Kelsey A. Reeves. KINETIC AND KINEMATIC ANALYSIS OF THE PHASES OF KICKING DURING ACCURATE AND MAXIMAL EFFORT CONDITIONS IN FEMALE SOCCER PLAYERS. (Under the direction of Patrick Rider, MS.) Department of Kinesiology, December 2019

Soccer is one of the most popular sports in the world and the substantial increase in participation over the last decade adds significance to understanding kicking mechanics as kicking is a key skill during a game. The biomechanics of soccer kicking have been widely investigated and there is a conventional belief that a tradeoff exists between speed and accuracy during kicking performance. However, the kinetics and kinematics of the kicking leg during the approach to the ball remain unclear and whether or not instep soccer kicks can be performed without a speed-accuracy tradeoff. The purpose of this study was to investigate the kinetic and kinematic differences between accurate and maximal effort soccer kicking in female soccer players.

Twenty female soccer players from the college club or varsity level performed three trials of an accurate kick and three trials of a maximal effort kick. Bilateral hip, knee and ankle joint angles and velocities and ground reaction forces (GRFs) of the kicking leg (KL) and plant leg (PL) were calculated. In addition, correlation coefficients were calculated between variables in each condition. During maximal effort kicking, players significantly increased peak hip, knee and ankle angles ($p = 0.000$, $p = 0.000$, $p = 0.034$), angular velocities ($p = 0.000$, $p = 0.000$, $p = 0.004$), and foot velocity ($p = 0.000$) in the KL. This was likely the result of the significant increase in peak horizontal GRF in the KL ($p = 0.000$) and PL ($p = 0.000$). Peak horizontal GRF in the KL had the strongest correlation with foot linear velocity in accurate kicking ($R = 0.77^*$) compared to in maximal effort kicking ($R = 60^*$), and had a stronger influence on foot velocity compared to peak horizontal GRF in the PL in both accurate ($R = 0.31^*$) and maximal effort (0.23) conditions. This suggests that peak horizontal GRF in the KL, rather than in the PL, plays

a more important role in kick velocity, especially when kicking accurately. Results indicate that increasing horizontal GRF in the KL in both conditions is key to improving velocity since that variable is highly correlated in each condition. In addition, less variation of horizontal GRFs in the KL in maximal effort kicking indicate faster kicks result in more consistent foot velocities and suggests that players reduce variability as they approach maximum velocity. These results provide evidence that accuracy may not have to be sacrificed when kicks are faster if players practice accurate performances when kicking with maximum velocity due to the less variability in the initial programmed pattern of movement during fast performances. Coaches and trainers may utilize these results to develop training protocols that involve increasing GRFs of the KL and practicing kicks that are both accurate and fast to increase overall accuracy during maximum velocity instep soccer kicks.

KINETIC AND KINEMATIC ANALYSIS OF THE PHASES OF KICKING DURING ACCURATE AND MAXIMAL EFFORT CONDITIONS IN FEMALE SOCCER PLAYERS

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CHAPTER I. INTRODUCTION

Soccer is one of the most popular sports in the world. Female participation has increased substantially, with a 54% increase in registered female soccer players worldwide from 2000 to 2006 (Kunz, 2007). With the rise in female participation, researchers have taken an interest in understanding the mechanics of female athletes. More specifically, this increase in female participation adds significance to understanding soccer kicking mechanics as kicking is a key skill during a game. The instep soccer kick is an important variation of the kicking skill in soccer, as it is the most commonly used technique when attempting to score a goal or target a pass to a teammate. During instep kicking, a player performs a series of motions that involve an initial approach to the ball, planting of the support leg next to the ball, and striking the ball with the kicking foot (Barfield, Kirkendall, and YU, 2002; Isokawa and Lees, 1988). While performing an instep kick, a player may prioritize accuracy or velocity to accomplish critical tasks during a match, such as scoring a goal. Therefore, accuracy and velocity are the two most commonly investigated traits of an instep soccer kick.

When comparing accuracy and velocity, instep kicking analyses in soccer have shown that differences exist between kicking accurately and kicking with maximal effort (i.e., trying to maximize ball velocity). According to Fitts law (1954), there is a tradeoff between speed and accuracy represented by a logarithmic relationship, meaning the level of accuracy starts to level off as speed increases. Nonetheless, Fitts law describes the conventional belief of the speed-accuracy tradeoff in that accuracy decreases as speed of the movement increases and vice versa. When examining this relationship in soccer kicking, a clear tradeoff between speed and accuracy was shown by van den Tillar and Ulvik (2014) when using different types of instructions prioritizing speed or accuracy in experienced soccer players. This study showed that velocity decreases while prioritizing accuracy, which suggests that prioritizing accuracy will lead to another kicking strategy. However, there is evidence that higher movement velocities may lead to higher accuracy. Through a series of experiments, Schmidt et al (1979) described how this tradeoff could be positively linear rather than logarithmic. They suggested that to achieve greater accuracy through reduced variability, the movement should be practiced fast. In addition to this idea, they also provide evidence for the generalized motor program (GMP), which is a notion that describes a pattern of movement or class of movements. According to Schmidt (1975), the GMP is thought to develop over practice and provides the basis for generating movement sequences within a class of movements that share the same invariant features, such as the relative timing or relative force. In other words, individuals may change the speed or force within their programmed pattern of movement, but the general pattern of movement will remain unchanged. For example, one may increase or decrease walking speed, but their walking pattern will stay the same. This idea coupled with the notion that individuals do not have a long enough reaction time to make feedback-based corrections during rapid movements, individuals therefore do not deviate from the initial programmed pattern of movement, resulting in no addition error in direction.

It is evident there are inconsistent ideas in the literature regarding the speed-accuracy tradeoff. Perhaps one reason for this inconsistency is the difference between the movement tasks performed in the Fitts and Schmidt et al experiments. Fitts law may only account for slower movements (> 500 milliseconds) while the principles described by Schmidt et al are relevant to rapid movements (< 500 milliseconds). Soccer kicking has been described as a fast, discrete movement (van den Tillaar & Ettema, 2003). Therefore, it is possible that the training principles described by Schmidt can be applied to a soccer kick. However, before training protocols can be effectively developed and prescribed, understanding mechanical techniques specific to kicking accuracy and velocity is critical in order to determine factors related to kick outcome. Biomechanical determinants and kinematic and kinetic characteristics of accurate and maximal effort kicking have been widely investigated to determine kick performance (Dichiera et al, 2006; Kawamoto et al, 2007; Clagg et al, 2009; van den Tillaar & Ulvik, 2014; Sinclair et al, 2017; Numone et al, 2018) as defined from plant foot heel strike to kicking foot ball contact. Most of these studies have failed to investigate the athlete's approach to the ball, which is an important aspect of performing a kick.

Kicking with accuracy depends on how fast the player approaches the ball (Hunter et al, 2018). To increase accuracy of a kick, the speed of the movement based on a percentage of the player's maximal effort will reduce. Hunter et al (2018) showed how a faster approach speed was usually less accurate and as the speed of the approach increased (i.e. as effort level increased) players performed less accurate kicks. Therefore, there appears to be an inverse relationship between approach speed and kicking accuracy. This reduction in approach speed when players aim to kick with accuracy has been associated with reduced ball velocities (Lees and Nolan, 2002; Sinclair et al, 2017; Numone et al, 2018), suggesting that when aiming to kick with accuracy players perform less powerful kicks. While approach speed is a highlighted kinematic factor of the approach that has clearly been shown to influence the outcome of a kick (Lees and Nolan, 2002; Hunter et al, 2018), kinetic factors, such as ground reaction forces, also play a key role in kick performance.

Kinetic analyses of the plant leg have been studied extensively to determine factors related to kick performance. The forces generated by the plant leg have been reported to be components that affect the resulting ball velocity and trajectory (Barfield, 1998; Harrison and

Mannering, 2007). While investigating ground reaction forces of the plant leg during maximal instep kicking, Orloff et al (2008) showed that higher peak braking forces under the support leg for females were associated with higher ball velocities providing support for a faster approach to load the plant leg. This indicates that stronger bracing of the plant leg exists about which the kicking leg can swing, thus assisting in developing greater kicking leg velocity and power.

Thus far, analyses of ground reaction forces have been limited to the plant leg as shown by previous studies. Ground reaction forces of the loading step (i.e., step before the plant step) should receive attention because a soccer kick involves an initial 2-4 step approach to the ball. Due to the lack in literature on this topic, investigating ground reaction forces of the loading step between accurate and maximal effort soccer kicking is necessary to help provide insight on how to improve performance of a kick. More specifically, little is known about the ground reaction forces in the loading step so investigating this missing piece of information may help provide a way to maximize both kicking accuracy and velocity, as well as help provide a clearer understanding of the speed-accuracy tradeoff in soccer kicking. Perhaps soccer kicking strategies exist in which players can use to increase kicking velocity while not having to sacrifice accuracy. Identifying mechanical factors that are common between the two kicking tasks could benefit coaches and trainers by providing insight on how to develop training protocols that are specific to improving these factors, thus helping to improve both accuracy and velocity of a kick. Examining ground reaction forces during the approach to the ball could provide insight to how these factors influence kick velocity in each kicking task.

Purpose

Evidence in the literature has shown that when kicking accurately, players sacrifice kicking velocity, and when players kick with high velocity, players sacrifice kicking accuracy. It is not ideal for players to sacrifice one skill for the other, as an optimal kick involves both velocity and accuracy. Therefore, the purpose of this study is to investigate selected kinetic and kinematic differences between accurate and high velocity kicking in female soccer players to 1) determine how the ground reaction forces during the approach influences kick performance, and 2) determine which mechanical factors are associated with ball velocity in each condition.

Delimitations

1) All participants were healthy without current lower extremity injuries that restricted kicking performance.
2) All participants were current female soccer players at the university club or varsity level, ages 18-25 years.
3) All participants were field players. No participants were goalkeepers.
4) The study design only examined instep kicking of a stationary ball.

