD across a wide range of sports.

### *2.2.3 Metrics for Assessing COD Performance*

COD ability has traditionally been assessed using total time to complete a task (e.g., 5-0-5, 5-10-5). The 5-10-5, also known as the pro-agility, is a COD test in which the athlete starts at a central line, sprints 5 yards to one side, reverses direction to sprint 10 yards to the opposite side, and then sprints 5 yards back to the starting line, with total time recorded as a measure of agility and COD performance. However, total time reflects not only COD ability but also sprint speed. For example, up to 70% of the performance outcome in a 5-10-5 test can be explained by linear sprint speed (Hader et al., 2015). To address this limitation, Nimphius et al. (2016) introduced the Change-of-Direction Deficit (CODD), calculated by subtracting 10 meter linear sprint time from the COD test time. CODD better isolates COD ability by removing the contribution of sprint speed.

Beyond time-based metrics, kinetic and kinematic variables provide deeper insight into COD performance. Buhmann et al. (2022) emphasized the correlation between force production and COD performance, while Loturco et al. (2019) demonstrated that although players with higher maximum acceleration rates tended to perform better in multidirectional speed tests they also exhibited higher CODD. Dos'Santos et al. (2019) point out a clear association between specific braking mechanics during the penultimate foot contact and overall COD proficiency, suggesting that comprehensive performance analysis should incorporate kinetics and kinematics in the assessment of COD performance and injury assessment. Dos'Santos, Thomas, McBurnie, et al. (2021a) also described a performance injury conflict, where the same mechanics that enhance performance may increase ACL strain. Viewed within the context of clinical research,

these findings underscore the need for multifaceted COD assessment that incorporates total time, CODD, kinetics, and kinematics to capture task performance, COD performance and injury risk.

#### *2.2.4 The 180° COD*

An essential component of COD assessment is the 180° COD, which represents one of the most mechanically demanding maneuvers in multidirectional sports (Dos'Santos, Thomas, Comfort, & Jones, 2018; Severn et al., 2011). Unlike shallow COD angles (e.g., 45° & 90°), the 180° COD involves rapid deceleration followed by acceleration in a completely new direction, which is mechanically distinct from 90° alterations where athletes maintain a relatively consistent speed (Frias Bocanegra & Fong, 2022). The 180° COD is a common and vital movement in many field and court sports (Morgan et al., 2022). Due to its importance in sports, tests like the 5-0-5 are commonly used to assess an athlete's ability to perform rapid CODs. The 5-0-5 test is a single-direction COD assessment in which the athlete sprints 15 yards, executes a 180° COD, and sprints back 5 yards. Timing is recorded only over the 5-yard section prior to and after the COD, isolating the COD rather than the full sprint. Ryan et al. (2023) emphasized the utility of the 5-0-5 test in evaluating 180° COD-specific agility and have published extensively on its reliability, sensitivity to training adaptations, and relevance in talent identification.

GRFs are influential in determining the outcome of 180° COD movements. GRFs during COD tasks not only reflect the force exerted on the ground but also serve as indicators of performance and potential injury risk. Players executing side-stepping tasks exhibited significant differences in GRFs compared to those performing 180° CODs, with the latter resulting in greater peak forces which highlights the increased demands associated with the 180° COD movement (Dos'Santos, Thomas, Comfort, & Jone, 2018). The larger and unique GRFs places increased stress on the knee and ankle, especially on the ACL. For instance, a comprehensive

study that compared various COD angles demonstrated that during 180° CODs, athletes are at a much higher risk of ACL injury than during 90° or shallower CODs (Schreurs et al., 2017). Specifically, 180° COD tasks require significant frontal plane loading, which is more pronounced than in side-step maneuvers (Cortes et al., 2011). Also worth mentioning, men used greater knee flexion during larger angle CODs when compared to females which may contribute to the increase ACL injury rate among women (Leppänen et al., 2021; Schreurs et al., 2017). The 180° COD also has implications for ankle injury. During greater angle CODs ankle dorsiflexion angle decreases, and the ankle inversion angle increases which can elevate lateral ankle sprain risk (Takeuchi & Anan, 2025).

Furthermore, developments in technology have facilitated more precise assessments of COD mechanics. For instance, Zago et al. (2019) utilized wearable sensors to monitor kinematic changes during such changes in direction, emphasizing the mechanical demands and the variation in energy expenditure during COD maneuvers. This approach could pave the way for more individualized conditioning programs tailored to the specific COD characteristics of athletes. Using new technology, Chin et al. (2021) provided a detailed three-dimensional motion capture analysis of 180° COD dynamics, breaking down the initial contact phases during the COD and underscoring the importance of understanding these mechanical loads to mitigate injury risks.

When compared to other COD tasks, such as 90° CODs, the 180° COD demands different biomechanical strategies. The injury mechanisms associated with the 180° COD are largely attributed to the biomechanics involved during the initial stance phase and subsequent rotational forces making rotational traction a critical variable during cutting. Hewett et al. (2005) identified that excessive loading on the knee joint, particularly during high-velocity deceleration

and sudden changes in direction, significantly correlated with ACL injury predisposition. Their findings indicated that improper body positioning prior to and during the 180° COD increases strain on the ACL, especially when combined with high GRFs and rotational traction. How athletes decelerate, orient the trunk, and position their lower limbs during the initial stance phase is critical in preventing injury.

Body positioning during COD movements is complex and influenced by multiple interacting biomechanical factors. In the context of 180° COD tasks, optimal technique requires coordinated control of the trunk, hip, knee, and foot. Proper positioning involves shifting the whole-body center of mass (COM) toward the intended COD (increased lean angle), which has been shown to reduce knee abduction moments. A failure to reposition the center of mass may increase knee loading (Donnelly et al., 2012). Similarly, inadequate lateral flexion and rotation of the trunk toward the intended direction of travel can also increase knee abduction moments, whereas trunk flexion and rotation in the intended COD is considered protective (Dempsey et al., 2007). At the hip, greater hip flexion and internal rotation at initial contact and during early stance have been associated with increased knee abduction moments (McLean et al., 2005). As for the knee, a dynamic valgus position characterized by combined knee abduction, hip adduction, and hip internal rotation is an indicator of ACL injury risk (Hewett et al., 2005). Foot placement also plays a critical role. Wider lateral foot placement has been shown to increase knee loading and potentially elevate ACL injury risk (P. A. Jones et al., 2015). Foot orientation in the sagittal plane is also important. Landing with a more plantar flexed foot (forefoot strike) during COD tasks has been associated with reduced knee joint loads and improved performance outcomes while a dorsiflexed foot (rear foot strike) is associated with greater loads placed on the knee joint and ACL (Donnelly et al., 2017). In the transverse plane, an internally rotated foot

position (toe inward) increases knee abduction and internal rotation moments (Nishizawa et al., 2022). Finally, in the frontal plane landing with a more everted foot can be an effective strategy to prevent large ankle inversion angles at initial contact which are associated with elevated ACL and lateral ankle injury risk (Miller et al., 2021).

Additionally, the combination of high traction levels and poor body position as described above during the 180° COD can lead to excessive knee joint loading, heightening the risk for lower extremity injuries (Wannop, 2012). This insight serves as fuel for athletes and coaches to focus on technique refinement and appropriate footwear to mitigate injury risks during these high-stress movements. This concept is further supported by findings from Cortes et al. (2011), who proposed that the biomechanics of 180° COD during sports activities can reveal critical insights regarding potential injury mechanisms.

In summary, the 180° COD is one of the most mechanically demanding movements in multidirectional sport due to the large braking and propulsion forces required to rapidly reverse momentum. High GRFs and rotational demands place substantial mechanical loading on the lower extremities and the shoe–surface interface. While athlete technique and body positioning influence how these loads are managed, surface properties and traction characteristics may also alter the external loading environment during such movements.

### **2.3 Shoe-Surface Interactions**

Across all non-contact ACL and ankle sprain injuries, one common denominator exists: the athlete’s shoe must interact with the playing surface. The mechanics of this interaction are often described in terms of friction and traction, which, while related, differ in important ways.

Classical (Coulomb) friction is defined as the resistive force acting parallel to a surface, countering the movement of an object in contact with that surface (Hibbeler, 1998). Traditional laws assume friction is independent of contact area and sliding speed. Instead, it is directly proportional to, and must be lower than, the normal (perpendicular, vertical) force exerted on the surface. Nineteenth-century refinements distinguished static friction (resisting the initiation of motion) from dynamic friction (resisting motion once in motion), with dynamic friction typically lower than static (Milburn & Barry, 1998). In athletic contexts, however, these assumptions often fail. Surfaces are compliant, footwear is specialized, and contact is rarely uniform. Under such conditions, friction can increase with contact area, depend on speed, and horizontal even exceed vertical load. Moreover, cleated footwear interacting with synthetic turf can produce situations where dynamic friction exceeds static (Shorten et al., 2003).

This departure from classical behavior introduces the concept of traction, defined by the American Society for Testing and Materials Committee on Sports Equipment and Facilities as the resistance to relative motion between a shoe outsole and a sports surface that does not necessarily obey classical (Coulomb) laws of friction (ASTM F2333, 2017). In practice, friction describes the property of surfaces, while traction describes the functional interaction between shoe and surface. Traction reflects an athlete's ability to generate forces required for acceleration, deceleration, and changing direction. Beyond linear traction, rotational traction also plays a role. Rotational traction refers to the torque generated when an object rotates against resistance (Frederick, 1986; Villwock, 2009). For example, when an athlete pivots on a planted foot during a 180° COD.

In essence, friction governs resistance at the surface level, whereas traction describes the broader, athlete-relevant forces that emerge from dynamic shoe–surface interactions. This

distinction is especially critical for field sports, where non-homogeneous surfaces and cleated footwear strongly influence movement mechanics and injury potential.

### *2.3.1 Traction Mechanics and Injury Risk*

Traction directly influences the performance and safety of COD movements, particularly the 180° COD. Severn et al. (2011) showed that increases in traction allows athletes to execute faster CODs. Supporting this, Schrier et al. (2014) compared cleated soccer shoes (higher traction) and indoor shoes (lower traction) on 3G AT. Cleats produced faster 5-0-5 drills (180° COD) by 0.11 seconds and generated higher linear and rotational traction, but they also increased ankle eversion and knee abduction/external rotation moments. Wannop et al. (2019) further demonstrated that AT surfaces with higher rotational traction elevated knee and ankle loading during COD maneuvers, suggesting a biomechanical pathway between traction and ACL injury. Excessive traction may be the product of a phenomenon dubbed as “footlock,” where the foot becomes overly fixed to the ground. Footlock generates abrupt torsional and shear loading of the knee, elevating the risk of ACL injury (Cawley et al., 2003).

The multidirectional and dynamic nature of field sports require some level of traction. For a given sport, it has been proposed that an optimal zone of traction exists in which performance is maximized while lower-limb injury risk is minimized (Luo & Stefanyshyn, 2011; Nigg & Segesser, 1988; Smeets et al., 2012). Higher levels of linear traction have been associated with improved performance and can even reduce injury frequency by limiting uncontrolled slipping (Ekstrand & Nigg, 1989; Wannop, 2012). However, excessive traction may restrict foot motion, elevate joint loading, and increase injury risk. While it may be intuitive to lower linear traction to avoid higher forces, insufficient linear traction increases the likelihood of

slip-related errors and compromises COD performance (Loud et al., 2024). The optimal traction zone highlights a performance–safety trade-off governed by shoe–surface traction characteristics.

Multiple studies have shown a direct relationship between higher mechanically measured rotational traction and increased rates of lower extremity and ACL injuries. Wannop (2012) found that non-contact lower extremity injury rates increased steadily with increased rotational traction, rising from 4.2 injuries per 1000 game exposures in the low-traction group (15–30.9 Nm) to 19.2 injuries per 1000 game exposures in the high-traction group (39–54.9 Nm), representing a 4.6-fold increase in injury risk. Similarly, Lambson et al. (1996) reported that athletes wearing edge cleat designs, which produced the highest rotational traction (mean  $31.0 \pm 2.6$  Nm), had a 3.4 times higher ACL injury rate compared to those using lower-traction cleats. Supporting this, Torg et al. (1974) observed a 2.4-fold reduction in knee injuries when teams transitioned from conventional high rotational traction shoes (74 Nm) to lower traction soccer-style shoes (38 Nm). The present studies reinforce the link between excessive rotational traction and elevated injury risk, particularly during COD movements that place high torsional loads on the knee.

In addition to knee injuries, traction has also been associated with ankle injury mechanisms. Frias Bocanegra & Fong (2022) demonstrated that athletes performing CODs on higher-friction surfaces exhibited greater utilized traction, resulting in significantly higher peak inversion velocity and peak internal rotation moment at the ankle. Similarly, studies manipulating traction properties show that increases in rotational traction are associated with elevated frontal and transverse plane joint loading at the ankle, while insufficient translation traction may increase the likelihood of slipping and delay stabilization, potentially leading to

uncontrolled inversion of the ankle (Wannop & Stefanyshyn, 2016). This evidence suggests that excessive rotational traction and insufficient linear traction may elevate ankle injury risk.

### *2.3.2 Artificial Turf and Traction*

Traction plays a critical role in both athletic performance and injury risk, particularly during high-demand CODs like the 180° COD. It is essential to understand the mechanisms behind traction and how AT design and environmental conditions shape the shoe-surface interaction. As a single stud plunges into the infill layer of AT a high-density resistance zone forms around the stud. As the cleat passes through the infill the high-density zone propagates in a conical shape from the stud in the direction of movement. At the same times a low-density zone, referred to as the “trench” is formed behind it (Forrester & Fleming, 2019). This “trench effect” can influence subsequent stud engagement, potentially altering whole-foot traction (McGhie & Ettema, 2014). Most recently, traction testing under variable normal stress confirmed that infill responses change with loading conditions, suggesting that trench formation is not fixed but dynamic and dependent on both athlete load and surface properties (McGowan et al., 2024, 2025). Such models represent the most up-to-date conceptual understanding of AT traction. It is also important to understand traction can be modified by four main sources, the footwear, sports specific movement, the playing surface, and the environment (Severn et al., 2011).

### *2.3.3 Natural Surface Factors*

Environmental and surface conditions play a critical role in shaping shoe-surface interactions. Orchard (2002) identified natural playing surface factors such as ground hardness, surface dryness, grass coverage, and root density, in addition to cleat design and game speed, as key determinants of traction. Later work reinforced these findings, Orchard (2005) showed that high levels of rotational traction increased the likelihood of an athlete’s foot becoming “trapped”

in the surface, particularly on natural grass with extensive root systems or dense thatch layers that restricted foot release. Extending this work, Orchard et al. (2013) analyzed over 229,000 player-weeks of injury data in soccer and Australian rules football and observed greater frequencies of ACL injuries and ankle sprains in warmer regions. This pattern was attributed not just to climate but to the surface properties of grasses more commonly used in warmer climates.

Surface variability also complicates field traction and injury risk. Kirby & Spells (2006) measured ball rebound resilience and rotational resistance across two natural grass football fields and a 3G AT pitch. They found substantial spatial variation in natural grass metrics depending on field location, with some values falling outside FIFA performance standards, underscoring how wear, grass cover, and field position can cause localized changes in surface properties on natural fields. Injuries on natural grass are more likely to occur in areas where these surface properties change abruptly. Straw et al. (2018) found substantial spatial variation in turf hardness, moisture, traction, and grass cover within fields and recorded injuries tended to occur in transition zones between sections of the turf with higher or lower surface quality.

In contrast, the 3G surface showed remarkable consistency. While natural grass is subject to significant variability over time and space, a properly maintained AT reduces that variability but may introduce consistently higher levels of traction. Supporting this, Villwock et al. (2009) reported that AT configurations generated significantly higher peak rotational torques compared to natural grass, reinforcing concerns that AT's consistency may come at the cost of elevated traction and potentially higher injury risk. However, the consistency of the surface may allow an athlete to choose a shoe with less aggressive cleats and reduce their injury risk.

#### *2.3.4 Footwear Factors*

Among the four main modifiable factors of traction, footwear, movement, surface, and environment (Severn et al., 2011), footwear is the most modifiable from the athlete's perspective. Serensits & McNitt (2014) emphasized that footwear choice can meaningfully alter traction outcomes, and Thomson et al. (2015) reported that certain shoe–surface combinations produced a 2.5-fold increase in lower limb injury risk in response to elevated levels of rotational traction. Cadaveric and biomechanical studies provide insight into the mechanisms behind these epidemiological findings. Drakos et al. (2010) demonstrated that specific cleat surface pairings significantly increase ACL strain during COD maneuvers. Supporting this, Dowling et al. (2010) showed that elevated rotational traction alters COD mechanics in ways that heighten injury risk. These studies confirm that the selected footwear directly influences joint loading and injury potential.

Although many shoe manufacturers produce a wide range of outsole designs with different materials and varying stud length, number, and orientation there is no universal “ideal” outsole design (Müller et al., 2010). Villwock et al. (2009b) expanded on this by systematically examining the combined effects of infill type, fiber structure, and shoe design on rotational traction. The research team analyzed three different types of CR infill, cryogenically processed, ambient ground, and extruded thermoplastic elastomer. Cryogenically processed CR is manufactured by freezing recycled rubber prior to grinding, resulting in more angular and rigid particle shape, whereas ambient ground CR is mechanically shredded at room temperature, producing more irregular particles. Extruded thermoplastic elastomer consists of engineered polymer particles with more uniform geometry and material properties. Between infill types, they found that cryogenically processed CR infill generated significantly higher peak torques

than ambient ground CR or extruded thermoplastic elastomer, regardless of cleat type used. This was likely due to tighter particle packing that increased resistance to stud rotation. In regard to surface, incorporating a nylon root zone layer, which is a simulated thatch layer at the base of the tufted turf that provides fiber support and reduces infill compaction, produced lower peak torques than without, suggesting that fiber structure also moderates cleat traction (Villwock et al., 2009b). Shoe design was also critical, edge and 12-studded models producing the highest torques, while turf shoes with short, dense cleats generated the lowest (Villwock, 2009). Further complicating the topic, rotational traction and linear traction are not necessarily linked. While testing shoe surface traction, Shorten et al. (2003) reported a significant shoe–surface interaction, demonstrating that footwear and surface properties influence linear traction and rotational traction in fundamentally different ways. Linear and rotational traction were strongly positively correlated across footwear conditions, while the opposite was seen across surfaces. Together, these findings underscore that both turf composition and footwear independently can significantly influence shoe–surface interaction. This reinforces the broader performance–safety trade-off, as design features that enhance traction and stability for performance may simultaneously elevate lower-limb injury risk.

In summary, playing surface and footwear design strongly influence the level of traction experienced by athletes. Natural grass surfaces are highly variable across space and time, while AT may provide greater consistency but often with higher baseline traction. Footwear serves as the easiest modifiable factor within the athlete’s control, yet its effects are still dependent on the surface properties and infill design. Ultimately, it is the interplay between surface and footwear that determines whether traction supports performance or elevates injury risk.

### 2.3.5 *In Vivo vs. Mechanical Testing*

Mechanical (machine) and biomechanical (human) approaches to surface stiffness and traction assessment often yield different outcomes and must be interpreted with caution. As noted by Sterzing et al. (2008), mechanical tests quantify the interaction between materials, while biomechanical tests evaluate the functionality of this interaction during human movement. Mechanical devices provide highly reliable data with low variability because loading conditions are standardized, but they cannot capture the adaptations athletes make in response to fatigue, surface conditions, or footwear. In contrast, biomechanical testing inherently shows greater variability, since athletes introduce differences in technique, strategy, and coordination, but this variability reflects the reality of COD performance. Thus, both approaches offer complementary insights, mechanical testing is valuable for controlled comparisons, whereas *in vivo* testing reveals how traction properties translate to human performance and injury risk.

Although traction is the primary focus of many mechanical shoe–surface assessments, it does not exist independently of other surface properties. Surface stiffness, typically evaluated using separate mechanical tests, is an important and modifiable surface variable (Wannop et al., 2020). Surface stiffness can substantially influence traction by altering the surface's vertical deflection and stud engagement. Clarke & Carré (2017) revealed on stiffer surfaces, limited vertical deflection reduces stud penetration, which may decrease available linear and rotational traction. At the same time, a stiffer surface will increase rate of force development and impact joint loading. In contrast, a more compliant surface allows for greater vertical deflection under load, increasing outsole contact area and stud penetration, which can elevate traction and reduce loading rates (Clarke & Carré, 2017). As a result, stiffness acts as a modifier of traction rather

than a standalone determinant. This reinforces the need to interpret mechanical traction data within the broader mechanical behavior of the surface.

Mechanical traction testing of the shoe–surface interface relies on standardized devices. Earlier standardized methods also include a rotational traction test, (ASTM F2333, 2017) in which a shoe is mounted to a mechanical apparatus to quantify peak torque under applied vertical load. Additional ASTM methods such as the British Pendulum test (ASTM E303, 2022) and the drag/pull procedure (ASTM F1551, 2023) have been used to assess linear traction. However, these tests have not been universally adopted for synthetic turf evaluation and present practical limitations when applied to infilled systems.

More modern traction testing devices such as the S2T2, a portable traction testing device developed by Exeter Research (USA) have emerged. The S2T2 features a prosthetic foot form (size US 10.5) mounted at 20° of plantar flexion so that only the forefoot studs contact the test surface (Serensits & McNitt, 2014; Stefanyshyn et al., 2010; Wannop, 2012). The S2T2 can evaluate rotational traction by rotating the foot, or linear traction by fixing the shoe’s alignment along its long axis and dragging it forward. Another key design element of the S2T2 is its floating foot mass, which ensures that any added weight applies vertical load directly through the shoe and onto the surface, without interference from the frame.

Another common device, the standard studded-boot apparatus (SBA), is used primarily on natural turf and employs a circular arrangement of six plastic studs (Twomey et al., 2013). This approach is conceptually similar to the rotational resistance methodology required under the FIFA Quality Program for Football Turf, which uses a standardized studded test foot and applied vertical load to quantify peak torque at the shoe–surface interface (Fédération Internationale de Football Association (FIFA), 2025). While convenient, such designs do not reflect real soccer

cleat patterns, raising concerns about ecological validity. Twomey et al. (2013) found that the SBA often produced higher traction measurements than actual player boots, suggesting overestimation of surface traction. More recently, Twomey et al. (2014) highlighted further limitations of the SBA, particularly its poor inter-operator reliability, and introduced an automated version of the device, the UB Turf Tester (UBTT). Although traction values were similar between the SBA and UBTT, automation improved reliability, emphasizing the need for updated testing technologies. Similarly, Sterzing et al. (2008) compared mechanical traction measures with player biomechanics during COD tasks and reported clear discrepancies in magnitude and pattern, underscoring that mechanical devices cannot replicate the complex loading strategies athletes use.

In addition to standard traction testing devices, a few specialized mechanical systems have been developed. Devices such as the Tennessee Athletic Field Tester (TAFT) and BioCore Elite Athlete Shoe-Surface Tester (BEAST), were created to allow multi-planar loading capabilities and programmable movement profiles to simulate COD mechanics beyond the simple fixed-axis rotation used in traditional studded-boot apparatuses (Thoms et al., 2013). Similarly, the traction device described by Wannop (2012) employed a custom mechanical system capable of controlling vertical load and rotational displacement while allowing manipulation of footwear and surface variables. However, these systems are largely singular research instruments, and data from these devices is limited.

Although standard devices like the S2T2, SBA and specialized devices like the BEAST provide standardized, repeatable measures, they are conducted under controlled conditions and exclude critical factors such as muscle forces, neuromuscular coordination, fatigue, and variable foot placement. For example, Kati (2012) reported that human foot rotation during a stop-and-

COD maneuver averaged only 11.6°, far less than the angular rotations typically required to reach peak torque in mechanical tests. Building on this discrepancy, Webb et al. (2014) modified a FIFA rotational device to capture the full torque angle relationship rather than reporting peak torque alone and found that athletes are likely operating within the initial high-stiffness region of the traction time curve. This updated testing approach has since been incorporated into revised FIFA requirements (Fédération Internationale de Football Association (FIFA), 2025), and commercial systems such as the Labosport RTA (Rotational Traction Athlete) sensor now quantify low angle (<10°) torque in addition to peak torque. These findings suggest that initial rotational traction, rather than peak traction from mechanical testing, may be a more realistic representation of the traction used by an athlete during a foot contact.

While mechanical traction tests provide essential data on footwear–surface interactions, they have inherent limitations, particularly when detached from athlete input. Such tests cannot capture the natural variability in human movement, which is influenced by footwear, surface properties, and individual movement strategies. However, comparisons between mechanical testing and player perception have demonstrated meaningful relationships. Cole et al. (2023), reported strong agreement between several Rotational Traction Tester and Advanced Artificial Athlete configurations and trained player perceptions of surface characteristics. Suggesting that mechanical outputs can reflect athlete experience when appropriate testing configurations and variables are selected.

Individual responses to footwear are highly variable. For example, changes in footwear can lead to unique GRF patterns for each person, and the same shoe may affect different athletes in distinct ways, potentially altering injury risk and performance (Horst et al., 2023; Mohammadi & Nourani, 2025; Siegel et al., 2025). For example, Sun et al. (2017) demonstrated this

phenomenon in soccer players performing straight-line running and 45° CODs on natural turf. When testing three cleat types, firm ground, artificial ground, and AT athletes altered their movement mechanics depending on the cleat worn.

Surfaces properties also effect athlete movement strategies. H. Jones et al. (2023) demonstrated that athletes adjust their techniques when performing tasks on surfaces of varying hardness, while Dowling et al. (2010) showed that available traction alters movement patterns. Both studies highlight that surface characteristics significantly influence athlete biomechanics.

Even when surface and footwear are controlled athletes exhibit notable intra-individual variability during COD movements. Foot kinematics, joint angles, and overall movement patterns can vary substantially across repeated trials of the same task within a single athlete (Unterreiner et al., 2019). This variability affects performance outcomes such as speed, force application, and joint loading (Petway et al., 2025), and is influenced by biomechanical determinants like lower limb strength, joint stiffness, and individual technique (Singh et al., 2025). Finally, athletes who are at higher risk for injury often display different movement mechanics compared to their peers (Hewett et al., 2005). These studies show how variable human movement can be even in controlled settings.

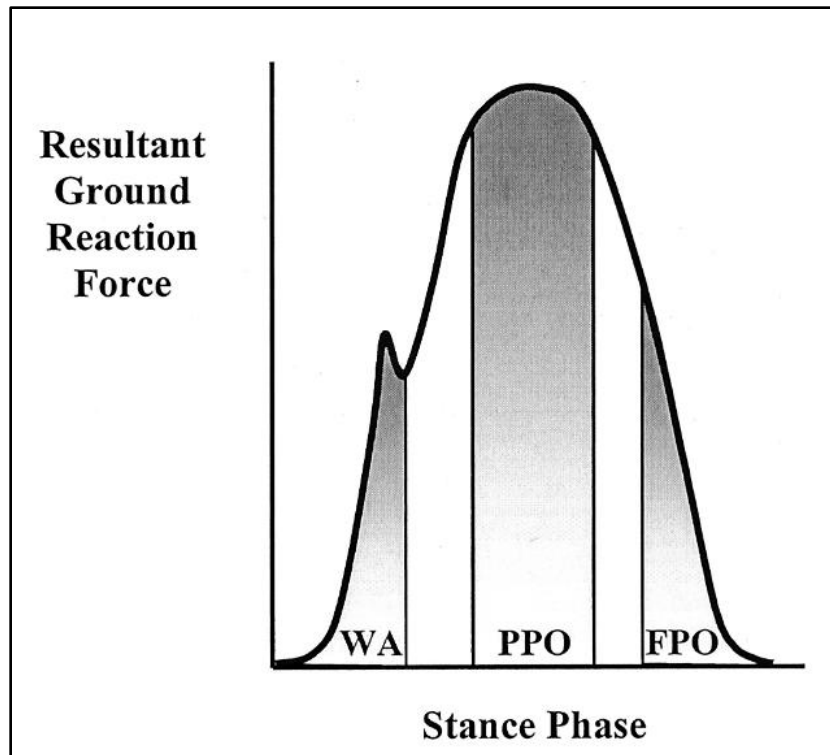
Further refinement of in vivo testing is possible by incorporating internal neuromuscular dynamics. Nasser et al. (2023) demonstrated that ACL loading estimates based solely on external biomechanics, such as motion capture and GRFs, may underestimate ligament strain because they do not account for muscle activation patterns. Using neuromusculoskeletal simulations, that integrate muscle forces with external kinematics provides a more complete representation of ACL loading during dynamic tasks.

Overall, these findings emphasize that human movement during COD is inherently variable and highly context dependent. Footwear, surface properties, and individual biomechanics all interact to influence movement patterns, force application, and injury risk. Mechanical traction tests, while valuable for standardized comparisons, cannot capture this complexity because they lack athlete input and do not account for dynamic adaptations, subtle movement strategies, or intra-individual variability. Consequently, in vivo testing is essential for understanding how athletes truly interact with surfaces during sport-specific movements and for developing strategies to optimize performance and reduce injury risk.