Limitations

1) The testing environment was not similar to game-like situations.
2) The analysis was limited to the accuracy of the motion capture system and force plates.
3) Maximal effort kicking was not validated due to room size constraint.

CHAPTER II. REVIEW OF LITERATURE

With 250 million players participating in over 200 countries, soccer is considered one of the most popular sports in the world. It is a sport that is unique in that players cannot use their hands to control or manipulate the ball. Instead, players must kick the ball using their feet either to a teammate or in an attempt to score a goal. Because of soccer's growth and popularity worldwide, much research has been conducted on the biomechanics of soccer-specific movements, such as the instep kick. The instep soccer kick is considered one of the most crucial kicking techniques for success of a task (Kellis and Katis, 2007a; Lees and Nolan, 1998). During an instep soccer kick, the player performs a series of motions that involve an initial approach to the ball, planting of the support leg next to the ball, and striking the ball with the kicking foot (Barfield, Kirkendall, and YU, 2002; Isokawa and Lees, 1988). While many studies have examined the plant leg and swinging leg mechanics, little research has been conducted on the initial approach to the ball including which factors may influence the outcome of a kick. The outcome of a kick can be defined as the result or consequence of a player's chosen kicking technique.

As kicking is the defining action of soccer (Lees, Asai, Andersen, Numone, & Sterzing, 2010), many researchers have conducted biomechanical analyses on its kinetic and kinematic characteristics. During instep kicking, the plant leg orients the player to the ball and serves as an axis of rotation for the swinging leg (Barfield, 1998). Barfield et al. (2002) stated that the kicking process is caused by the "sequential transfer of momentum from proximal to distal body segments in the swing or kicking limb". Kinetic energy generates in the hip and is transferred to the foot where there is a proportional increase in foot speed (Kreighbaum and Barthels, 1996). Similarly, Dorge et al. (2002) describes a skillful soccer kick as an open kinetic chain where the kicking leg performs a “whip-like” movement towards the ball, suggesting that the movement is initiated at the hips and ends with the foot accelerating through contact with the ball. The motions of instep kicking are well-established throughout the literature. Therefore, it is evident that the position of the plant foot next to the ball, ground reaction forces generated from the plant leg, and the kicking leg swing motions are important components that determine performance of a kick (Barfield, 1998; Harrison and Mannering, 2007; Kellis et al., 2006; Katis and Kellis, 2010; Scurr et al., 2009). Because kicking is a vital skill in soccer, understanding its mechanics are critical for coaches and trainers to develop effective training strategies on how to optimize kick performance. Despite the depth of research in instep kicking, knowledge regarding common factors between accurate kicks and maximal effort kicks, as well as differences between both of these techniques, remain unexplored.

Accurate Kicking

Kicking with accuracy is known to be an effective kicking strategy during a soccer game as players must try to keep the ball out of reach of the opponent and the goalkeeper to score a goal. During a soccer game, players are required to decide on where to place the ball in order to avoid the hands of the goalkeeper by aiming either high, low, left, right, or a combination of any of these. It has been reported that kicking with accuracy also depends on how fast the player approaches the ball (Godik et al., 2003; Kellis and Katis, 2007). If players are instructed to kick with maximal effort, the kick is less accurate due to the faster approach speed. Hunter et al. (2018) supported this idea by showing a higher ball velocity was usually less accurate in both vertical and horizontal dimensions. This study also showed that increasing the speed from 18 to 30 m/s decreases the chance of placing the ball inside the goalpost from 90% to 76%. Similarly, Lees and Nolan (2002) found that ball velocity decreased to 75% of maximal ball velocity when executing an accurate kick. Therefore, it can be suggested that kicking accuracy decreases as velocity increases.

Differences in kinematic patterns were also shown between accurate kickers and inaccurate kickers. When players kick with accuracy, Dicheira et al (2006) showed that accurate kicks involve greater pelvic tilt and hip and knee flexion in both the support limb and kicking limb compared to inaccurate kickers during the period from support limb ground contact to kicking limb ball contact. Increasing support limb knee flexion lowers the center of gravity, thereby increasing stability of the body. It can be suggested that lowering the center of gravity and increasing stability contributes to increased kicking accuracy. Recent data from Sinclair et al (2017) supports this idea after examining knee angle during accurate kicking compared to maximal effort kicking, in which players demonstrated greater support limb knee flexion as a result of prioritizing accuracy. In addition to the analyses of joint angle from the time of support limb contact to kicking foot ball contact, muscle activation patterns during this phase have also been a key focus of attention among a wide range of studies.

In a study that investigated EMG muscle activity during accurate kicking, Scurr et al (2011) found significant differences in EMG activity when kicking towards targets high and low, and left and right. EMG values of 77% for the rectus femoris, 89% for the vastus lateralis, and 83% for the vastus medialis were identified during the contact phase of the kick (Scurr et al., 2011). These values are lower than previously reported by Dorge et al. (1999), however, Dorge et al analyzed maximum effort kicks. Additionally, Katis et al (2013) found that accurate kicks aiming at a top target showed higher tibialis anterior (TA) and biceps femoris (BF) activation and lower gastrocnemius (GAS) activation compared to inaccurate kicks, and accurate kicks aimed at a bottom target displayed a lower TA and rectus femoris (RF) activation compared to inaccurate kicks. These results suggest that the more activated the TA, the more dorsiflexed the ankle, thus enabling a higher trajectory of the ball.

In contrast, the more activated the GAS, the more plantarflexed the ankle, thus limiting the ability to lift the ball off the ground and kick towards a high target. This study indicated that muscle activation patterns of the kicking leg represent one mechanism that influence the accuracy of a kick. However, only the kicking phase from support limb ground contact to initial ball contact was examined without taking into consideration the entire kicking movement, including ground contact of the kicking limb before ball contact. It is unclear what mechanisms exist prior to the swing phase that may influence these muscle activation patterns.

Kicking accuracy has been shown to depend on the location of foot-ball contact. Foot-ball contact can be known as the direction of applied force. If the ball is struck at the center, it would follow a near straight trajectory and gain the maximum possible velocity with minimal spin. If the force is applied at an angle relative to the desired target, then the ball will demonstrate a lower speed, a higher spin, and a longer and more curved path with a possible change in the final direction of the ball (Nunome et al., 2002; Carre et al., 2002). An accurate kick can be performed using either of these techniques. Teixeira et al. (1999) found that soccer kicks aimed at a defined target have longer duration and smaller ankle displacement and velocity compared with kicks performed towards an undefined target. This suggests that when a player is instructed to perform an accurate kick, then there is a reduction in ball speed, and the approach speed, joint rotation and velocities are lower compared to those during a powerful kick (Lees and Nolan, 1998; Kellis and Katis, 2007). However, it is unknown how much the ground reaction forces of the loading step impact these variables.

In a study that investigated 3D kinematic differences in rugby kicking, Sinclair et al (2017) found more ankle dorsiflexion and external rotation at ball contact when kicking for accuracy. This finding aligns with previous soccer-based analyses (Levanon and Dapena, 1998) which have documented similar findings in accurate kicks. To maximize kicking accuracy, Sinclair et al (2017) stated that participants may have used a more side-foot technique by externally rotating the ankle to ensure ball contact with the medial aspect of the foot. A recent study conducted by Hunter et al (2018) supported this idea by showing that side-foot kicking is used when there is a requirement for accuracy whereas faster or more powerful kicks require striking the ball with the top of the foot (laces). This relationship among kicking technique, speed and accuracy exemplifies the speed-accuracy tradeoff for a player attempting to kick with maximal effort, suggesting that a player can only achieve top speed by using a less-accurate technique.

Maximal Effort Kicking

A powerful kick is a very valuable tool in soccer. Research suggests that goals are scored from powerful kicks by surprising the goalkeeper with the velocity of the ball (van den Tillaar, R. and Ulvik, A., 2014), giving them less time to react, thus improving the player's chances of scoring. In addition, powerful kicks can be used to clear the ball away from a team's defensive zone which also aids in the importance of powerful kick. Whether scoring a goal or kicking for long-range, powerful kicks are a useful and important technique for soccer players to possess. It has been reported that players achieve top ball velocity by kicking the ball with the top of the foot (Hunter et al., 2018) because at foot-ball contact, powerful kickers keep the ankle joint locked and tightly plantarflexed so forces propelling the ball can be maximized (Chyzowych, 1978; Tsaousidis and Zatsiorsky, 1996). However, more plantarflexion of the ankle has been associated with less accurate kicks (Sinclair et al, 2017) suggesting that there is a tradeoff between speed and accuracy and indicates that players can only prioritize speed or accuracy and not both. Furthermore, maximal effort kicks have been found to be associated with higher ball velocities (Nunome et al, 2018), thus approach speed has been shown to affect ball velocity. Using the forward translation to their advantage, players produce a higher ball velocity when they approach the ball faster (De Witt and Hinrichs, 2012). Macmillan (1976) reported that approach speed (as indicated by linear hip velocity) had a strong influence on foot speed. This signifies that increasing speed of approach to the ball generates higher foot speeds resulting in higher ball velocities.

During a soccer match, many types of kicks are performed during different plays, including short passes, long passes, balls in flight and shots on goal. Thus, players are required to kick the ball with a wide range of velocities. Such kicking skills have received much interest from researchers to improve kicking performance. While examining segmental interactions of the kicking leg during soccer instep kicks at three different levels of submaximal effort, Numone et al (2018) found that the hip muscle moment and its forward angular impulses, as well as the knee muscle moment, were significantly increased with each effort level. These findings suggest that proportional adjustments are conducted at each segment during the kick and align with previous findings regarding the proximal to distal sequence found in soccer instep kicking.