In summary, mechanical traction tests provide standardized and reliable data for controlled comparisons but fall short of replicating real-world sport interactions. In vivo testing, though more variable, captures essential adaptations in human movement and identifies biomechanical mechanisms linked to injury. Moving forward, the integration of mechanical testing, in vivo experimentation, and computational modeling offers the most comprehensive approach to understanding traction and injury risk.

## **2.4 Foot Contact**

During effective CODs an athlete must place a significant amount of force into the ground rapidly to effectively change direction. The corresponding GRF profile often resembles a double hump, typically divided into a landing (or weight acceptance) and a propulsion phase (Welinski et al., 2021). While different authors label these phases differently, Besier et al. (2001), defined the first phase as the weight acceptance phase, spanning from heel strike to the first trough in the resultant GRF (Figure 2.2). This is followed by the propulsive phase, where athletes generate a second surge in force to redirect their momentum in the new intended direction.



**Figure 2.2:** Schematic of the three stages of stance phase, determined using resultant ground reaction force. weight acceptance (WA), peak push off (PPO), final push off (FPO) (Besier et al., 2001).

Although both phases are important for performance the weight acceptance phase is particularly critical due to its strong association with ACL injury. Video analyses of ACL ruptures in basketball consistently show that injury typically occurs during the landing phase (Krosshaug et al., 2007). Supporting this, Dempsey et al. (2007) examined the side-step COD and reported that the weight acceptance period contained the greatest knee valgus and internal rotation moments, two hallmark indicators of ACL injury risk.

Koga et al. (2010) further highlighted the danger of the early landing phase through model-based video analysis of ten non-contact ACL injuries in female team handball and basketball players. They found that injuries consistently occurred around 40ms after initial foot contact and typically coincided with a rapid increase in knee valgus, a shift from external to

internal tibial rotation, and vertical GRFs peaking at ~3.2 body weights. Similarly, cadaveric work by Bates et al. (2020) demonstrated that ACL strain peaked around 53ms (48-61ms) after initial contact. Bates et al. (2020) later suggest that non-contact ACL injuries are expected to occur between 0 and 61 milliseconds after initial contact. Across in vivo and cadaveric studies, evidence identifies the early stance/weight acceptance phase as the most hazardous period for non-contact ACL injury, where high forces and vulnerable joint positions converge. As a result, many COD studies focus exclusively on this phase. For example, David et al. (2017) restricted their analysis to the first 40% of stance because it represents the period of highest risk potential.

Early stance also has important implications for traction mechanics. Forrester & Fleming (2019) describe the traction mechanics during the early stance phase as beginning with a period of low resistance, when the studs are the only portion of the cleat engaged with the surface, followed by a high resistance period when the outsole makes broader contact with the surface. This short but intense window is characterized by high forces and rapid loading rates. The resulting traction rapidly decelerates the foot to a quasi-static condition until it accelerates again during the later propulsion phase of stance.

The early stance phase of COD movements represents a critical window where high joint loads, hazardous biomechanics, and elevated traction demand intersect. Within the first 100ms after ground contact, the athlete produces large GRFs and experiences the greatest knee loading while the knee is in the most vulnerable position. Evidence from vivo video analyses, cadaveric strain studies, and traction research all converge on this early period as the decisive phase in which non- contact ACL injuries most commonly occur. Therefore, understanding the characteristics of early stance traction and biomechanics is for both injury prevention and performance optimization.

## **2.5 The Penultimate Step**

### *2.5.1 Biomechanical Role in Deceleration and Performance*

COD typically does not occur with a single step, multiple approach steps are typically required to effectively change direction (James et al., 1977). The penultimate step, taken just before the final plant step, plays a critical role in deceleration and injury risk reduction. P. Jones et al. (2016) demonstrated that the penultimate step is characterized by greater knee flexion, increased horizontal braking forces, and lower average horizontal GRFs compared to the final plant step. These braking characteristics help to distribute the load prior to the final plant step, reducing the magnitude of potentially hazardous knee abduction moments during the final plant step.

### *2.5.2 Injury Risk Implications*

Dos'Santos et al. (2021) highlighted the penultimate step as a critical determinant of both COD performance and lower limb loading. Their work shows that the penultimate step plays a primary role in braking and postural alignment, allowing athletes to lower the center of mass, control trunk orientation, and absorb braking impulse before the final plant step. This distribution of braking earlier in the sequence enables the final plant step to be shorter and more propulsive, thereby enhancing performance (Dos'Santos, Thomas, & Jones, 2021). Conversely, insufficient braking in the penultimate step shifts large deceleration demands to the final step, which increases knee joint moments associated with ACL injury risk (Dos'Santos, Thomas, et al., 2019). This knowledge is especially important when sharper angles and higher approach speeds are at play because earlier braking helps dissipate the higher forces during sharper and faster CODs. Overall, the penultimate step directly influences the final plant step by absorbing load and positioning the body to execute the COD safely and effectively.

### *2.5.3 Planned vs. Unplanned Changes in Direction*

Whether the COD is planned or unplanned also influences the movement strategy used by the athlete during the COD. Byrne et al. (2022) reported that during planned 45° side-stepping, athletes positioned the penultimate step more effectively relative to the center of mass, which lead to improved trunk and pelvic alignment, whereas reactive CODs demonstrated less optimal positioning. Mulligan et al. (2024) further found that reactive CODs often involve reduced braking during the penultimate step, forcing athletes to compensate with greater braking demands at the final plant step. This strategy is linked to both reduced performance and increased joint loading. Supporting this, Zhu et al. (2025) observed that unanticipated CODs elicited higher peak vertical and posterior GRFs, along with elevated GRF loading rates during the final plant step. Similarly, Meinerz et al. (2015) showed that unanticipated land-to-COD tasks resulted in less knee flexion at initial contact, greater ankle toe-in displacement, and altered hip and knee joint moments. Such mechanics have been linked to increased ACL injury risk (Yu & Garrett, 2007). Insufficient braking during the penultimate step in unanticipated CODs shifts deceleration demands on the final plant step, placing athletes in mechanically disadvantaged positions that may hinder performance and increase injury risk.

Anticipated movements, in contrast, allow athletes to use the penultimate step to align the body and distribute forces effectively, mitigating injury risk (Byrne et al., 2022). Given that most real-world sports scenarios are unanticipated (Farrow et al., 2005), the COD should be unplanned or the penultimate step should be removed to better capture the mechanics of the final plant step.

## **2.6 Influence of Approach Speed**

Speed is a fundamental driver of COD performance and injury risk. Dos'Santos et al. (2018) emphasize the angle-velocity trade off, where faster approach velocities limit the feasible

angle of the COD without compromising stability or increasing injury risk. Faster approach velocities at larger angled CODs elevate knee joint loading, thereby increasing non-contact ACL injury risk. This trade-off reflects a central tension between speed and safety in multidirectional sport contexts. Because of its critical role, approach speed warrants careful consideration and standardized reporting in COD research.

Given its importance, one might expect approach speed to be consistently reported in COD studies. However, substantial variation exists in how researchers define and measure it. In testing, COD tests are performed at a spectrum of speeds ranging from near maximal sprint approaches (~5–7 m/s) to moderate-speed controlled runs (~2–4 m/s). Studies rarely standardize the time point at which approach speed is defined or disclose the number of approach steps used by the subject (Dos'Santos, Thomas, Comfort, & Jone, 2018). Kristianslund et al. (2014) and Zou et al. (2024) both report approach speed at initial contact of the final plant step, Nedergaard et al. (2014) reported the approach speed .5 m prior to the final plant step, Kimura & Sakurai (2025) and Vanrenterghem et al. (2012) both reported approach speed 2 m from the final plant step. Without consistent reporting, comparisons across studies and translation to sport practice become challenging.

Despite inconsistent reporting, speed is known to influence trial validity and athlete injury risk. Vanrenterghem et al. (2012) found that during a 45° COD, speeds >5 m/s compromised task completion for some athletes and pushed knee valgus moments toward dangerous thresholds, while speeds <4 m/s did not load the knee sufficiently. This suggests only a narrow speed window yields a valid and safe test. Zou et al. (2024) further observed that unanticipated 180° CODs were performed at slower entry speeds than anticipated CODs, which may justify using more moderate velocities in testing to replicate real world CODs.

Interestingly, at higher approach speeds faster speeds do not necessarily increase the final steps GRFs. Nedergaard et al. (2014) showed that during a 135° COD increasing approach speed shifted braking demands to the penultimate and even antepenultimate steps, while the final step remained relatively unaffected. This reliance on the penultimate and antepenultimate steps highlights a methodological challenge. If the focus of the research is on the final plant step researchers should look to limit the approach velocity to non-influential speeds or restrict the number of approach steps used to decelerate.

One potential solution is to allow only a single penultimate step to capture the mechanics of the final plant step, avoiding excessive influence from high approach speeds. Alternatively, removing the penultimate step entirely would limit any posture adjustments or braking to the final foot contact. Although the penultimate step is advantageous for redistributing braking demands and optimizing posture, it is highly likely that many sports situations will not allow the athlete to use a penultimate step. In such scenarios, athletes rely on the final step to absorb deceleration demands. Therefore, eliminating the penultimate step can be justified as a methodological approach to examine a mechanically demanding scenario in which the athlete has limited opportunity to adjust posture or redistribute load prior to the final plant step.

## **2.7 Summary and Gaps in Literature**

AT has undergone significant development over the past six decades, with modern 3G systems designed to replicate natural grass while offering durability and lower maintenance demands. Despite these improvements, modern 3G systems using CR infill are associated with environmental, thermal, and injury-related concerns. Alternative infills such as EW systems have been introduced to mitigate these issues, and mechanical testing has shown differences in vertical

stiffness and traction characteristics compared to CR. However, athlete-based studies examining how these newer infills affect biomechanics during high-demand sport movements are limited.

COD tasks, and particularly 180° CODs, represent one of the most mechanically demanding and injury-relevant maneuvers in multidirectional sport. The penultimate step and the early stance of the final plant step are critical phases where large GRF's and high joint loads occur. While previous research has examined the effects of approach speed, anticipation, and COD angle, no studies have evaluated how the number of approach steps influences loading during the final plant step. Standardized short approaches such as 1-step and 2-step entries may provide valuable insight into how athletes execute CODs under controlled but realistic conditions.

#### *2.7.1 Novelty and Contribution of the Study*

This study advances the literature in two ways. First, it provides athlete-based biomechanical testing of an alternative EW infill compared to the widely used CR infill during a maximal-effort 180° COD. Second, it evaluates how number of approach steps (1-step vs. 2-step) influences early stance shoe-surface biomechanics during the same maneuver. By examining these two factors, this study isolates the effects of surface properties and approach mechanics, contributing novel insights into both turf design evaluation and COD testing methodology.

#### *2.7.2 Rationale for Study Design*

The 180° COD was selected as the test movement because of its high mechanical demands and strong association with ankle sprain and non-contact ACL injury mechanisms. Early stance was the focus of analysis because it coincides with peak GRFs, landing traction, and

the proposed timing of most ACL injuries. The comparison of CR and EW infills addresses an important gap in surface performance testing, as athlete-based evidence is limited. The inclusion of both 1-step and 2-step approach conditions allows for an evaluation of how approach steps influence biomechanical loading, providing clarity on the underexplored factor of approach steps. This design enables an investigation of two variables that are central to both sport performance and injury risk.

### 3. METHODS

Note: Due to the large overall scope of the project from which this thesis was generated and the multiple documents that are being generated that need to have the methods explained, the following chapter is co-authored by Raoul F. Reiser II, Laura T. Taylor, Colden D. Clark, & Logan C. Randall.

#### **3.1 Subjects**

Twenty-one of 23 healthy, varsity high school or higher competitive athletes (10 females; whole group age range: 18–30 years) completed the two laboratory visits of this investigation. To ensure recent and relevant exposure to the athletic movements, participants were required to engage in physical activities involving jumping, landing, and COD at least once per week over the preceding month. Additionally, participants must have competed in ground-based field sports requiring cleated footwear (e.g., soccer, rugby, lacrosse, but not baseball) at the varsity high school level, college/university club level, or higher within the past two years. Those not currently competing were eligible if they had worn cleated footwear at least once in the previous month. All participants were free of workout-related soreness at the time of testing.

Prior injuries were not exclusionary if the subject met all other criteria listed above. However, individuals were excluded if they reported any medical condition or use of medication that could influence balance or motor function, required the use of braces that restricted joint movement, had residual unilateral deficits in strength or range of motion due to previous injury, or any condition preventing them from performing cutting and pivoting movement with maximum effort. Women were also excluded if pregnant.

Prior to data collection, all procedures were explained to participants, and eligibility was confirmed through a health-history questionnaire. Written informed consent, approved by the

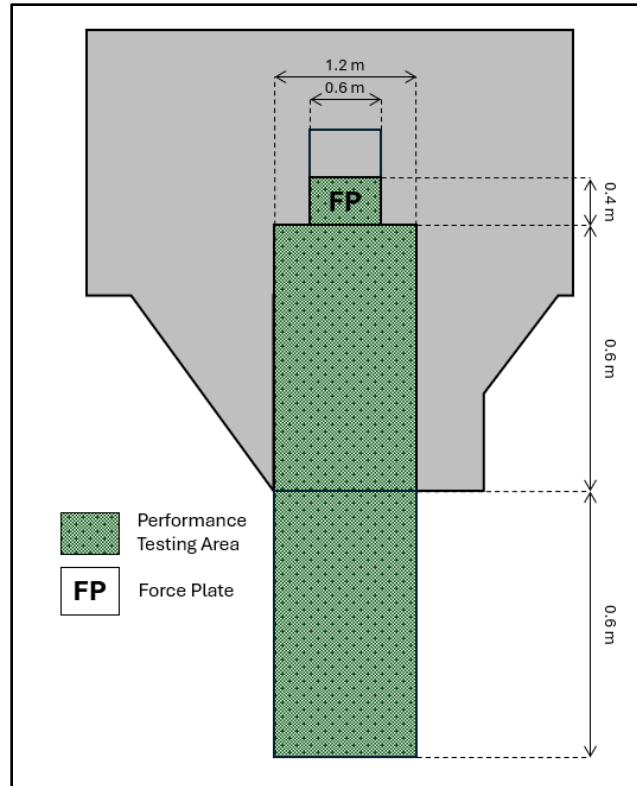
Colorado State University Institutional Review Board, was obtained from all participants.

Subjects were monetarily compensated for their time.