In a study that compared instep kicking between male and female collegiate soccer players, Orloff et al (2008) found that females tend to lean away from the ball more than males which led to less ball speed. Thus, to kick harder players should be more over the ball with a more upright stance while kicking. Numone et al (2018) also suggested that the instep kick is a better strategy for maximal effort kicking as compared to the side-foot kick because instep kicking showed a higher ball-foot velocity ratio. Therefore, striking the ball with a more upright stance, more towards the center of the ball (less medial contact) and with the laces of the shoe aids in the performance of maximal effort kicks.

While comparing kinetics and kinematics of plant leg position during instep kicking, Orloff et al (2008) found no significant difference in plant leg position between males and females. However, females had significantly greater trunk lean, plant leg angle, and medial-lateral ground reaction force during kicking than males. Masuda et al (2005) examined the relationship between ball velocity, approach angle, and strength of the plant leg and found that ball velocity and strength of the plant leg correlated when kicking from a large approach angle. Isokawa and Lees (1998) and Masuda et al (2005) have shown that kicking with an increased approach angle results in increased ball velocity. These findings provide evidence that an off-axis kick may require increased strength and stability in the plant leg compared to a straighter approach leading to higher ball velocities.

Due to the importance of similar bilateral kicking ability during a soccer game, dominant and non-dominant limbs have been examined during maximal effort instep kicking and it has been reported that higher ball speeds are achieved when soccer players kick with their dominant limb (Isokawa and Lees, 1988; Mognoni et al., 1994; Dorge et al., 2002; Nunome et al., 2006). In addition, S.E. Clagg et al. (2009) found that approach condition, as well as plant leg dominance, influenced kicking strategy when planting with the dominant versus non-dominant leg. This indicates that higher ground reaction forces are placed on the plant leg as maximum velocity is generated, but it is unclear if this occurs as a result of the step before the plant step using greater ground reaction forces to load the plant leg in this way.

A wide range of studies exists on the kinetics and kinematics of the plant leg and kicking leg during the swing phase. However, none consider that an important part of the technique starts prior to plant leg contact, such as kicking foot ground contact and how its kinetics and kinematics in this phase of the approach set forth the following motions. Because a soccer kick typically involves an initial 2-3 step approach to the ball (Kellis and Katis, 2007), examining the ground reaction forces and kinematics of this initial phase is deemed important.

Previous research has shown that lower peak braking forces under the support leg were associated with higher ball velocities for female soccer players (Orloff et al., 2008). In contrast, Lees et al (2010) showed that higher braking forces and a stronger support leg can provide greater stabilization for the kick enabling larger forces to be developed during maximal effort kicks. Differences in braking forces of the plant leg were seen between Lees et al (2009) and Kellis et al (2004), where Lees et al showed braking forces to be wholly negative while Kellis et al showed a small positive force in the initial stages of plant leg ground contact. This difference may be due to the use of a one-step approach versus a multiple step approach to the ball indicating that factors involving the approach to the ball, specifically ground reaction forces, may affect kick performance.

The ground reaction forces of the plant leg have been reported for a maximal instep kick as 15-20, 4-6, and 5-6 $N \bullet kg^{-1}$ in the vertical, posterior (braking), and lateral (towards the non-kicking side) direction respectively (Kellis, Katis, & Gissis, 2004; Lees et al., 2009) but slightly higher values have been reported by Orloff et al (2008). All three studies showed that the horizontal forces are directed solely in the posterior and lateral directions. These force data suggest that the motion of the body is slowed during the kicking action. Lees et al (2010) reported that this slowing may have benefits for influencing the kicking leg action. However, little is known on what influences the plant leg action during the approach to the ball. To our knowledge, approach speed, approach angle and stride length are the only factors that have been examined and ground reaction force analyses have been limited to the plant leg. Therefore, we aim to examine the ground reaction forces associated with the loading step to better understand their role in instep soccer kicking.

Loading Step

In studies that have examined initial phases of instep soccer kicking (Clagg et al., 2009; Anderson & Dorge, 2011; Ali et al., 2012), approach speed, approach angle and stride length have been the primary variables investigated. The kicking leg ground reaction forces from kicking leg heel-strike to toe-off have received little consideration. When performing instep kicks, players prefer to use an approach distance that requires them to take a number (2-4) of steps (Lees et al., 2010). Because of this multiple step requirement for instep soccer kicks, kicking foot ground contact prior to plant foot ground contact is inevitably involved in kicking action. The only studies (Stoner and Ben-Sira, 1981; Lees and Nolan, 2002; Cockcroft and Van Den Heever, 2016) to report findings on the plant leg's loading step only investigated stride length, in which it was shown that a longer last step length leads to more a more powerful kick. When players kick long-range or with maximal effort, Stoner and Ben-Sira (1981) and Lees and Nolan (2002) showed that players use a longer last stride length compared to medium-range kicks or submaximal kicks. In addition, it is known that longer stride lengths are associated with increased impact forces during walking and running (Martin and Marsh, 1992). Therefore, research investigating ground reaction forces during the approach to the ball, specifically the step initiating the last stride, appears necessary to understand their role in kick performance.

A common issue of applied biomechanics in soccer is searching for performance indicators that help to achieve success in soccer kicking (Vieira et al., 2018). Ball velocity and accuracy are considered the main factors that contribute to a successful kicking outcome (van den Tillaar & Ulvik, 2014; Vieira et al., 2016). Being able to determine the differences between these two kicking strategies may help coaches and trainers tailor drills specific to the common factors that contribute to both accuracy and power. The ground reaction forces of the loading step during initial approach to the kick are unknown factors that may shed valuable insight into improving this technique and to our knowledge have not been examined. Therefore, evaluating the kinematic and kinetic characteristics of full motion instep kicking between accurate and maximal effort kicking techniques seems necessary to identify factors that can influence performance, thus providing new information for coaches and trainers on how to improve kicking ability.

Motor Control

A player is required to kick the ball with power, accuracy, or both depending on the game situation. Scoring a goal is considered a successful kick and the ultimate objective in soccer. It involves not only placing the ball inside the goal but also out of the goalkeeper's reach. Therefore, a combination of power and accuracy is ideal for goal scoring. Previous biomechanics research of soccer kicking appears to indicate a mandatory reduction in accuracy for an increase in power and vice versa. In the motor control literature, earlier studies have reported different tradeoffs between velocity and accuracy that apply to different movements and were based on different theoretical principles (Fitts, 1954; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979;

Plamondon & Alimi, 1997). For example, Fitts' law showed a logarithmic function between speed and accuracy, which Fitts based on principles of limited information processing capacity. Most studies that examined this relationship were performed on simple tasks, unlike the fast discrete tasks or movements used in sports such as throwing and kicking (van den Tillaar & Ettema, 2003). According to Fitts, fast movements and small targets result in greater error rates due to the speed-accuracy tradeoff. Additionally, as the speed of the movements increases, the accuracy of the movement decreases. Van den Tillaar & Etteman (2003, 2006) found that throwing velocity decreases when accuracy is more important and vice versa, while Bezodis et al (2007) confirmed the findings of Asami et al (1976) and Lees and Nolan (2002) by showing that ball velocity was decreased when accuracy was the sole aim of a kick. Therefore, we expect to find differences in kicking performance when instructed to perform an accurate kick versus when instructed to kick with maximal effort. More specifically, we expect to find that GRFs during the approach are greater in maximal effort kicking as compared to accurate kicking.

Many studies (e.g., Baumeister, 1984; Wulf, 2013; van den Tillar et al, 2014) have shown that the type of instruction influences the outcome of performance. For example, Baumeister (1984) showed that directing attention internally (to the motion of the body parts) led to worse performance than focusing attention externally (to the motion of the apparatus or object being controlled). Wulf (2013) showed that an external focus of attention is better to improve learning and performance because an internal focus of attention disrupts coordination and performance then suffers. In a study investigating the influence of instruction on kicking performance, van den Tillar et al (2014) showed significant effects of the type of instruction during soccer kicking. When there was no instruction on accuracy, ball velocity was significantly higher, and when the aim of the task was only to kick accurately, ball velocity was found to be significantly lower.

This study indicated that a tradeoff existed between velocity and task prioritization of accuracy which follows Fitts' law (1954) that suggested that one can only prioritize speed or accuracy and not both. However, while this speed-accuracy tradeoff has been well supported for over half a century, the evidence provided by Schmidt et al (1979) argues a way in which both speed and accuracy can coexist during a movement.

A widely accepted theory to account for Fitts's law was proposed by Crossman and Goodeve (1963) which emphasized the feedback control of movement. According to this idea, a movement is made up of a series of corrections each requiring a constant amount of time and having a constant relative accuracy. Movements with a longer distance, or aimed at smaller targets, require more movement time because there are more corrections required. Thus, movement time is determined by the number of corrections that an individual must make in achieving the target. In other words, the amount of error in achieving the target is dependent on how fast the movement is performed, which is determined by the number of corrections needed to make. However, Schmidt (1976) provided considerable evidence that contradicts this idea in that individuals have a difficult time processing feedback, meaning individuals require a much longer reaction time to make such corrections, as opposed to the Crossman-Goodeve theory.

Schmidt et al (1979) base their theory on the analysis of the motor-output variability in producing movement inaccuracy and the role of certain movement variables, such as movement distance and movement time. This theory suggests that during rapid movements, there is not enough time for individuals to make feedback-based corrections of the original pattern to achieve a target. When movement time is longer, feedback is possible. However, Schmidt et al (1979) showed that variability in the measure of accuracy is proportional to the variability in velocity, and the variability in velocity is proportional to the impulse variability of acceleration. This means that movement time is inversely proportional to impulse variability, thus the faster the movement is performed, the less variability in the initial programmed pattern of movement. Therefore, it is reasonable to suggest that if individuals practice a movement both fast and accurately, the accuracy of the movement should increase during fast performances. In support of this idea, making a movement more rapid would involve applying proportionally more force to each of the muscles for a shorter amount of time. Too much force in one muscle would be counteracted by a proportional amount of force in another, resulting in the movement having a straight pathway and no additional error in direction, thus increasing accuracy and achieving the target if the movement is practiced in this manner.

Evidence is clear that impulse variability is a major determiner of accuracy during fast movements. The experiments by Schmidt et al (1979) clearly show how errors are smaller with faster movement time, as shown by the decreased impulse variability. This has been observed before, but these results provide more formal evidence and a theoretical basis for it. A possible explanation for the difference in ideas regarding the speed-accuracy tradeoff between Fitts's law and Schmidt et al (1979) is that Fitts law might only account for slower movements, while the principles described by Schmidt et al (1979) are only relevant to rapid movements. However, it is still unclear whether relatively fast movements, such as a soccer kick, can be performed accurately when the speed of the movement is increased.

Summary

Many studies have attempted to explain the speed-accuracy tradeoff during human movement. In addition, the majority of literature regarding soccer kicking describes factors that are associated with speed and accuracy. However, most fail to perform kinetic and kinematic analysis with both goals to investigate which mechanical factors cause differences between these two kicking tasks. Because of the lack of kicking leg kinetics in maximal effort versus accurate soccer kicking in existing research, it would seem appropriate to investigate kinetic and kinematic factors that could cause these differences in kicking strategies. To our knowledge, no investigations have attempted to determine loading step ground reaction forces during the approach to the ball and how these mechanics may influence the outcome of the kick.

CHAPTER III. METHODS

Participants

Twenty-two soccer players were recruited to participate in this study from the club and varsity level but only twenty were kept for analysis due to data error. Participants were included if they were at least 18 years of age and a current, female, college-aged soccer player. Individuals were excluded if (1) their primary position was goalkeeper or (2) had any recent lower extremity injuries that prevented them from performing the tasks required in this study. Varsity-level players were cleared by athletic staff before performing the protocol. The protocol lasted approximately 30 minutes and consisted of each participant coming into the lab one time. Participant characteristics are shown in Table 1. All participants read and signed an informed consent which was approved by the Institution's Review Board.

Table 1. Participant Characteristics (Mean ± Standard Deviation). N = 20

Age (years)	19.9 ± 1.42
Height (m)	1.70 ± 0.06
Weight (kg)	62.2 ± 4.83
BMI (kg/m^2)	21.4 ± 1.32
Kicking Leg (R/L)	18/2
Time Playing (years)	14.3 ± 2.52
Total Exposure Time Per Week (min)	612 ± 311

Procedure

Prior to arriving in the lab, participants were instructed to wear a t-shirt, spandex or shorts, and their tennis shoes. When participants arrived in the lab, height and weight were measured and their body mass index (BMI) was calculated after obtaining university IRB approved informed consent. Each participant answered a brief questionnaire that asked for age, preferred kicking leg (dominant limb), preferred stance or support leg, playing position, years of soccer experience, previous injuries, training time per week, match time per week, and total exposure time per week (training time plus match time).

Figure 1. Marker placement on each participant during all kicking trials.

Kinematic data were collected at a sampling frequency of 250 Hz using a ten-camera 3D motion capture system (Opus 300+ Cameras, Qualisys, Goteborg, Sweden). Ground reaction force (GRF) data were collected at an analog sampling frequency of 1250 Hz using two force plates (AMTI, Newton, Massachusetts). Participants had 22 reflective markers attached bilaterally on their acromion processes, iliac crests, greater trochanters, anterior and posterior superior iliac spines, medial and lateral femoral epicondyles, medial and lateral malleoli, and first and fifth metatarsal heads (Figure 1). A central marker was placed on the jugular notch of the sternum, C7 vertebra, and umbilicus. On both legs of each participant, clusters of four markers were attached laterally on thighs and shanks, and clusters of three markers were attached on the back of the shoe so that participants were able to kick a soccer ball without marker interference.

Before data collection, the volume of recording space was calibrated. A static trial was captured with the participant standing still in anatomical position to establish the relative positions between the anatomical landmarks and tracking clusters. After the static trial, static markers were removed (iliac crests, greater trochanters, medial and lateral femoral condyles, medial and lateral malleoli, and first and fifth metatarsal heads) and participants were allowed to complete practice trials of the kicking tasks prior to beginning each testing condition. Before maximal effort kicking trials, participants were allowed to complete a self-selected number of warm up trials of 50%, 75%, and 90% of their maximal effort kicking. Before accurate kicking trials, participants were allowed a self-selected number of kicks to practice aiming and hitting a target placed on the net. The net was located approximately one meter in front of the participant and the target height was approximately 0.70 meters above the ground.

Participants completed two instep soccer kicking tasks: an accurate kick and a maximal effort kick. During the maximal effort kicking condition (see video for maximal effort condition), participants were instructed to kick a size 5 stationary ball as hard as they could. During the accurate kicking condition (see video for accurate condition), participants were instructed to solely aim and hit the target placed on the net. The distance from the ball to the target was approximately 1.22 meters. No instruction on effort level was given. For each condition, participants took a 2-step approach, with each step landing on a separate force plate and the second step being the plant step next to the ball. Measurements of maximal effort or accuracy were not recorded. Each condition was solely characterized by the type of instruction given. Ground reaction force data was collected for the plant leg as well as the kicking leg. Three successful trials of each condition were kept for analysis. A trial was successful if the participant landed with a foot on each force plate and the participant subjectively stated it was a good kick. The order of conditions was randomized.

Data Analysis

Kinematic and kinetic data was synchronized and processed using Qualisys Software (Qualisys, Goteborg, Sweden). A biomechanical model was created for each participant using the reflective markers placed on the participant during testing using Visual 3D Sofware (C-Motion, Germantown, Maryland). This model was scaled using the participant's height and weight and anatomical positions in the static calibration trial. Kinematic data was derived from the biomechanical model movements based on the 3D trajectory of the reflective markers. High-frequency error was removed using a low-pass filter with a cut-off frequency of 6 Hz for kinematic data, and a cut-off frequency of 45 Hz for kinetic data (Kuhman et al, 2018).

Joint angular velocity was defined as a vector that describes the relative angular velocity of one segment relative to another segment and was calculated using Visual 3D Software. In Visual 3D, joint angular velocity was expressed in Euler angles using the default Visual 3D convention of an XYZ sequence for the Cardan angle (C-Motion, Wiki Documention). Joint angle was defined as the orientation of one segment relative to another segment and was calculated as the transformation of the distal segment from the proximal segment using the local coordinate system of the proximal segment as the frame of reference (C-Motion, Wiki Documention). In Visual 3D, the proper Cardan sequence of rotations (x, y, z) was chosen based on the direction of travel (+y), where:

X = flexion/dorsiflexion (-), extension/plantarflexion (+)

Y = abduction (-), adduction (+)

Z = longitudinal rotation

Foot segment linear velocity was described as the velocity of the center of mass of the segment. From the filtered displacement data, foot linear velocity in the y direction was derived by finite difference computation:

$$\Delta y/\Delta t$$

where $\Delta y = y_{i+1} - y_i$, and Δt is the time between adjacent samples y_{i+1} and y_i (Winter, 2009).

Inverse dynamics using Newton's equations of motion were used to calculate torques in the hip, knee and ankle as the lower extremity was modeled as a rigid, linked system. The inverse dynamic analysis was applied to the kinematics of the biomechanical model and to the location, magnitude, and direction of externally applied forces (e.g., ground reaction forces acting on the foot). The ground and joint reaction forces were applied to the foot segment to determine individual torques from horizontal and vertical forces. The reaction forces and torque at the ankle were reversed and applied to the leg and the process repeated for knee forces and torque. Finally, knee kinetics were used to calculate the hip forces and torque. These calculations were performed using Visual 3D Software. All torque values were normalized to body weight (Nm/kg).

In Visual 3D (C-Motion, Wiki Documention), ground reaction force is represented by three vectors: force (F_x, F_y, F_z), center of pressure (COP_x, COP_y, COP_z), and free moment (FM_x, FM_y, FM_z). The analog signals collected from the force platform channels (F_x, F_y, F_z, M_x, M_y, M_z) are used to compute the force signals by pre-multiplying the analog signals by the force platforms' calibration matrix to convert the signals from volts to newtons. The force platform is supported by 4 tri-axial transducers, one located in each corner, where the coordinates of each transducer are (0, 0), (0, Y), (X, 0), and (X, Y), and where X and Y are the dimensions of the force platform. The force vector was equal to the intermediate force signals:

Force [X] = F_x (medial-lateral direction; right side (+) / left side (-))

Force [Y] = F_y (horizontal direction; propulsive (+) / braking (-))

Force [Z] = F_z (vertical direction (+))

The location of the center of pressure (COP) was determined by the relative vertical forces seen at each of the corner transducers. The vertical forces were designated as F_{00}, F_{X0}, F_{0Y}, and F_{XY} thus the total vertical force was $F_Z = F_{00} + F_{X0} + F_{0Y} + F_{XY}$. The COP was then computed as follows:

$$COPx = \frac{X}{2}[1 + \frac{(F_{X0} + F_{XY}) - (F_{00} + F_{0Y})}{F_Z}]$$

$$COPy = \frac{Y}{2}[1 + \frac{(F_{0Y} + F_{XY}) - (F_{00} + F_{X0})}{F_Z}]$$

where X and Y are the dimensions of the force platform and F_{00} is the origin (Winter, 2009). Finally, free moments FM_x and FM_y were assumed to be equal to zero and free moment FM_z was computed as follows:

$$FM_z = M_z - [(COPx * F_y) - (COPy * F_x)$$

All ground reaction forces were normalized to body weight (BW). Pearson's correlation coefficient was used to calculate the strength of association between variables in each condition using the following equation:

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}}$$

where r is the correlation coefficient, n is the number of subjects, $\sum x$ is the sum of variable x, $\sum y$ is the sum of variable y, and $\sum xy$ is the product of $\sum x$ and $\sum y$. Three trials were analyzed for each condition in each participant. Mean and standard deviation of each variable were calculated for all participants in each kick condition. Absolute values all of variables were used when calculating correlation coefficients.