### 3.2 Experimental Design

This study utilized a 3G AT system composed of a 5cm woven monofilament and slit-film fiber blend with 1.25cm spacing (GreenFields USA, Dayton, TN), fastened to a 2.54cm thick expandable foam shock pad (PowerBase YSR, Brock USA) using screws and carpet tape. A sublayer of silica sand was applied before being covered with a CR or EW performance layer infill. The ratio of sand to infill was consistent with the manufacturer's recommendations at ratios of 4.9/20.0 kg/m<sup>2</sup> EW/sand and 9.0/17.1 kg/m<sup>2</sup> CR/sand. The CR was composed of new ambient-ground SBR granules derived from recycled automotive tires (Genova USA, Inc., Beaumont, TX) and the EW was composed of sized, smoothed, and shaped yellow pine particles (BrockFill, Brock USA, Boulder CO). The turf system was constructed to cover a primary performance zone measuring 1.2 x 3.7m with surrounding turf panels to ensure athlete safety during trials. All turf, infill, and shock pad components were new prior to the study (Figure 3.1).

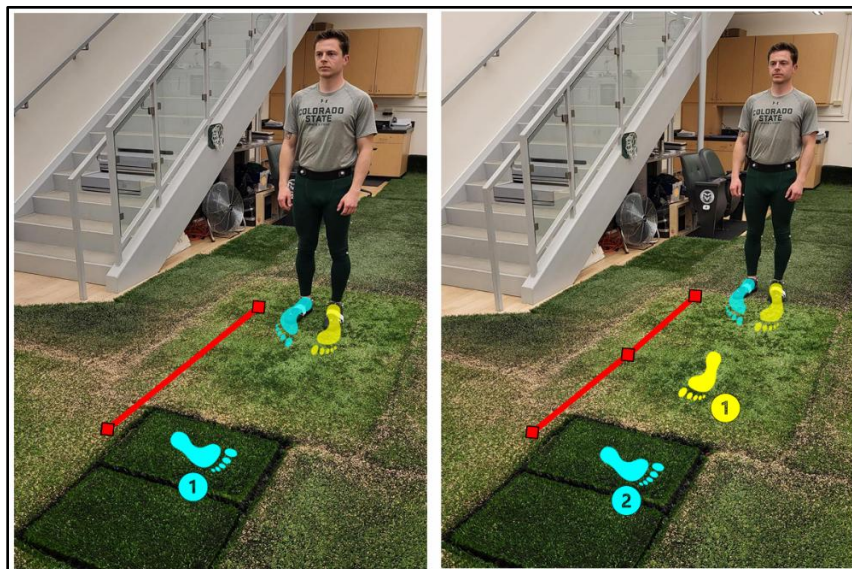
The main testing area included a single isolated 40 x 60cm force plate (Bertec Corp., Columbus OH) with 3mm clearance on each side embedded flush within the concrete floor. The isolated turf/shock pad panels were secured to the force plate with carpet tape, and new, athlete conditioned panels over the force plate were installed every 10 subjects. Infill depth was checked and appropriately adjusted before each subject to maintain a consistent 16mm blade reveal. GRFs and three-dimensional kinematic data were collected simultaneously during all trials. GRFs were sampled at 1200Hz and synchronized with a 10-camera Nexus optical motion capture system operating at 300Hz (Vicon, Englewood, CO).



**Figure 3.1: Overview of the performance testing area used for the 180° COD task. Force plate location (FP), approach and outrun path (Green), extended AT surface for safety (Grey).**

All data collection occurred across two laboratory visits, separated by no more than ten days. The first laboratory visit included anthropometric measurements and data collection for two 90° COD movements. The second visit had the subjects perform a single-leg stopping movement on their left foot followed by the 180° COD on their right foot. Participants were instructed to refrain from strenuous physical activity for at least 24 hours prior to each visit. At both sessions, after donning tight-fitting, spandex-like athletic clothing and their own cleats, a lower-body set of 16 retroreflective markers consistent with Vicon Plug-in Gait were applied for three-dimensional motion capture. A static calibration trial with temporary medial knee and ankle markers was recorded with the participant in a standardized “motorcycle” pose.

Prior to testing, participants completed a standardized dynamic warm-up consisting of 5 minutes on a stationary bike, lateral shuffles, high knees, butt kicks, jog with reversal, open/close the gate, walking lunges with a twist, and single leg anterior/posterior and medial/lateral hops. Subjects then performed task-specific practice trials. Each dynamic movement was performed first with a 1-step approach condition and then the 2-step condition. All trials were performed on one surface before having a 10-minute break to repeat trials on the second surface. The order of surface presentation was randomized and counterbalanced across participants. At least one successful practice trial at maximum effort was required before collecting data for each condition, with additional practice allowed as needed. Participants completed six to eight acceptable trials per condition. The testing protocol initially required six trials but was later expanded to eight after noticing gaps in marker data that couldn't always be filled. All trials were performed in the same pair of their own cleated footwear. 180° COD trials were performed under both 1-step and 2-step approach conditions, with approach type determining the athlete's self-selected starting distance from the force platforms (Figure 3.2).



**Figure 3.2: Diagram depicting COD approach conditions. The 1-step (Left) and 2-step (Right) approaches are distinguished by the additional step as seen in the 2-step diagram. Left foot (Yellow) and right foot (Blue).**

For each trial, participants began in a static, “calm and quiet” stance with feet flat and approximately shoulder width apart. Upon hearing the cue “3, 2, 1, GO,” they initiated the movement by stepping forward and rapidly executing a 180° COD on the force plate (subjects were allowed to make a false, retreat step with their lead limb if desired). Immediately following the 180° COD plant step on the force plate, participants were instructed to take two explosive steps in the opposite direction they came from before decelerating to a controlled stop. The goal was to complete the COD and initial steps as quickly as possible while maintaining balance and control. Proper force plate contact during the COD and visible marker capture were required for a trial to be deemed acceptable.

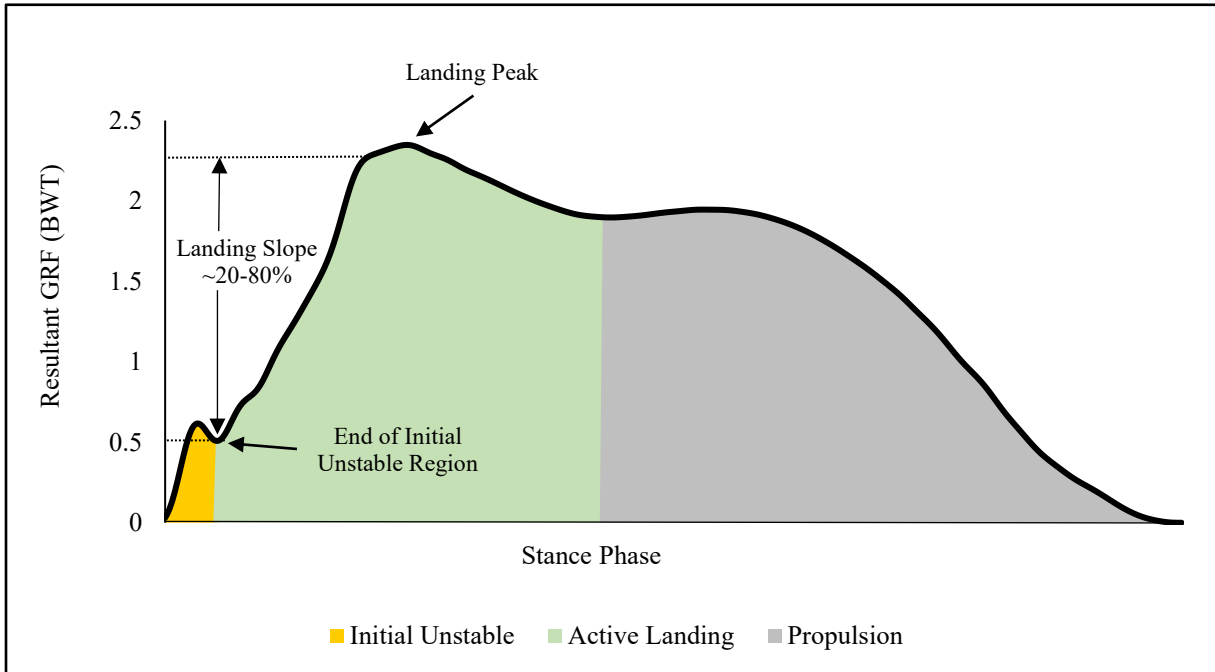
At the conclusion of data collection, participants provided short qualitative feedback on perceived differences between the two surfaces and the two approach conditions. Responses were recorded as short written comments. Responses were not analyzed statistically but were used to provide supplemental context for the interpretation of the findings.

### **3.3 Analysis of Biomechanical Variables**

From the 21 subjects, 523 valid trials were included in the analysis, with each subject contributing between six and eight trials for each of the four conditions (2 surfaces x 2 approach steps). Joint kinematics and kinetics were calculated via inverse dynamics using the Plug-in Gait model after filtering marker trajectories and GRFs at 12 Hz with a low-pass recursive Butterworth filter. Plug-in-Gait model outputs and raw GRFs were exported for further processing with custom Matlab code (MathWorks, Natick, MA). All metrics derived from optical motion capture were up-sampled to 1200Hz to match the GRFs.

Exported raw GRFs were low-pass recursive Butterworth filtered at 100 Hz. Initial contact was based on the resultant GRF exceeding 10 N. The typical resultant GRF profile

included a landing peak followed by a propulsion peak, though an initial unstable region at first contact was also often present (Figure 3.3). Vertical and horizontal resultant GRF profiles were similar to the resultant GRF profile but lower in magnitude.



**Figure 3.3:** Typical resultant GRF profile of a final foot contact during a 180° COD showing the 3 phases of stance (initial unstable [orange], active landing [green], and propulsion [grey]). The landing peak is indicated, and the shaded region represents the portion of the landing slope (from the end of the initial unstable region (~20%) to 80% of the landing peak) used to calculate landing loading rate.

### 3.3.1 At Initial Contact

At initial contact the right foot COM resultant horizontal (hFtVel) and vertical velocity (vFtVel, positive upwards) were analyzed along with foot pitch, roll, and yaw orientations from the Plug-in-gait 'bones'. All foot orientations were set to 0° in neutral stance with a positive pitch angle indicating plantar flexion (FtPlantFlex), a positive roll angle indicating eversion (FtEversion), and a positive yaw angle indicating internal rotation (FtIntRot). Also at initial contact, the horizontal resultant (hCOMVel) and vertical whole-body COM velocity (vCOMVel, positive upwards), the horizontal resultant COM velocity angle (hCOMVelAngle), and medial

lean angle (LeanAngle) were analyzed. The whole-body COM was calculated as the average location between the right and left posterior superior iliac spine markers. The horizontal COM velocity angle was defined as  $0^\circ$  when approaching the force plate at the start and  $180^\circ$  after performing the  $180^\circ$  COD. A smaller and possibly negative horizontal COM velocity angle denotes less turning at initial contact. The lean angle was defined as the angle between the body COM and the center of pressure relative to a vertical axis ( $0^\circ$ ) at the end of the initial unstable region or 20ms if no unstable region was present.

### *3.3.2 During Stance Phase*

During the stance phase, the magnitudes of the landing peak vertical (PvGRF) and horizontal GRFs (PhGRF) were analyzed as were the respective average loading rates calculated from the average slope of the GRF from the end of the initial unstable region to 80% of the resultant peak GRF (AvGRFLoadRate) and (AhGRFLoadRate). The VFM, the moment around the vertical axis at the center of pressure of the foot, the coefficient of rotational traction (RCOT), the ratio of VFM to the vertical GRF, and the coefficient of linear traction (LCOT), the ratio of horizontal GRF to the vertical GRF were all analyzed at the time of the peak resultant GRF. Horizontal resultant linear displacement of the right toe marker from initial contact to the minimum right toe horizontal velocity (hToeDisp) was analyzed along with the time that this event occurred relative to initial foot contact (ToeStopTime). All GRFs, GRF loading rates, and VFMs were normalized to subject bodyweight (BWT).

## **3.4 Statistical Analysis**

All statistical analyses were conducted using IBM SPSS Statistics (version 29, IBM Corp., Armonk, NY, USA). Statistical analyses were performed using a linear mixed-effects model (LMM) to account for the repeated-measures design and within-subject variability. Fixed

effects included infill type (CR vs. EW), approach condition (1-step vs. 2-step), their interaction, and sex (male vs. female). Even though we did not examine sex differences, it was included as a fixed effect due to previously documented differences in COD between men and women (Crenshaw et al., 2004; Donelon et al., 2024). Subject was included as a random effect to account for repeated trials within individuals. A LMM test was selected because it appropriately accounts for the repeated-measures structure of the study, where multiple trials are nested within athletes. The LMM allows subject-level variability to be modeled as a random effect while estimating fixed effects of infill type, approach condition, sex, and their interaction. This approach also accommodates unequal numbers of trials per participant, missing data, and heterogeneity in variance across conditions (West et al., 2014; Winter, 2013).

All outcome variables were checked for normality and homoscedasticity using residual diagnostics from the LMM in R (version 4.5.1; R Core Team, Vienna, Austria). Two variables, average vertical GRF loading rate and average horizontal GRF loading rate violated these assumptions and were log-transformed before analysis. Outliers were assessed with none needing removal. Pairwise comparisons of estimated marginal means (EMMs) were conducted with significance accepted at  $p < 0.05$ . If a main effect interaction was significant, a Bonferroni post hoc test was performed to explore the within step and surface relationship.

## 4. RESULTS

### 4.1 Participant Characteristics

Table 4.1 contains the whole-group and individual sex demographics of the twenty-one participants (10 female, 11 male) that completed both visits. Two additional subjects enrolled in the study but could not complete the second visit due to injuries that occurred outside the lab. Sports backgrounds were diverse, with representation from soccer, lacrosse, ultimate frisbee, rugby, and football. With the varied sports and participants wearing their own cleats, a variety of stud geometries were present but similar overall stud count. Leg dominance was predominantly right sided across the whole group.

**Table 4.1: Participant Characteristics. Group means and (standard deviations) are presented for age, height, body mass, and number of studs. Frequencies (n) are reported for sport played, stud shape, and dominate leg.**

	<b>Whole Group</b>	<b>Female</b>	<b>Male</b>
<b>n</b>	21	10	11
<b>Age [yrs]</b>	19.9 (1.3)	19.7 (0.8)	20.3 (1.8)
<b>Height [cm]</b>	174.9 (9.8)	167.4 (4.7)	181.8 (7.8)
<b>Mass [kg]</b>	73.1 (12.2)	63.0 (6.9)	82.3 (7.7)
<b>Sport Played</b>	Soccer (4) Lacrosse (5) Ultimate Frisbee (3) Rugby (6) Football (3)	Soccer (3) Lacrosse (3) Rugby (4)	Soccer (1) Lacrosse (2) Ultimate Frisbee (3) Rugby (2) Football (3)
<b>Stud Shape</b>	Triangle (7) Round (6) Triangle Blade (4) Combination (3) Irregular Round (1)	Triangle (3) Round (3) Triangle Blade (2) Combination (2)	Triangle (4) Round (3) Triangle Blade (2) Combination (1) Irregular Round (1)
<b>Number of Studs</b>	13.0 (1.7)	13.6 (1.9)	12.4 (1.3)
<b>Leg Dominance</b>	Right (19) Left (2)	Right (10)	Right (9) Left (2)

## 4.2 Surface

At initial contact horizontal foot velocity was 0.15 m/s greater on CR than EW, while vertical foot velocity was similar across the two surfaces (Figure 4.4, Table 4.2). The foot orientation was 0.68° more plantar flexed on EW and 0.86° more everted on CR, with no significant difference in internal rotation (Figure 4.7, Table 4.2).