The kinematic and kinetic variables of interest in both limbs were peak hip, knee and ankle joint angle, peak hip, knee and ankle joint angular velocity, peak hip flexor torque, knee extensor torque and ankle dorsiflexor torque, peak foot segment linear and medial-lateral velocity of the kicking foot, and peak vertical and horizontal ground reaction force of the loading step and plant step. The loading step (LS) is defined as the last stance phase of the kicking leg prior to ball contact or the step leading into the plant step (PS). The kicking leg (KL) is defined as the swing phase of the leg kicking the ball and the plant leg (PL) is defined as the support limb during KL swing phase.

Statistical Analysis

Data from three official trials for each experimental condition and each participant were averaged for analysis. A two-tailed, paired Student's t-test analysis was performed to evaluate the differences in the means of each variable between the maximal effort condition and accurate condition. To compare the means of each variable between conditions, the differences between all pairs of data were calculated and the t-test statistical value was calculated using the following equation:

$$t = \frac{m}{s/\sqrt{n}}$$

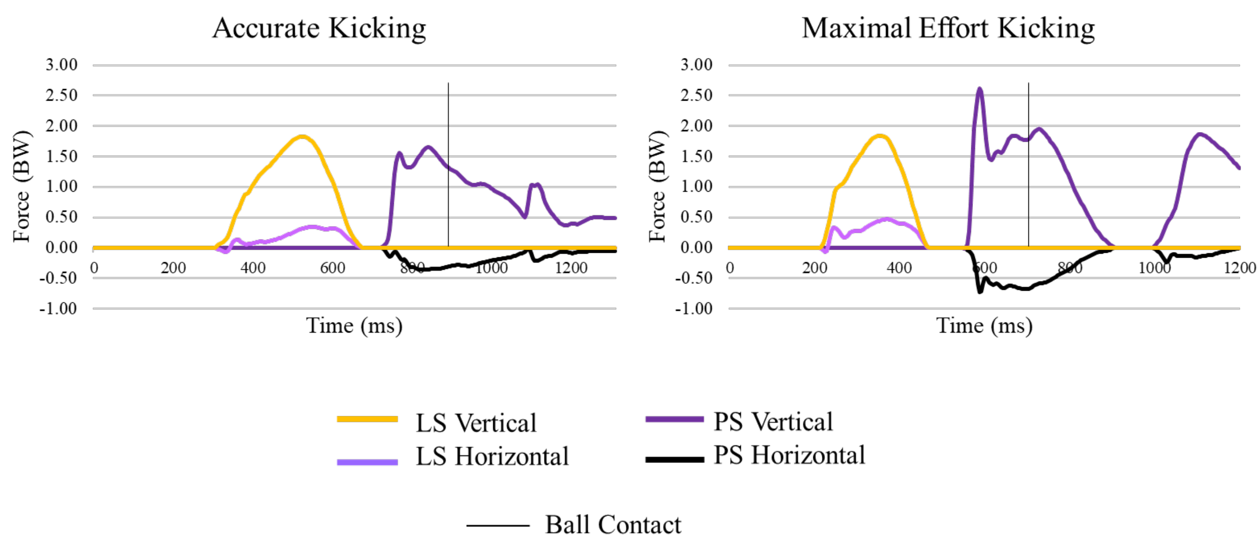
where m and s are the mean and standard deviation of the differences between all pairs of data and n is the sample size. Significance was established at $P \leq 0.05$.

CHAPTER IV. RESULTS

Ground Reaction Forces

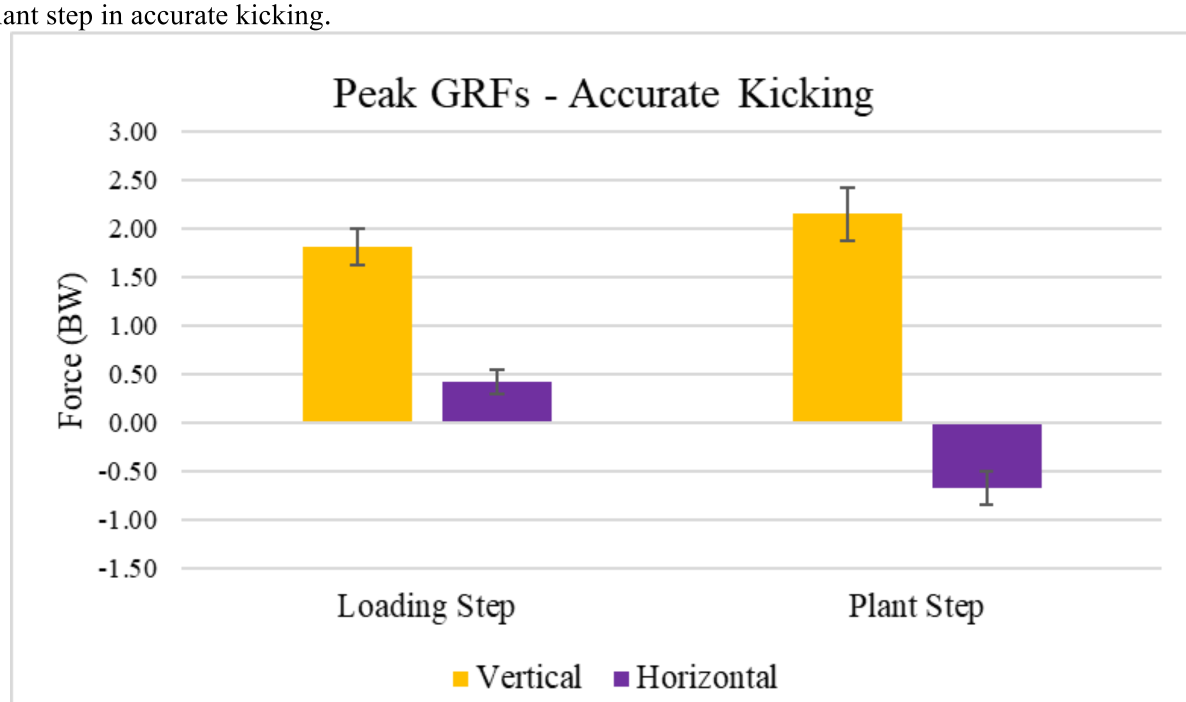
Higher peak ground reaction forces are shown during maximal effort kicking in one representative participant (Figure 2). As a result of the peak horizontal force in the loading step increasing from 0.34 BW to 0.47 BW in the maximal effort compared to the accurate kicking condition, there was a greater peak horizontal force in the plant step (-0.36 BW to -0.74 BW) in the maximal effort kicking condition representing a stronger braking force produced by the plant leg when kicking with maximal effort. The vertical ground reaction forces in the loading step between conditions were similar for the representative participant in Figure 5, and this pattern was consistent across all participants. The loading step spent more time in contact with the ground when kicking with accuracy compared to kicking with maximal effort, which may be the cause of the smaller peak vertical ground reaction force seen in the plant step during accurate kicking due to a slower movement time requiring less force.

Figure 2. Ground reaction forces (GRFs) during accurate and maximal effort kicking from one representative participant. LS Vertical = vertical GRF of the loading step; LS Horizontal = horizontal GRF of the loading step; PL Vertical = vertical GRF of the plant step; PL Horizontal = horizontal GRF of the plant step.



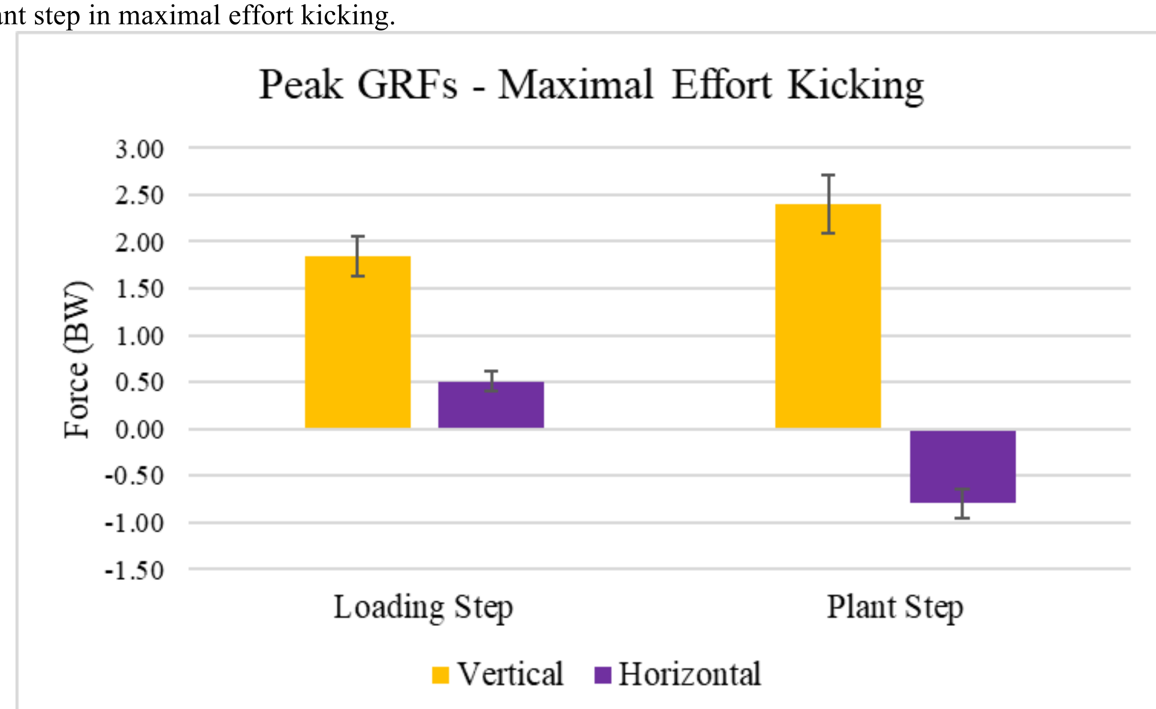
Ground reaction forces are reported as the mean (± S.D.) of the peak forces across all participants. In accurate kicking, peak vertical ground reaction force in the loading step was 1.81 ± 0.19 BW. The peak horizontal ground reaction force in the loading step was 0.42 ± 0.13 BW which was only 23% as large as the peak vertical ground reaction force (Figure 3). The peak vertical and horizontal ground force in the plant step was 2.16 ± 0.27 BW and -0.67 ± 0.17 BW, respectively (Figure 3). The negative horizontal ground reaction force represents the braking force in the plant step as the player is loading the kicking leg to kick the ball which is approximately one-third as large as the vertical ground reaction force.