Surface effects extended to the COM kinematics where lean angle was 0.35° further from vertical on EW and horizontal COM velocity angle was 2.02° larger on CR (Figure 4.5, Table 4.2). No significant surface effects were observed for horizontal COM velocity or vertical COM velocity (Figure 4.5, Table 4.2). However, a significant interaction effect between Surface and Approach was observed for horizontal COM velocity. Within each surface, pairwise comparisons revealed horizontal COM velocity was 0.499 m/s and 0.600 m/s faster in the 2-step condition for CR and EW, respectively (Figure 4.6). In contrast, within Approach pairwise comparisons revealed no significant differences between Surface in the 1-step condition or the 2-step condition.

Peak vertical GRF and peak horizontal GRF were 0.14 BWT and 0.09 BWT larger on EW compared to CR, respectively. Average vertical GRF loading rate and average horizontal GRF loading rate were 0.12 Log BWT/sec and 0.10 Log BWT/sec higher on EW compared to CR, respectively (Figure 4.1, Table 4.3). The horizontal toe displacement was .003 m greater on CR than EW despite the time it took for the toe to reach a minimum velocity not differing (Figure 4.4, Table 4.3).

No significant differences between Surface were found for the VFM, LCOT, or RCOT at the time of the peak resultant GRF (Figure 4.2, Table 4.3). However, a significant interaction

effect was observed for the VFM, indicating that the combined influence of Surface and Approach impacted this variable. Pairwise comparisons revealed that within the 2-step condition, the CR surface produced a 0.002 Nm/BWT larger VFM than the EW surface (Figure 4.3).

### **4.3 Approach**

The 1-step approach produced 0.12 m/s greater horizontal foot velocity, while vertical foot velocity did not differ at initial contact (Figure 4.4, Table 4.4). The foot orientation was 3.90° more internally rotated in the 2-step condition, but 4.34° more plantar flexed and 2.25° more everted in the 1-step condition (Figure 4.7, Table 4.4). Also, in the 2-step condition, participants' lean angle was 4.94° greater, horizontal COM velocity angle was 3.10° larger, horizontal COM velocity was 0.55 m/s faster and vertical COM velocity was 0.25 m/s slower compared to the 1-step condition (Figure 4.5, Table 4.4).

Significant main effects of Approach were observed for most kinetic variables. The 2-step condition produced a 0.24 Log BWT/sec higher average vertical GRF loading rate, 0.30 Log BWT/sec higher average horizontal GRF loading rate, and a 0.13 BWT higher peak horizontal GRF but not peak vertical GRF (Figure 4.1, Table 4.5). The LCOT was 0.03 hGRF/vGRF higher in the 2-step condition, while the RCOT and VFM did not differ (Figure 4.2, Table 4.5). The horizontal toe displacement was 0.010 m greater during the 2-step condition, with no difference in the time it took for the toe to reach minimum velocity between conditions (Figure 4.4, Table 4.5).

### **4.4 Participant Feedback**

Sixty-seven percent of participants reported a preference for EW over CR, while 24% indicated no surface preference and 10% favored CR. Participants who preferred EW anecdotally

reported that the surface allowed for improved push-off, easier planting and turning, and greater perceived stability during the landing phase. EW was frequently described as feeling stiffer and less compliant, with reduced “sinking” underfoot, which participants associated with improved traction and overall confidence during the COD task. Several participants also noted that EW felt easier to stop on, produced less sliding, and allowed for faster entry into and exit from the COD, as well as improved acceleration out of the movement.

In relation to Approach, the majority of participants (81%) reported a preference for the 2-step approach, describing it as faster, more repeatable, comfortable, aggressive, powerful, and natural. Only 5% of participants preferred the 1-step approach, while 14% indicated no preference. Participant feedback on traction between approaches was mixed; some reported no difference, whereas others noted traction challenges when performing the 2-step approach.

**Table 4.2: Linear mixed-effects model results across surfaces (EW and CR) for initial contact variables. Estimated marginal means (EMM), pairwise differences (Dif), degrees of freedom (df), F statistic (F), and standard errors (SE) are reported along with p-values. Significant effects ( $p < 0.05$ ) are indicated in bold.**

Initial Contact Variables	df	F	Surface EMM		Dif	Significance <i>p</i>
			EW	CR		
hFtVel [m/sec]	1, 499.1	8.56	2.63	2.78	0.15	<b>0.004</b>
SE			0.14	0.14		
vFtVel (m/sec)	1, 499.0	0.29	-0.93	-0.92	0.01	0.590
SE			0.05	0.05		
FtPlantFlex [deg]	1, 493.0	4.75	-2.00	-2.68	0.68	<b>0.030</b>
SE			1.40	1.40		
FtEversion [deg]	1, 493.0	6.22	18.65	19.51	0.86	<b>0.013</b>
SE			1.48	1.48		
FtIntRot [deg]	1, 493.0	0.36	95.19	94.82	0.37	0.549
SE			2.50	2.50		
LeanAngle [deg]	1, 499.0	4.96	40.41	40.06	0.35	<b>0.026</b>
SE			0.60	0.60		
hCOMVelAngle [deg]	1, 499.1	8.02	-0.74	1.28	2.02	<b>0.005</b>
SE			1.16	1.16		
hCOMVel [m/sec]	1, 499.1	0.02	2.45	2.44	0.00	0.898
SE			0.07	0.07		
vCOMVel [m/sec]	1, 499.0	0.96	-1.01	-1.00	0.02	0.328
SE			0.06	0.06		

**Table 4.3: Linear mixed-effects model results across surfaces (EW and CR) for during stance variables. All GRFs, GRF loading rates, and VFMs were normalized to subject bodyweight (BWT). Estimated marginal means (EMM), pairwise differences (Dif), degrees of freedom (df), F statistic (F), and standard errors (SE) are reported along with p-values. Significant effects ( $p < 0.05$ ) are indicated in bold.**

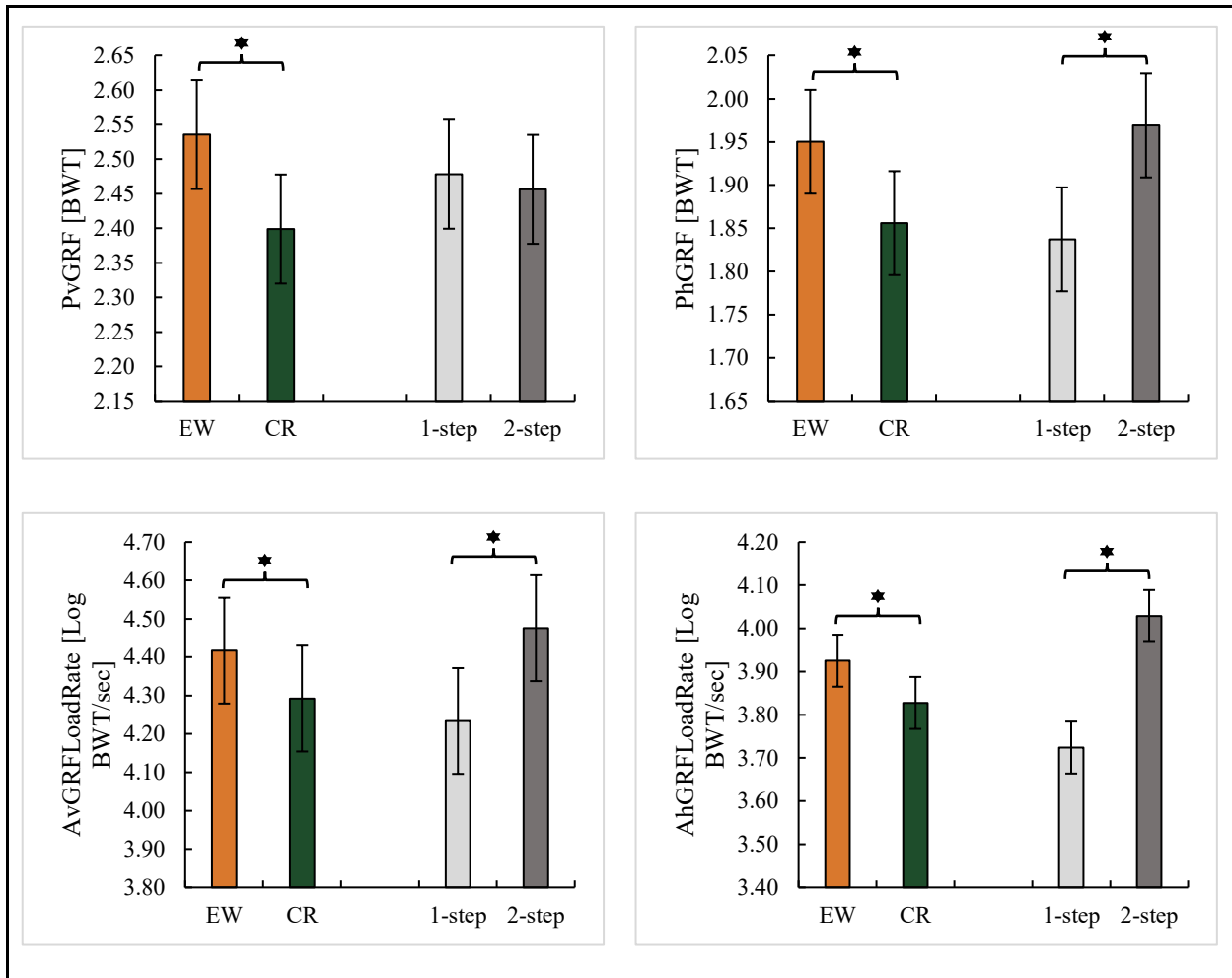
During Stance Phase Variables	df	F	Surface EMM		Dif	Significance <i>p</i>
			EW	CR		
PvGRF [BWT]	1, 499.0	24.12	2.54	2.40	0.14	<b>0.000</b>
SE			0.08	0.08		
AvGRFLoadRate [Log BWT/sec]	1, 470.3	15.34	4.42	4.29	0.12	<b>0.000</b>
SE			0.14	0.14		
PhGRF [BWT]	1, 499.0	17.53	1.95	1.86	0.09	<b>0.000</b>
SE			0.06	0.06		
AhGRFLoadRate [Log BWT/sec]	1, 470.4	8.58	3.93	3.83	0.10	<b>0.004</b>
SE			0.12	0.12		
RCOT [Nm/vGRF]	1, 497.0	0.55	0.0052	0.0055	0.0003	0.459
SE			0.0004	0.0004		
LCOT [hGRF/vGRF]	1, 497.2	0.71	0.73	0.72	0.01	0.401
SE			0.02	0.02		
VFM [BWT/m]	1, 499.1	2.59	0.0015	0.0026	0.0011	0.108
SE			0.0011	0.0011		
hToeDisp [m]	1, 499.1	6.19	0.053	0.057	0.003	<b>0.013</b>
SE			0.003	0.003		
ToeStopTime [sec]	1, 499.1	0.00	0.148	0.148	0.000	0.981
SE			0.007	0.007		

**Table 4.4: Linear mixed-effects model results across approach (1-step and 2-step) for initial contact variables. Estimated marginal means (EMM), pairwise differences (Dif), degrees of freedom (df), F statistic (F), and Standard errors (SE), are reported along with p-values. Significant effects ( $p < 0.05$ ) are indicated in bold.**

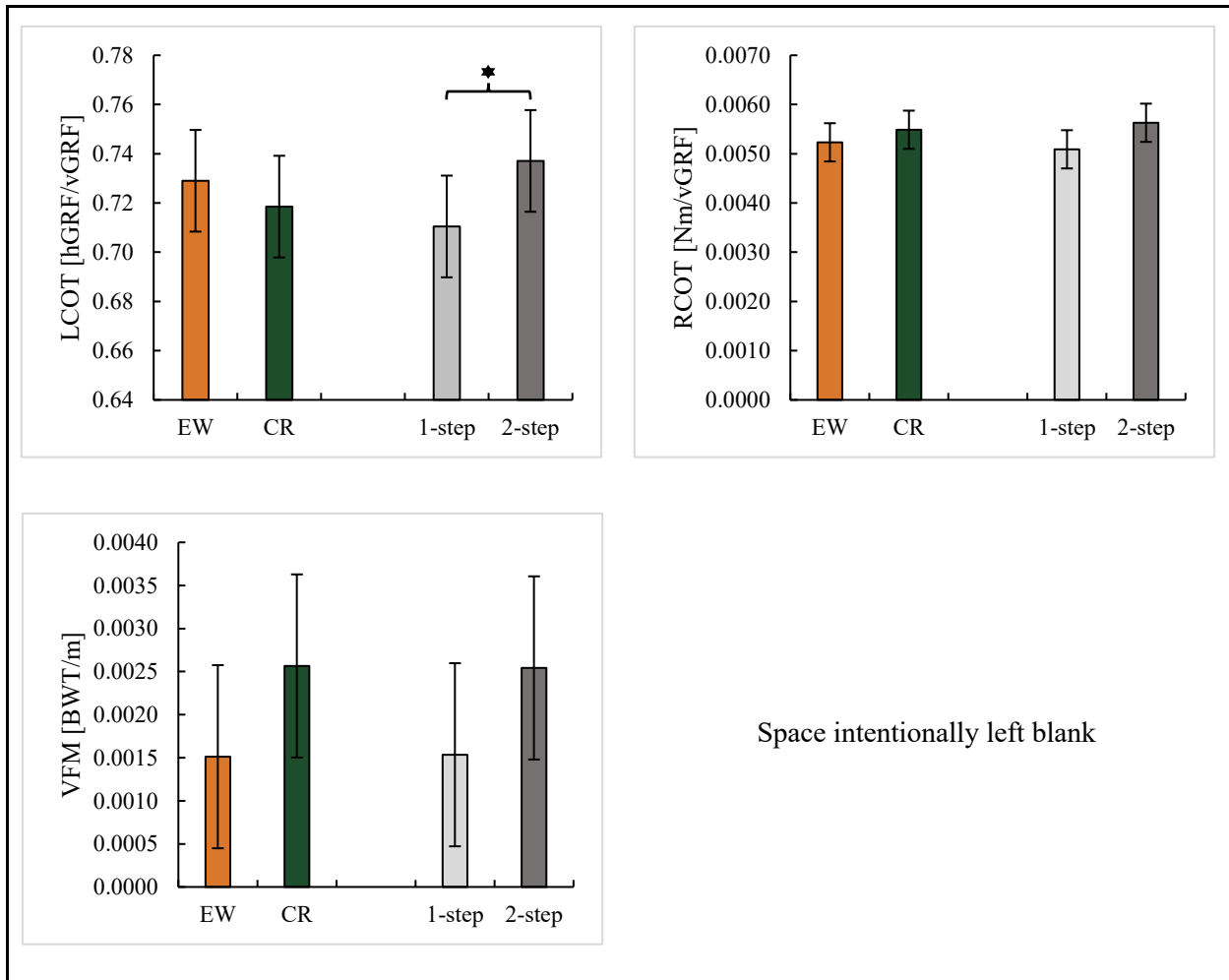
Initial Contact Variables	df	F	Approach EMM		Dif	Significance <i>p</i>
			1-step	2-step		
hFtVel [m/sec]	1, 499.1	5.92	2.76	2.64	0.12	<b>0.015</b>
SE			0.14	0.14		
vFtVel [m/sec]	1, 499.0	0.07	-0.92	-0.92	0.00	0.790
SE			0.05	0.05		
FtPlantFlex [deg]	1, 493.0	194.43	-0.17	-4.51	4.34	<b>0.000</b>
SE			1.40	1.40		
FtEversion [deg]	1, 493.0	42.64	20.20	17.95	2.25	<b>0.000</b>
SE			1.48	1.48		
FtIntRot [deg]	1, 493.0	39.73	93.05	96.96	3.90	<b>0.000</b>
SE			2.50	2.50		
LeanAngle [deg]	1, 499.0	1004.94	37.76	42.70	4.94	<b>0.000</b>
SE			0.60	0.60		
hCOMVelAngle [deg]	1, 499.0	18.89	1.82	-1.28	3.10	<b>0.000</b>
SE			1.16	1.16		
hCOMVel [m/sec]	1, 499.0	526.40	2.17	2.72	0.55	<b>0.000</b>
SE			0.07	0.07		
vCOMVel [m/sec]	1, 499.0	212.11	-1.13	-0.88	0.25	<b>0.000</b>
SE			0.06	0.06		

**Table 4.5: Linear mixed-effects model results across approach (1-step and 2-step) for during stance variables. All GRFs, GRF loading rates, and VFMs were normalized to subject bodyweight (BWT). Estimated marginal means (EMM), pairwise differences (Dif), degrees of freedom (df), F statistic (F), and Standard errors (SE), are reported along with p-values. Significant effects ( $p < 0.05$ ) are indicated in bold.**

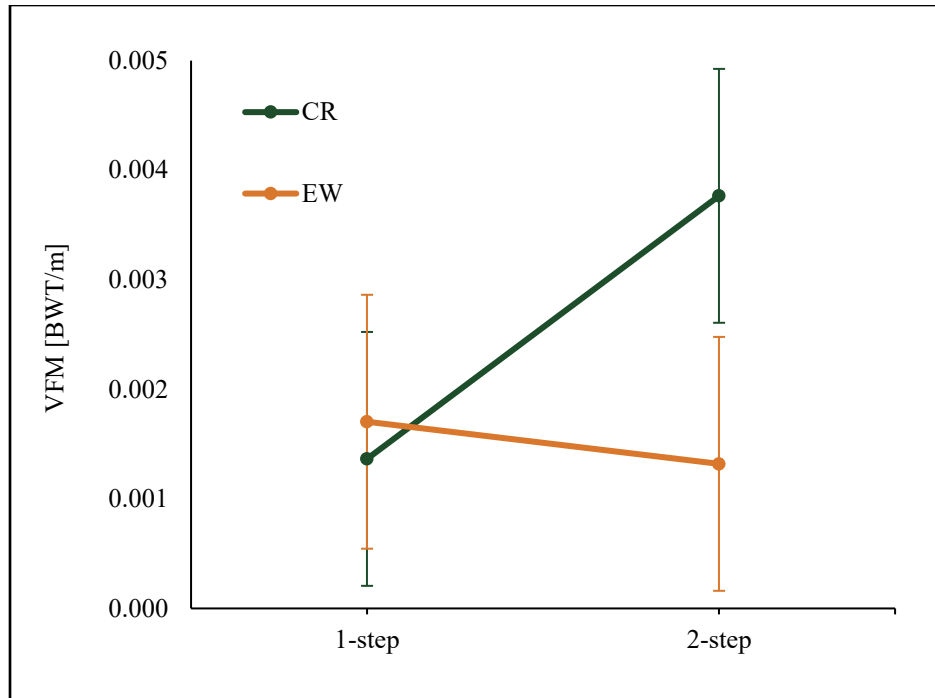
During Stance Phase Variables	df	F	Approach EMM		Dif	Significance p
			1-step	2-step		
PvGRF [BWT]	1, 499.0	0.62	2.48	2.46	0.02	0.432
SE			0.08	0.08		
AvGRFLoadRate[Log BWT/sec]	1, 470.4	57.11	4.23	4.48	0.24	<b>0.000</b>
SE			0.14	0.14		
PhGRF [BWT]	1, 499.0	34.38	1.84	1.97	0.13	<b>0.000</b>
SE			0.06	0.06		
AhGRFLoadRate[Log BWT/sec]	1, 470.6	82.60	3.72	4.03	0.30	<b>0.000</b>
SE			0.12	0.12		
RCOT [Nm/vGRF]	1, 497.0	2.44	0.0051	0.0056	0.0005	0.119
SE			0.0004	0.0004		
LCOT [hGRF/vGRF]	1, 497.2	4.54	0.71	0.74	0.03	<b>0.034</b>
SE			0.02	0.02		
VFM [BWT/m]	1, 499.1	2.37	0.0015	0.0025	0.0010	0.124
SE			0.0011	0.0011		
hToeDisp [m]	1, 499.1	59.80	0.050	0.060	0.010	<b>0.000</b>
SE			0.003	0.003		
ToeStopTime [sec]	1, 499.0	0.79	0.146	0.149	0.003	0.375
SE			0.007	0.007		



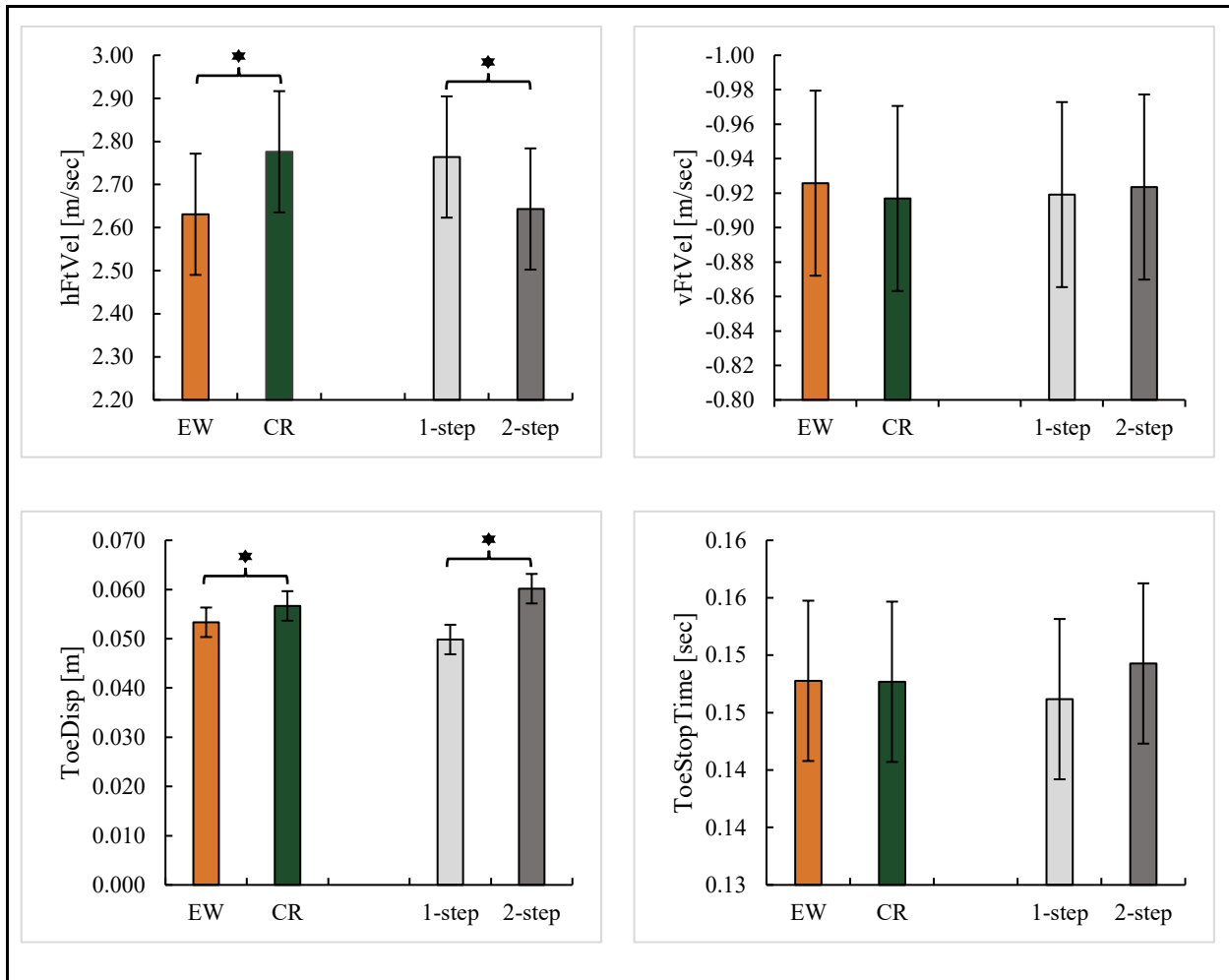
**Figure 4.1: Estimated Marginal Mean ( $\pm$  SE) peak vertical GRF (PvGRF; top left), peak horizontal GRF (PhGRF; top right), peak vertical GRF Loading Rate (AvGRFLoadRate; bottom left), and peak horizontal GRF Loading Rate (AhGRFLoadRate; bottom right) across surface and approach conditions. All GRFs and GRF loading rates were normalized to subject bodyweight (BWT). Values are shown for engineered wood (EW) and crumb rubber (CR) surfaces, as well as 1-step and 2-step approaches during the 180° COD. Statistically significant differences between conditions marked with bracket ( $p < 0.05$ ).**



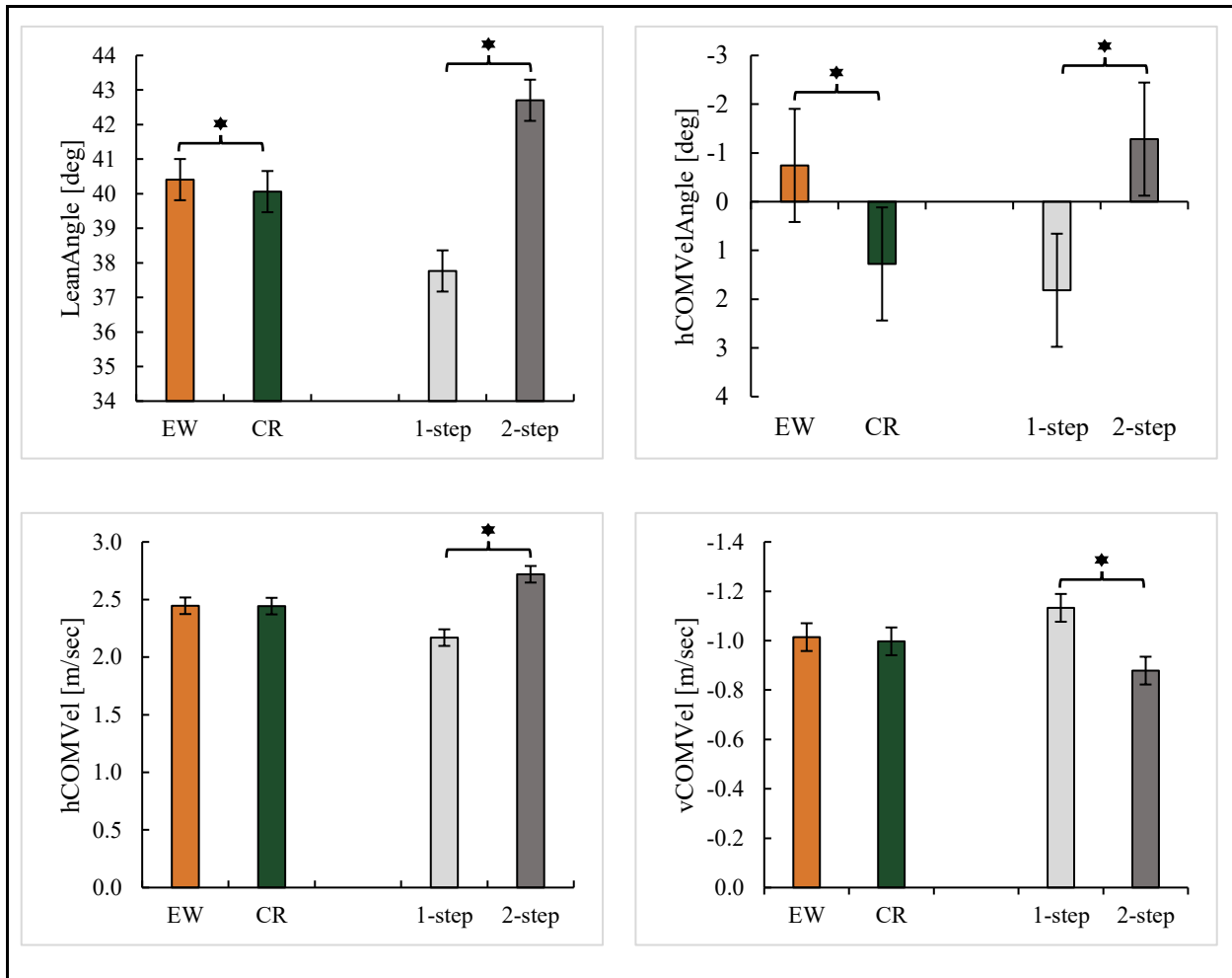
**Figure 4.2: Estimated Marginal Mean ( $\pm$  SE) Linear coefficient of traction (LCOT; top left), Rotational coefficient of traction (RCOT; top right), vertical free moment (VFM; bottom left) across surface and approach conditions. VFM was normalized to subject bodyweight (BWT). Values are shown for engineered wood (EW) and crumb rubber (CR) surfaces, as well as 1-step and 2-step approaches during the 180° COD. No statistically significant differences between conditions ( $p < 0.05$ ).**