Figure 3. Mean (± S.D.) of peak vertical and horizontal ground reaction forces of the loading step and plant step in accurate kicking.



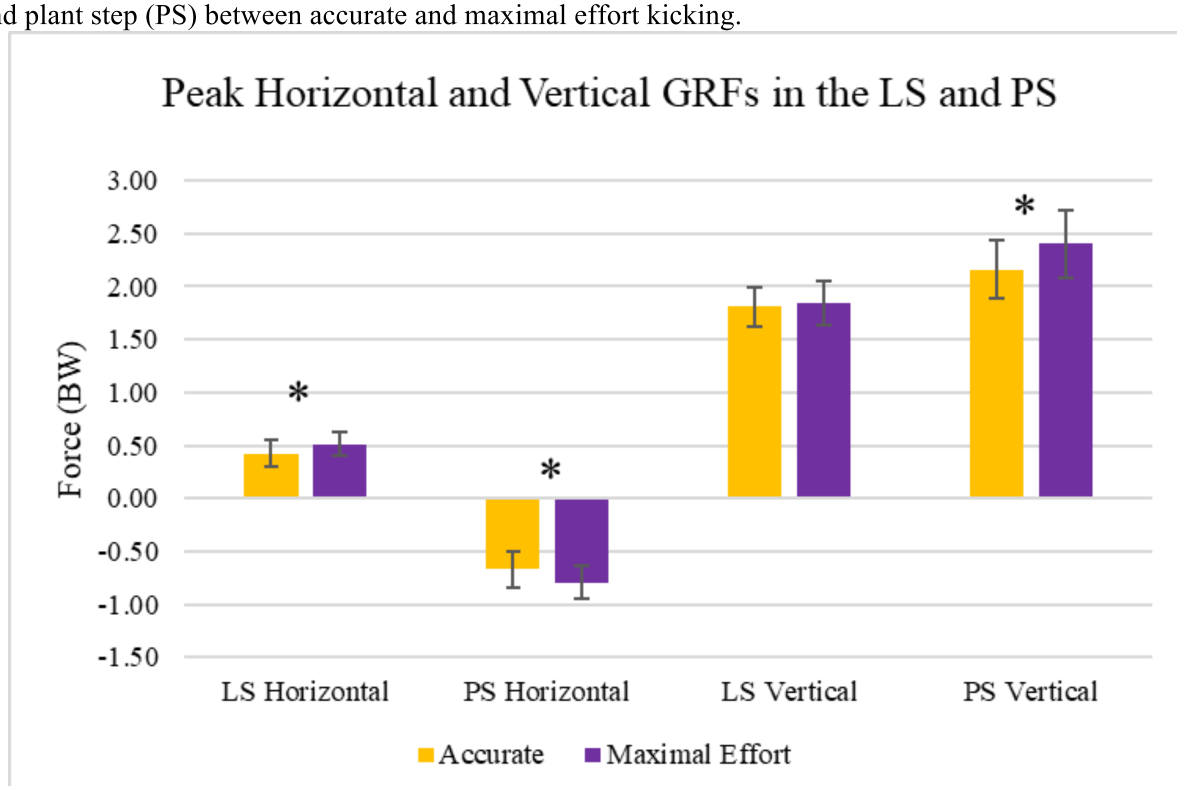
In maximal effort kicking, the peak vertical ground reaction force in the loading step was 1.84 ± 0.21 BW. The peak horizontal ground reaction force in the loading step was 0.51 ± 0.11 BW which was 28% as large as its vertical ground reaction force and 5% larger than in accurate kicking (Figure 4). The peak vertical and horizontal ground reaction forces in the plant step during maximal effort kicking were 2.40 ± 0.31 BW and -0.79 ± 0.15 BW, respectively (Figure 4). The horizontal (braking) force in the plant step during maximal effort kicking is one-third as large as its vertical ground reaction force, similar to that during accurate kicking which indicates that the vertical and horizontal ground reaction forces of the plant step increase proportionally during maximal effort kicking.

Figure 4. Mean (± S.D.) of peak vertical and horizontal ground reaction forces of the loading step and plant step in maximal effort kicking.



During maximal effort kicking (Figure 5), players significantly increased peak horizontal ground reaction force in the loading step (0.42 $\pm$ 0.13 BW vs. 0.51 $\pm$ 0.11 BW, $p < 0.001$) which represented a 21% increase, and plant step (-0.67 $\pm$ 0.17 BW vs. -0.79 $\pm$ 0.15 BW, $p < 0.001$) which represented an 18% increase. In addition, peak vertical ground reaction force in the plant step significantly increased (2.16 $\pm$ 0.27 BW vs. 2.40 $\pm$ 0.31 BW, $p < 0.001$) when kicking with maximal effort which represented an 11% increase. There was not a significant difference in peak vertical ground reaction force in the loading step between accurate and maximal effort kicking conditions (1.81 $\pm$ 0.19 BW vs. 1.84 $\pm$ 0.21 BW, $p = 0.157$).

Figure 5. Mean ($\pm$ S.D.) of peak horizontal and vertical ground reaction forces in the loading step (LS) and plant step (PS) between accurate and maximal effort kicking.



Correlations

In maximal effort kicking, horizontal ground reaction force of the loading step had strong significant associations with foot medial-lateral velocity (R = 0.75*) and foot linear velocity (R = 0.60*) (Figure 6). The horizontal (braking) force in the plant step showed a weak but significant correlation with foot medial-lateral velocity (R = 0.33*) but a weak and non-significant correlation with foot linear velocity (R = 0.23). In accurate kicking, horizontal ground reaction force of the loading step also showed strong significant associations with foot medial-lateral velocity (R = 0.74*) and foot linear velocity (R = 0.77*) (Figure 7). The plant step braking force showed significant correlations with foot velocity in both the linear (R = 0.31*) and medial-lateral (R = 0.33*) directions. The relationships between plant step braking force and foot velocities do not appear to be as strong as the relationships between loading step horizontal ground reaction force and foot velocities. In both limbs, the strength of these relationships are similar across kicking conditions, with the horizontal ground reaction produced by the loading step showing to be a better predictor of foot velocity, both in the linear and medial-lateral direction. Therefore, one might suggest that increasing loading step horizontal ground reaction force in both conditions is key to improving velocity since that variable is highly correlated in each condition.

Figure 6. Correlations between horizontal ground reaction forces (GRFs) and foot velocities in maximal effort kicking. Data points are the peak forces in all individual trials. LS hGRF = loading step horizontal ground reaction force; PS hGRF = plant step horizontal ground reaction force; M-L = medial-lateral.