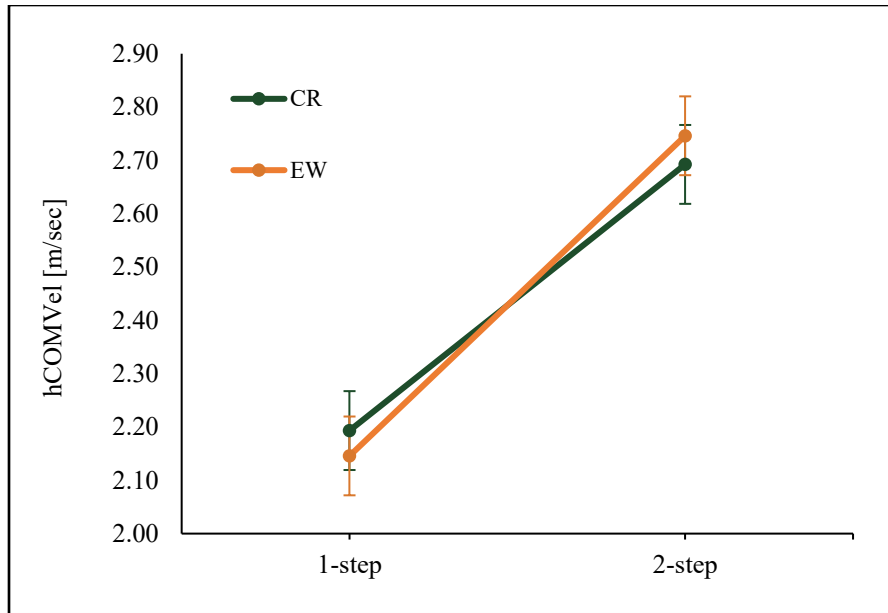
**Figure 4.3: Estimated Marginal Mean ( $\pm$  SE) vertical free moment (VFM) across surface (engineered wood [EW], crumb rubber [CR]) and approach step (1-step, 2-step) conditions during the 180° COD. VFM was normalized to subject bodyweight (BWT). Two significant surface  $\times$  step interactions were observed, with VFM significantly greater in the 2-step compared to the 1-step condition on CR and CR producing a significantly greater VFM than EW during the 2-step condition ( $p < 0.05$ ).**



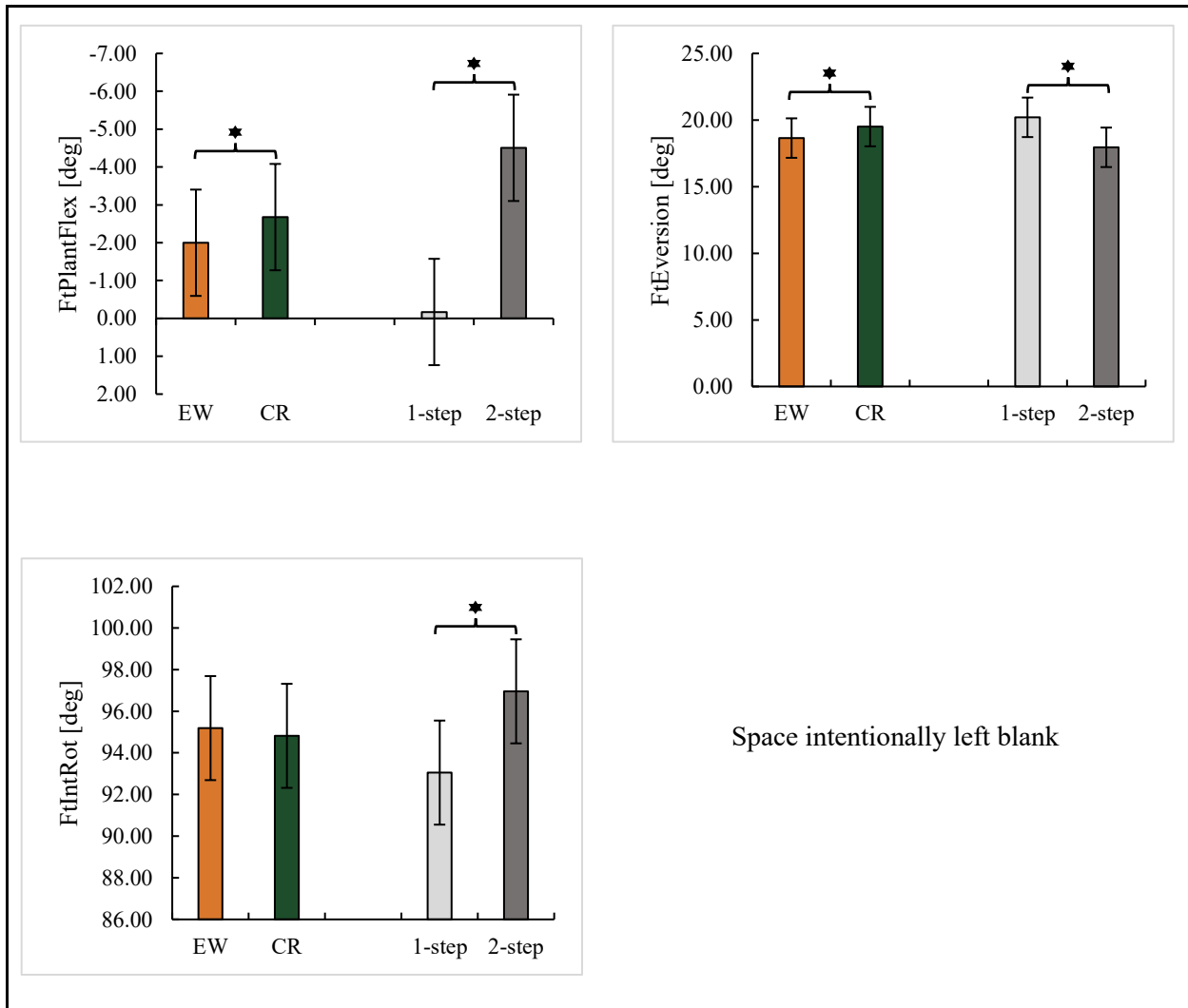
**Figure 4.4: Estimated Marginal Mean ( $\pm$  SE) horizontal foot velocity (hFtVel; top left), vertical foot velocity (vFtVel; top right), toe displacement (ToeDisp; bottom left), and toe stop time (ToeStopTime; bottom right) across surface and approach conditions. Values are shown for engineered wood (EW) and crumb rubber (CR) surfaces, as well as 1-step and 2-step approaches during the 180° COD. Statistically significant differences between conditions marked with bracket ( $p < 0.05$ ).**



**Figure 4.5: Estimated Marginal Mean ( $\pm$  SE) lean angle (LeanAngle; top left), horizontal velocity angle (hCOMVelAngle; top right), horizontal COM velocity (hCOMVel; bottom left), vertical COM velocity (vCOMVel; bottom right) across surface and approach conditions. Values are shown for engineered wood (EW) and crumb rubber (CR) surfaces, as well as 1-step and 2-step approaches during the 180° COD. Statistically significant differences between conditions marked with bracket ( $p < 0.05$ ).**



**Figure 4.6: Estimated Marginal Mean ( $\pm$  SE) horizontal COM velocity (hCOMVel), across surface (engineered wood [EW], crumb rubber [CR]) and approach step (1-step, 2-step) conditions during the 180° COD. A significant surface  $\times$  step interaction was observed, with hCOMVel significantly greater in the 2-step compared to the 1-step condition on both CR and EW ( $p < 0.05$ ).**



**Figure 4.7: Estimated Marginal Mean ( $\pm$  SE) Foot plantar flexion (FtPlantFlex; top left), foot eversion (FtEversion; top right), foot internal rotation (FtIntRot; bottom left) across surface and approach conditions. Values are shown for engineered wood (EW) and crumb rubber (CR) surfaces, as well as 1-step and 2-step approaches during the 180° COD. Statistically significant differences between conditions marked with bracket ( $p < 0.05$ ).**

## 5. DISCUSSION

The purpose of this study was to examine how turf infill type and reduced approach steps influence the shoe-surface interaction during a maximal 180° COD. We analyzed differences between CR and EW infill systems and evaluated how 1-step and 2-step approaches altered loading and movement mechanics. Specifically, we analyzed GRFs and traction behavior during the initial part of stance and both whole-body COM and foot kinematics at initial contact. Overall, the results partially support our hypotheses, with several variables showing clear sensitivity to infill type and approach condition, while others demonstrated smaller or no effects.

### 5.1 Surface

#### *5.1.1 Surface alters movement mechanics*

Lean angle and horizontal COM velocity angle at initial contact differed between surfaces. Lean angle was slightly greater on EW compared to CR. These increases in lean angle may reflect participants making a subtle adjustment toward a more aggressive COD posture on EW, likely due to the perceived increase in traction and surface stability. Horizontal COM velocity angle was smaller on EW, suggesting subjects redirected their COM earlier on CR, which may be a sign of reduced traction as subjects could be trying to turn more before landing with the final cut step. However, with both of them only being a 2° difference or less, it isn't clear if these were meaningful changes.

Foot orientation at initial contact was also affected by surface differences. The foot was slightly more everted on CR and more plantar flexed on EW. However, again the differences were small (<1°) and likely not biologically meaningful on their own, but when combined with the subtle adjustments in COM posture they align with previous research suggesting that athletes

land with a slightly different COD mechanics depending on the perceived traction of the surface (Frias Bocanegra & Fong, 2022; Luo & Stefanyshyn, 2011). Overall, with the limited number of approach steps it was not anticipated that there would be differences between surfaces at initial contact. The presence of small but consistent differences therefore partially contrasts with our initial hypothesis. In this case the initial foot orientation on CR may influence how the studs engage with the infill during early stance, possibly allowing a larger number of cleats to engage with the infill in an attempt to gain traction.

### *5.1.2 Initial toe displacement is greater on CR*

The reduced horizontal toe displacement observed on EW may be attributed to the greater rotational and horizontal stiffness of the EW system documented in mechanical tests (McGowan et al., 2024, 2025). On stiffer surfaces, there is less infill compression which results in earlier stud engagement and greater resistance to horizontal motion, constraining horizontal toe displacement during the COD. Horizontal toe displacement and horizontal foot velocity at initial contact were significantly greater on CR, likely because CR is a more compliant surface which allowed for greater infill compression prior to full stud engagement (Sombatsompop, 1999). Despite the differences in horizontal toe displacement, horizontal foot velocity, GRFs, and GRF loading rates, the time it took for the toe to reach minimum velocity did not differ between surfaces. This suggests that EW reduced the magnitude of horizontal toe displacement without shortening the time it took for the toe to reach minimum velocity. In other words, the EW surface limited horizontal displacement, but it did not appear to arrest foot motion more quickly.

Participant perceptions were consistent with these mechanical findings, with many reporting greater “stability” and less “sliding” on EW relative to CR. Although these perceptual differences align with the reduced horizontal toe displacement observed on EW, the implications

of altered initial toe displacement for injury risk during COD remain unclear, especially considering that toe displacement was not halted sooner. Excessive rotational traction has been described as contributing to a “foot lock” mechanism, where the limited ability of the foot to slip may increase torsional loads to the knee (Shorten et al., 2003; Wannop et al., 2010). However, because the time it took for the toe to reach a minimum velocity did not differ between surfaces, there is no evidence that earlier fixation or excessive foot lock occurred on EW. In conclusion, while perceived stability increased, the mechanical data did not suggest a heightened locking response that could elevate injury risk.

### *5.1.3 Ground reaction forces and loading rates are higher on EW*

All GRFs and their corresponding loading rates were significantly higher on EW compared with CR, with peak vertical and horizontal GRFs 0.14 BWT and 0.09 BWT greater on EW, respectively, and average vertical GRF loading rate and average horizontal GRF loading rate 0.12 Log BWT/sec and 0.10 Log BWT/sec higher. These differences are consistent with the greater stiffness of the EW system documented with mechanical testing (McGowan et al., 2024, 2025) and our observed reduction in horizontal toe displacement, which likely reduces energy absorption at the shoe-surface interface and increases the magnitude of impact forces transmitted to the athlete.

From a performance perspective, higher GRF magnitudes may increase an athlete’s ability to start, stop, and change direction quickly. However, increased GRFs also elevate mechanical demands on the lower extremity during braking by increasing joint moments at the knee and ankle (Dos’Santos, Thomas, McBurnie, et al., 2021a; H. Jones et al., 2023). At the knee, increased horizontal GRFs are associated with greater shear forces, which may elevate ACL strain during COD tasks. Higher vertical GRFs increase overall knee joint loading and

quadriceps demand, both of which have been implicated in non-contact ACL injury mechanisms (Lin et al., 2025). At the ankle, excessive horizontal GRFs may increase inversion moments, particularly when the foot is constrained by the surface and does not have the ability to slide (Chin et al., 2021; Kristianslund et al., 2011). Importantly, although GRFs and loading rates were higher on EW, the magnitude of these differences was modest, and it remains unclear whether such changes meaningfully alter injury risk at the knee or ankle during COD.

Despite larger GRFs on EW, there was no difference in any traction variables. Because traction metrics were calculated as ratios of horizontal GRF (LCOT) or VFM (RCOT) to vertical GRF, proportional increases in both would result in similar traction values. Higher vertical GRFs are needed to maintain traction when higher horizontal GRFs or VFM are produced, which seems to be happening linearly with the EW.

Participant feedback aligned with the mechanical behavior observed. In this study, 67% of the participants favored EW over CR, citing greater confidence in traction, a more solid feel under foot, and overall preference for the surface. Despite no statistically significant differences in traction metrics, the participants consistently perceived EW as the superior surface in this regard.

#### *5.1.4 Surface traction properties may be specific to approach*

While no significant main effect was observed for LCOT, RCOT or VFM, a significant Surface x Approach interaction was observed for the VFM, indicating that rotational resistance is influenced by the combination of surface and approach. Pairwise comparisons revealed that CR produced a significantly larger VFM than the EW surface during the 2-step approach. Early mechanical investigations similarly reported that linear and rotational traction characteristics do

not scale proportionally across surface, with shoe–surface interactions differing depending on turf construction and infill composition (Shorten et al., 2003).

Mechanical traction testing using an automated rotational traction tester has shown that EW produces greater torque under increasing normal loads compared to CR (McGowan et al., 2024). Based on these findings, higher VFMs might be expected on EW due to its higher normal forces. However, the opposite pattern was observed during in vivo testing. Within CR alone, the 2-step approach generated a higher VFM compared to the 1-step approach. This may reflect the viscoelastic nature of CR, as infill materials with greater viscoelastic properties (CR) produce higher peak torques at higher rotational velocities, whereas less viscoelastic materials (EW) may not demonstrate the same velocity dependent torque amplification (McGowan et al., 2023).