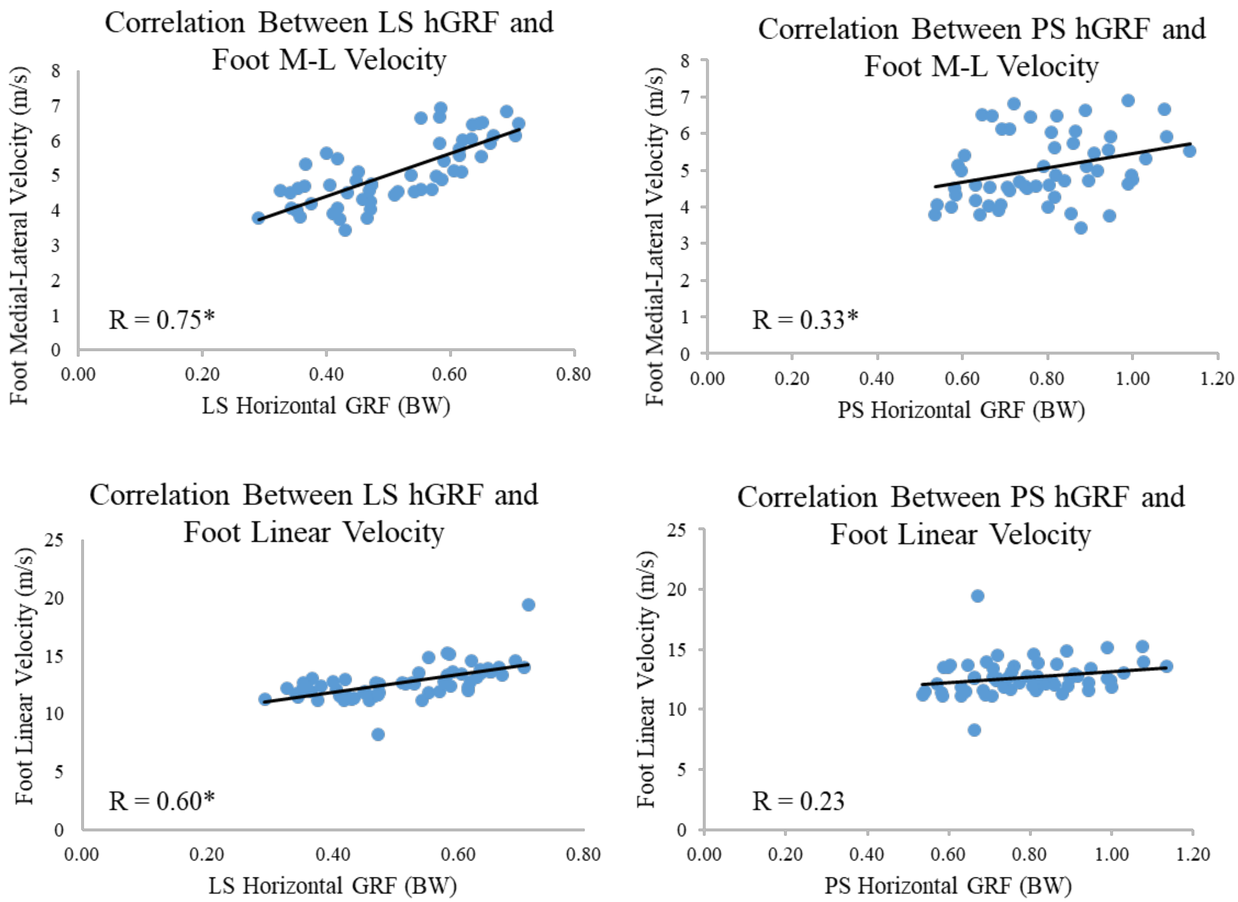
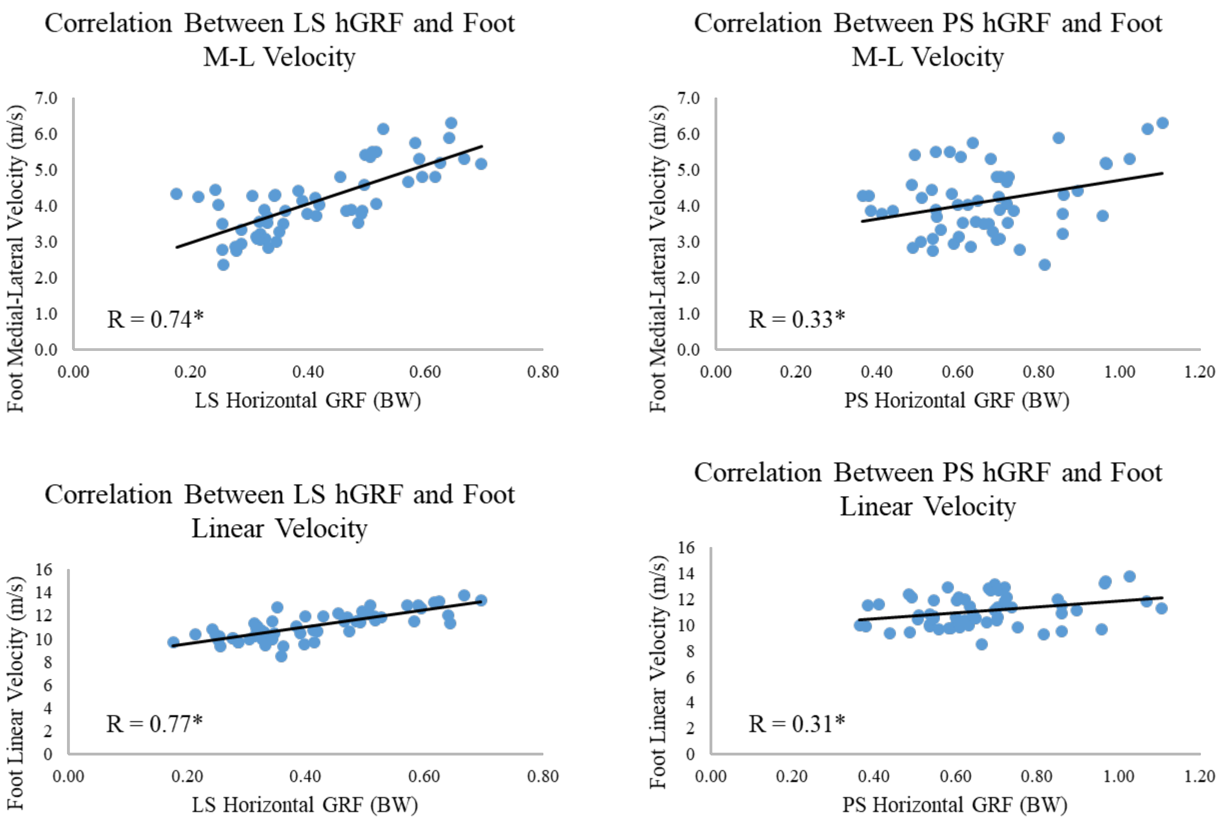


Figure 7. Correlations between horizontal ground reaction forces (GRFs) and foot velocities in accurate kicking. Data points are the peak forces all individual trials. LS hGRF = loading step horizontal ground reaction force; PS hGRF = plant step horizontal ground reaction force; M-L = medial-lateral.



In addition to kicking foot velocities during maximal effort kicking, horizontal ground reaction force of the loading step had significant correlations with hip angular velocity in the kicking leg (R = 0.34*), and knee angular velocity (R = 0.36*) and peak knee flexion (R = 0.33*) in the plant leg. In accurate kicking, loading step horizontal ground reaction force was significantly correlated with hip angular velocity of the kicking leg (R = 0.43*) and plant leg (R = 0.42*), knee angular velocity in the kicking leg (R = 0.62*) and plant leg (R = 0.61*), peak knee flexion of the plant leg (R = 0.35*), and horizontal (R = 0.41*) and vertical (R = 0.46*) ground reaction force in the plant step (Table 2).

Moderate yet significant correlations were seen with plant step horizontal ground reaction force and hip angular velocity in the kicking leg (R = 0.33*) and plant leg (R = 0.32*), plant leg ankle angular velocity in the plantarflexion direction (R = 0.54*), plant leg peak ankle dorsiflexion (R = -0.61*) and kicking leg ankle torque (R = -0.32*). These results reveal the influence of the braking force in the plant step during maximal effort kicking (Table 2). Plant step braking force during accurate kicking, however, was seen to have a greater amount of significant correlations including kicking leg hip angular velocity (R = 0.49*), plant leg hip torque (R = 0.32*), plant leg knee angular velocity (R = 0.55*) and torque (R = 0.36*), plant leg ankle angular velocity in the plantarflexion direction (R = 0.71*), plant leg peak ankle dorsiflexion (R = -0.66*), kicking leg foot linear velocity (R = 0.31*) and foot medial-lateral (R = 0.33*) velocity (Table 3).

In maximal effort kicking, vertical ground reaction force in the loading step was found to be significantly correlated with plant leg hip extension (R = 0.32*), hip torque in the kicking leg (R = 0.29*) and plant leg (R = 0.32*), knee angular velocity in the plant leg (R = 0.35*), kicking leg knee torque (R = 0.30*) and plant leg ankle angular velocity (R = 0.44*). In accurate kicking, vertical ground reaction force in the loading step was significantly correlated with hip extension in the kicking leg (R = 0.42*) and plant leg (R = 0.57*) and plant leg knee flexion (R = 0.31*).

Vertical ground reaction force in the plant step was found to have little influence on most outcome variables in the maximal effort condition with the exception of plant leg hip torque (R = 0.30*), kicking leg peak knee flexion (R = 0.39*) and plant leg ankle dorsiflexion (R = -0.27*). However, this was not the case in the accurate kicking condition. Plant step vertical ground reaction force was also found to have a greater amount of significant correlations with outcome variables in the accurate kicking condition including foot linear velocity (R = 0.40*) and foot medial-lateral velocity (R = 0.35*), whereas foot linear and medial-lateral velocities did not seem affected by plant step vertical ground reaction force when kicking with maximal effort (R = -0.12 and R = -0.17, respectively).

Table 2. Correlation coefficients between ground reaction forces and all outcome variables from plant step heel strike to ball contact in maximal effort kicking. *Indicates significance ($p \leq 0.05$)

	LS Horizontal	PS Horizontal	LS Vertical	PS Vertical
Hip Angular Velocity - KL	**0.34***	**0.33***	0.22	-0.05
Hip Angular Velocity - PL	0.21	**0.32***	0.16	0.14
Hip Extension – KL	-0.05	-0.19	**0.33***	0.02
Hip Extension – PL	-0.14	-0.09	0.22	0.21
Hip Torque – KL	0.02	0.13	**0.29***	0.23
Hip Torque – PL	0.02	0.12	**0.32***	**0.30***
Knee Angular Velocity – KL	0.20	0.09	0.15	0.14
Knee Angular Velocity – PL	**0.36***	0.18	**0.35***	0.03
Knee Flexion - KL	0.03	-0.15	-0.14	**-0.39***
Knee Flexion - PL	**0.33***	-0.23	0.07	-0.05
Knee Torque – KL	0.00	0.18	**0.30***	0.23
Knee Torque – PL	0.14	0.19	-0.13	0.22
Ankle Angular Velocity - KL	0.21	0.09	0.18	0.19
Ankle Angular Velocity – PL	0.19	**0.54***	**0.44***	-0.08
Ankle Dorsiflexion - KL	**-0.27***	0.12	-0.11	0.07
Ankle Dorsiflexion - PL	-0.12	**-0.61***	0.15	**-0.27***
Ankle Torque – KL	0.05	**-0.32***	0.21	0.07
Ankle Torque - PL	0.00	-0.13	-0.02	-0.12
Foot M-L Velocity – KL	**0.60***	**0.33***	0.14	-0.12
Foot Linear Velocity – KL	**0.75***	0.23	0.03	-0.17
Horizontal – LS		0.16	0.00	-0.03
Horizontal – PS	0.16		-0.19	**0.46***
Vertical – LS	-0.00	-0.19		0.21
Vertical – PS	-0.03	**0.46***	0.21	