From a biomechanical perspective, elevated VFM indicate increased resistance to foot rotation, which may increase torsional loads transferred to the knee during the COD tasks and is associated as a ACL injury mechanism (Yu & Garrett, 2007). Elevated rotational resistance may also increase torsional loading at the ankle. Excessive rotational traction has been shown to increase torsional loads at the ankle, and cadaveric studies have shown externally applied rotational torque can result in injury (Villwock, 2009). However, the in vivo relationship between VFM magnitude and ankle injury risk remains unclear.

## **5.2 Approach**

### *5.2.1 2-step approach is more aggressive*

During the 2-step approach, participants had greater horizontal COM velocity, while vertical COM velocity was faster during the 1-step. The addition of a penultimate step allowed participants to move 22% faster horizontally and lower their COM before contacting the force

plate adopting a more aggressive cutting posture prior to final foot contact. In contrast, without the penultimate step, vertical COM velocity at initial contact was 25% faster. This notion of a more aggressive strategy is supported by the 2-step producing a significantly larger (more aggressive) lean angle. During the 2-step, participants also appeared to limit the amount of turning done on the penultimate step as seen by a slightly smaller (more negative) horizontal COM velocity angle at initial contact. Participants likely used the additional step to gain horizontal and vertical momentum and not execute the COD. Although the difference in horizontal COM velocity angle was only 3°, it suggests athletes were at least attempting to get further into the turn during the 1-step approach.

The velocities achieved at initial contact were comparable to or exceed those reported in previous 180° COD studies. Dos'Santos et al. (2021b) reported horizontal COM velocities of  $2.70 \pm 0.34$  m/s in multidirectional sport athletes performing 180° CODs, while Zou et al. (2024) reported  $2.60 \pm 0.26$  m/s for anticipated and  $2.38 \pm 0.22$  m/s for unanticipated 180° CODs in female athletes. In the current study, the 1-step approach resulted in a horizontal velocity of  $2.20 \pm .07$  m/s, closely matching unanticipated trials, whereas the 2-step approach reached velocities of  $2.70 \pm .07$  m/s, exceeding unanticipated values.

The majority of participants (81%) anecdotally stated that they preferred the 2-step over the 1-step. Participants stated they felt the 2-step approach was faster, more repeatable, comfortable, aggressive, powerful and natural. Only 1 participant preferred the 1-step and 3 participants had no preference. Those who had no preference noted the 2-step was faster but felt slower out of the COD because of the greater momentum.

It is well established that the braking demands of a COD are distributed across the antepenultimate, penultimate, and final foot contacts when multiple steps are utilized

(Dos'Santos, Thomas, et al., 2019). Despite the reduction of approach steps, during the 2-step approach participants were able to achieve similar velocities at initial contact similar to comparable anticipated trials, while the 1-step closely reflected velocities observed during unanticipated 180° CODs. However, the influence of anticipation on performance with reduced approach steps remains unknown and warrants investigation in future studies.

### *5.2.2 Approach effects foot position*

Approach condition revealed differences in foot orientation and velocity at initial contact. During the 2-step approach, the foot was significantly more internally rotated, whereas the 1-step approach produced a more plantar flexed and everted foot orientation and a greater horizontal foot velocity. Using the 2-step approach, participants provided themselves with a greater opportunity to prepare the foot for the COD, as seen by a reduced horizontal foot velocity, and a more internally rotated foot oriented in the new direction of travel. Additionally, the increased lean angle necessitates a less everted foot to expose the studs of the cleat to the surface to maximize traction and gain engagement with the turf. In contrast, the less aggressive lean angle used during the 1-step approach results in a greater horizontal foot velocity, and a more everted foot posture at contact. Despite differences in foot orientation and COM velocity, vertical foot velocity did not differ between approaches, likely due to vertical adjustments being made at the COM, such as differences in the vertical COM velocity. This strategy could be a result of the final plant step being constrained by the targeting of a force plate.

Despite the increased momentum observed in the 2-step condition, participants did not adopt a more plantar flexed foot position at initial contact. During COD tasks, forefoot landings have been associated with reduced vertical loading rates compared to dorsiflexed rearfoot landings, potentially facilitating improved force attenuation during landing (Donnelly et al.,

2017). The 2-step approach resulted in a less plantar flexed position and therefore does not reflect loading strategies commonly associated with improved force attenuation during landing (Donnelly et al., 2017).

In the transverse plane, the 2-step approach resulted in greater internal rotation of the foot at initial contact. A more internally rotated foot position during COD has been associated with increased knee abduction and internal rotation moments, both of which are implicated in non-contact ACL injury mechanisms (Donelon et al., 2024). When combined with the elevated loading observed in the 2-step condition, this foot orientation may increase mechanical loading at the knee. While these adjustments in foot orientation may assist in managing increased momentum by attenuating larger forces, they may also alter loading at the knee.

### *5.2.3 2-step approach produces larger horizontal but not vertical forces*

The addition of a penultimate step allowed athletes to move faster and execute the COD more aggressively, resulting in a significant increase in Peak horizontal GRF as well as both average vertical GRF loading rate and average horizontal GRF loading rate. Because participants approached with greater horizontal momentum, they needed to generate higher forces to decelerate and complete the 180° COD as quickly as possible. Interestingly, although peak vertical GRF did not increase, average vertical GRF loading rate was significantly greater in the 2-step condition. This shows that vertical force was applied more rapidly rather than reaching a higher magnitude. The increase in peak horizontal GRF and not peak vertical GRF is likely due to the more aggressive lean angle directing greater force horizontally rather than vertically. Although peak vertical GRF magnitude did not differ, the increased vertical and horizontal loading rates observed in the 2-step approach may be relevant from an overuse injury perspective

though these studies have typically focused on running, not COD movements (Hreljac, 2004) and are heavily debated (Edwards, 2018).

The magnitude of the GRFs observed with reduced approach steps were comparable to those reported in 180° COD studies with longer approaches. P. Jones et al. (2014) reported peak vertical GRFs of  $2.31 \pm 0.57$  BWT for anticipated and  $2.74 \pm 0.52$  BWT for unanticipated 180° CODs. In the present study, peak vertical GRFs were  $2.48 \pm 0.08$  BWT for the 1-step and  $2.46 \pm 0.08$  BW for the 2-step approach. In addition, P. Jones et al. (2014) also reported peak horizontal GRFs of  $1.60 \pm 0.26$  BWT for anticipated and  $1.76 \pm 0.34$  BWT for unanticipated 180° CODs, while the 1-step and 2-step approaches in this study produced  $1.84 \pm 0.06$  BWT and  $1.97 \pm 0.06$  BWT, respectively. Notably, the 2-step approach increased horizontal GRF by 7.1%, compared to a 9.5% increase reported when switching to unanticipated trials (P. Jones et al., 2014). However, the vertical GRF increase was not replicated, P. Jones et al. (2014) observed a 17% increase between anticipated and unanticipated trials, whereas the difference between 1-step and 2-step approaches was -0.9%.

The current findings indicate that reducing approach steps replicates some, but not all loading characteristics associated with unanticipated 180° CODs. The reduction of approach steps reproduced the vertical GRFs similar to those reported for unanticipated 180° CODs, while horizontal GRFs were comparable to those observed in anticipated CODs in previous studies. Adding a penultimate step replicated the horizontal GRF increase seen in anticipated versus unanticipated trials but did not produce a corresponding increase in vertical GRFs. Unanticipated tasks typically elevate both horizontal and vertical demands due to last-moment posture adjustments (P. Jones et al., 2014), while in this study reduced approach steps elevated horizontal braking demands but did not produce the high-impact vertical forces seen in unanticipated

CODs. In conclusion, reduced approach steps mimic certain aspects of unanticipated cutting demands, but not the full loading profile. Future research should investigate how anticipation influences GRFs when approach steps are limited.

#### *5.2.4 2-step approach requires more linear traction*

The 2-step approach required 3% more LCOT than the 1-step approach. This modest increase was driven by higher peak horizontal GRF without a corresponding increase in peak vertical GRF, thereby elevating the horizontal-to-vertical force ratio and increasing traction demand at the shoe–surface interface to prevent slipping. The 2-step approach also produced a significantly greater horizontal toe displacement following initial contact, suggesting that additional approach momentum and greater peak horizontal GRF resulted in increased horizontal toe displacement before full stud engagement with the turf. The lack of an increase in the peak vertical GRF with the increased peak horizontal GRF most likely explains increased horizontal toe displacement. Despite the differences in horizontal toe displacement and peak horizontal GRF, there was no difference in the time it took for the toe to reach a minimum velocity. This shows that increased horizontal momentum was absorbed through greater displacement rather than a longer time, suggesting the time it takes for the toe to reach a minimum velocity may not scale linearly with horizontal GRF.

Although neither RCOT nor VFM were numerically greater during the 2-step approach, neither reached significance. The magnitude of the differences was small in relation to their standard errors (RCOT:  $0.0005 \pm 0.00038$  Nm/vGRF; VFM:  $0.0010 \pm 0.001$  BWT/m). This shows considerable variability in rotational traction responses across participants. Given the sensitivity of the two rotational traction variables to foot orientation and loading, the ability to detect significant differences across approaches is limited.

Given the comparable approach velocities and GRF magnitudes between conditions, the 2-step approach may provide a more appropriate in vivo framework for examining surface traction characteristics. The observed increase in LCOT, combined with consistent participant reports of greater perceived traction, suggests that the 2-step condition may offer a more ecologically valid assessment of shoe–surface interaction than the 1-step approach. However, effects of infill differences do not all appear to scale linearly, such as the VFM, and the influence of additional preparatory steps remains unclear.

### **5.3 Limitations**

Several limitations should be considered when interpreting the findings of this study. First, the investigation was limited to a 1-step and 2-step approach, and therefore the results cannot be entirely generalized to longer or more variable approach conditions that may occur during real sport COD tasks. Longer approach distances with variable approach steps may further influence shoe–surface interaction. We did not investigate longer approach distances out of caution for the participant’s safety. The force plates need to be isolated from the surrounding surface creating a small gap that could cause injury if accidentally landed on when planting their foot. There also might be enhanced targeting of the force plate when approaching from an increased distance that would alter their natural biomechanics and increase trial-to-trial variability. Furthermore, unlike a full-sized field install where the turf is not directly attached to the shock pad and base below it, the need to do this in the laboratory setting may have slightly decreased linear foot motion in all conditions.

Second, this study did not examine sex-based differences in COD mechanics or traction demands. While roughly equal numbers of both men and women participated in the study, we did not match for sport or cleats worn. Both could add differences that aren’t true sex-based

differences. Therefore, the present findings should not be used to evaluate potential differences between male and female athletes.

Third, this study aimed to investigate how surface and approach conditions influence the general shoe–surface interaction. In turn, the results are not intended to capture subtle differences across specific sports, movement strategies, or cleat designs. Differences in stud configuration, outsole geometry, and sport-specific cutting demands may meaningfully influence traction and were outside the scope of this study.

Finally, although ankle and knee biomechanics are highly relevant to both performance and injury risk during CODs and were discussed when correlations to our measures were available, they were not a primary focus of the present analysis. The current study emphasized shoe-surface interaction and traction-related metrics, with plans for detailed ankle and knee mechanics to be examined and reported separately.

## **5.4 Conclusion**

This novel study demonstrates that both turf infill type and the reduction of approach steps meaningfully influence shoe-surface mechanics during a maximal 180° COD task. The EW infill produced higher GRFs and loading rates than CR, consistent with its stiffer mechanical profile documented from mechanical testing. These loading differences were accompanied by reduced horizontal toe displacement and horizontal foot velocity, and participant reports of greater stability and traction on the EW surface, suggesting earlier stud engagement and increased resistance to horizontal motion during early stance, though it did not ‘lock’ the foot with the time it took for the toe to reach a minimum velocity being similar on both surfaces. Participants appeared to utilize this perceived increase in traction, by performing the COD more

aggressively on EW than CR as reflected by a greater lean angle and lower horizontal COM velocity angle.

Approach strategy altered foot and COM orientation at initial contact and how traction was utilized. The 2-step approach was more aggressive as seen by a greater lean angle and increased horizontal COM velocity. The modified technique resulted in larger peak horizontal GRF and average horizontal GRF loading rate and average vertical GRF loading rate without a corresponding increase in peak vertical GRF, elevating LCOT and resulting in greater horizontal toe displacement. These findings indicate that approach mechanics meaningfully influence shoe-surface interaction through changes in force application, magnitude and foot orientation, which is reinforced by participant testimony of the 2-step feeling faster and more comfortable. In addition, the reduction of approach steps produced initial contact COM velocities and GRF magnitudes like that of similar CODs with longer lead-ins and the reduction of approach steps mimicked some features of an unanticipated COD such as an increase in horizontal GRFs in the 2-step condition.

The 2-step approach resulted in altered foot orientation at initial contact, including a less plantar flexed and more internally rotated foot position, suggesting adjustments in foot orientation to manage altered posture and increased momentum. While these technique modifications may be perceived as facilitating performance, they may also place increased loads on the ankle and knee particularly when combined with elevated loads and traction demands.

Although rotational traction has frequently been implicated in non-contact ACL injury risk, no statistically significant differences in RCOT nor VFM were observed between infill types or approach conditions. However, an interaction between surface x approach was seen in the VFM on CR, with the VFM being substantially greater during the 2-step approach. This

interaction suggests increased rotational loading at the shoe–surface interface during higher intensity CODs on CR, likely due to the rate dependent loading behavior of rubber materials. This finding is important because rotational loading transmitted through the foot has been linked to elevated knee and ankle joint injury during COD. These results indicate that lower GRFs and loading rates do not necessarily equate to reduced rotational traction, and that injury-relevant mechanics may emerge differently depending on surface properties, cleat design, and movement strategy.

This evidence highlights limitations of mechanical traction testing, which may not capture the dynamic relationship between athlete and surface observed during human movement. While mechanical testing remains valuable for characterizing material properties, human testing is necessary to evaluate how infill characteristics and approach conditions interact to influence the shoe-surface interaction.

From a practical perspective, EW may enhance perceived stability and performance during COD tasks, but at the cost of increased loading rates and GRFs. Conversely, CR may reduce GRFs and permit greater horizontal toe displacement but may expose athletes to higher rotational loading during higher intensity CODs, as reflected by elevated VFM. Finally, EW may reduce foot motion while also avoiding abrupt foot fixation, evident in similar time before the toe reached a minimum velocity between surfaces. This may be beneficial for allowing controlled release of the foot, reducing excessive translational loading that can occur when the foot becomes constrained under high traction conditions.

This study helps refine experimental design choices, specifically when selecting how many approach steps to employ when studying surface effects or more general movements with

COD. Our findings highlight the need to further investigate the influence of approach steps and infill type on lower limb biomechanics to optimize athlete performance and safety on AT.

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