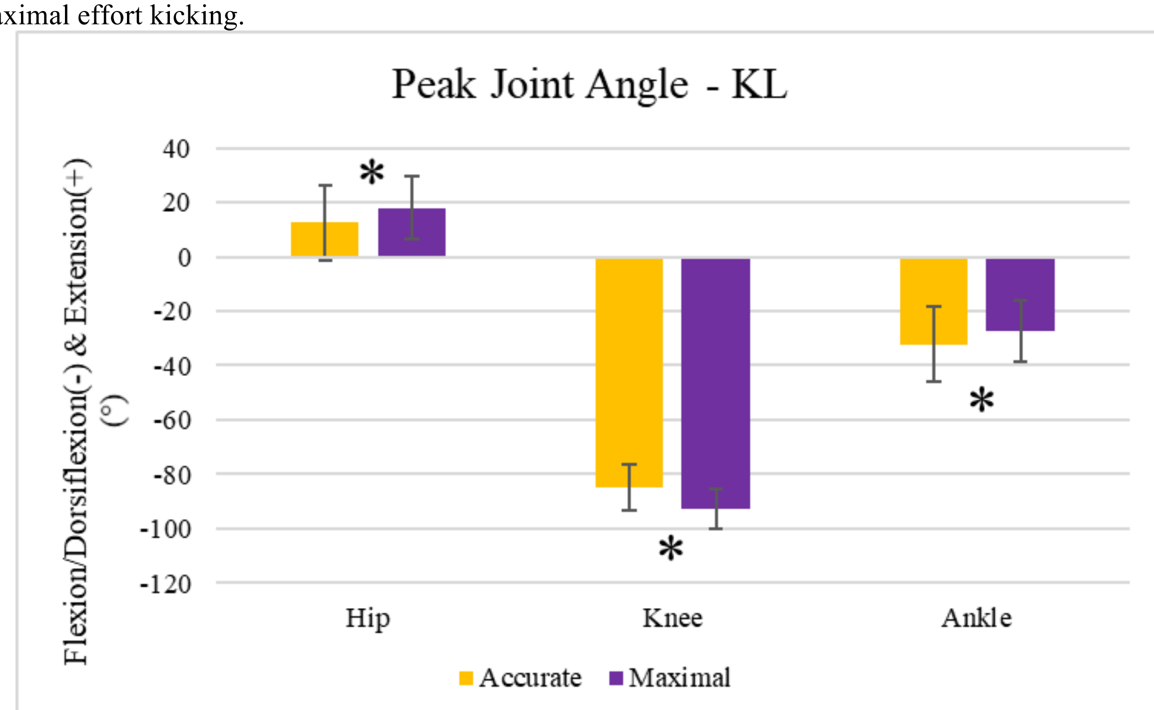
Table 3. Correlation coefficients between ground reaction forces and all outcome variables from plant step heel strike to ball contact in accurate kicking. *Indicates significance ($p \leq 0.05$)

	LS Horizontal	PS Horizontal	LS Vertical	PS Vertical
Hip Angular Velocity - KL	**0.43***	**0.49***	-0.00	**0.29***
Hip Angular Velocity - PL	**0.42***	0.00	0.12	0.07
Hip Extension – KL	0.21	0.00	**0.42***	0.06
Hip Extension – PL	0.03	-0.11	**0.57***	-0.00
Hip Torque – KL	0.19	-0.09	0.22	0.07
Hip Torque – PL	0.15	**0.32***	**0.31***	**0.36***
Knee Angular Velocity – KL	**0.62***	0.16	0.20	0.15
Knee Angular Velocity – PL	**0.61***	**0.55***	0.03	**0.50***
Knee Flexion - KL	-0.07	-0.18	-0.13	-0.16
Knee Flexion - PL	**0.35***	-0.02	**-0.31***	0.09
Knee Torque – KL	0.18	0.08	0.18	0.14
Knee Torque – PL	0.12	**0.36***	-0.09	0.21
Ankle Angular Velocity - KL	0.10	-0.04	-0.17	-0.17
Ankle Angular Velocity – PL	0.25	**0.71***	-0.25	**0.41***
Ankle Dorsiflexion - KL	-0.09	0.04	-0.05	0.07
Ankle Dorsiflexion - PL	-0.22	**-0.66***	0.22	**-0.35***
Ankle Torque – KL	0.15	-0.24	**0.37***	0.05
Ankle Torque - PL	-0.15	-0.23	**-0.36***	**-0.27***
Foot M-L Velocity – KL	**0.74***	**0.33***	0.00	**0.35***
Foot Linear Velocity – KL	**0.77***	**0.31***	0.02	**0.40***
Horizontal – LS		**0.41***	0.11	**0.46***
Horizontal – PS	**0.41***		0.15	**-0.63***
Vertical – LS	0.11	-0.15		0.16
Vertical – PS	**0.46***	**0.63***	0.16	

Kinematics

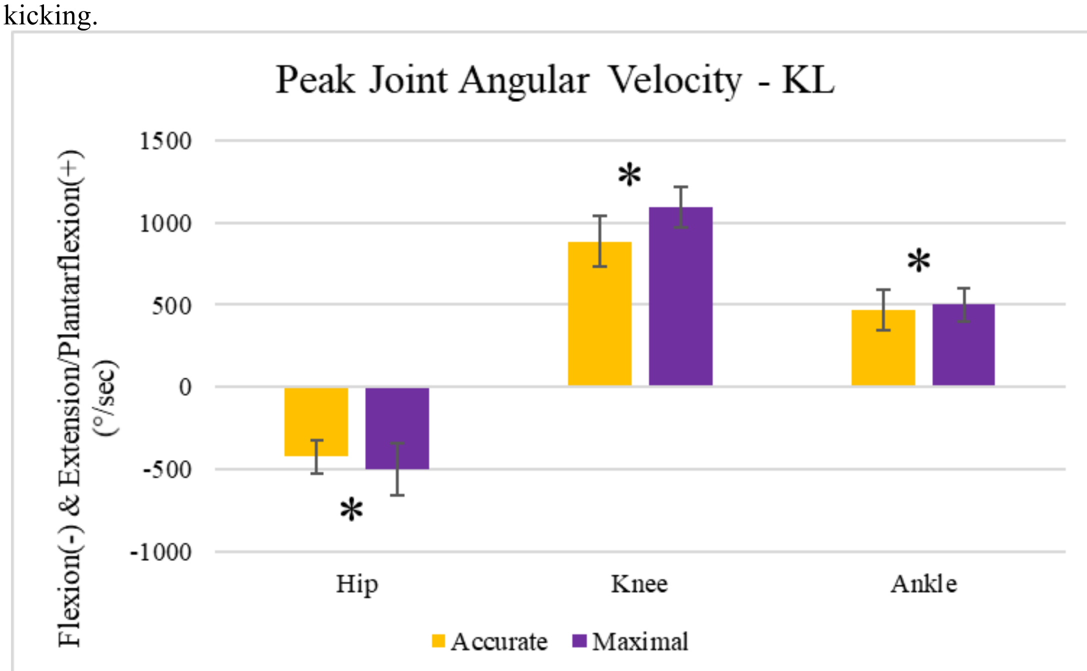
All kinematic data are reported as the mean (± S.D.) of the peak hip, knee and ankle angle or angular velocity across all participants. There was a significant increase in peak hip extension (13 ± 14° to 18 ± 11°), representing a 44% increase, and peak knee flexion (-85 ± 8° to -93 ± 7°), representing a 10% increase, and a significant 8% decrease in peak ankle dorsiflexion (-32 ± 15° vs. -27 ± 8°) of the kicking leg in the maximal effort kicking condition compared to the accurate kicking condition (Figure 8).

Figure 8. Mean (± S.D.) of peak hip, knee and ankle angle of the kicking leg between accurate and maximal effort kicking.



The significantly less ankle dorsiflexion when kicking with maximal effort indicates that players may have used greater plantarflexion to tightly lock the ankle joint and produce greater force on the ball. The significant increases in hip extension and knee flexion during maximal effort kicking were followed by significant increases in hip (-425 ± 104°/sec vs. -500 ± 155°/sec) and knee (886 ± 155°/sec vs. 1095 ± 126°/sec) angular velocities (Figure 9), representing an 18% and 24% increase, respectively. There was also a significant 8% increase in ankle angular velocity (466 ± 123°/sec vs. 502 ± 102°/sec) of the kicking leg during maximal effort kicking.

Figure 9. Mean (± S.D.) of peak joint angular velocities of the kicking leg between accurate and maximal effort kicking.



In the plant leg (Figure 10), there was a significant 4% increase in peak knee flexion (-88 $\pm$ 7 vs. -92 $\pm$ 8°) when kicking with maximal effort compared to kicking with accuracy. There were no significant differences in peak hip extension (-2 $\pm$ 13° vs. -1 $\pm$ 13°) or peak ankle dorsiflexion (-49 $\pm$ 9° vs. -47 $\pm$ 16°) in the plant leg between kick conditions, which were found to actually decrease (4% and 33%, respectively) during maximal effort kicking unlike the increase we saw in peak knee flexion (Figure 8). However, a significant difference was seen in hip angular velocity of the plant leg (-357 $\pm$ 70°/sec vs. -437 $\pm$ 179°/sec), which represented a 22% increase during maximal effort kicking (Figure 9). The significant 4% increase in peak knee flexion of the plant leg may have led to the significant increase in peak knee angular velocity (536 $\pm$ 68°/sec vs. 559 $\pm$ 88°/sec) that we saw during maximal effort kicking, which also represented a 4% increase (Figure 11). This may indicate that as players increase peak knee flexion when kicking with maximal effort, there is an equal increase in peak knee angular velocity in the plant leg. No significant differences were seen in peak ankle angular velocity in the plant leg between kick conditions (422 $\pm$ 105°/sec vs. 433 $\pm$ 121°/sec), which only differed by 3%.

Figure 10. Mean (± S.D.) of peak hip, knee and ankle angle of the plant leg between accurate and maximal effort kicking.

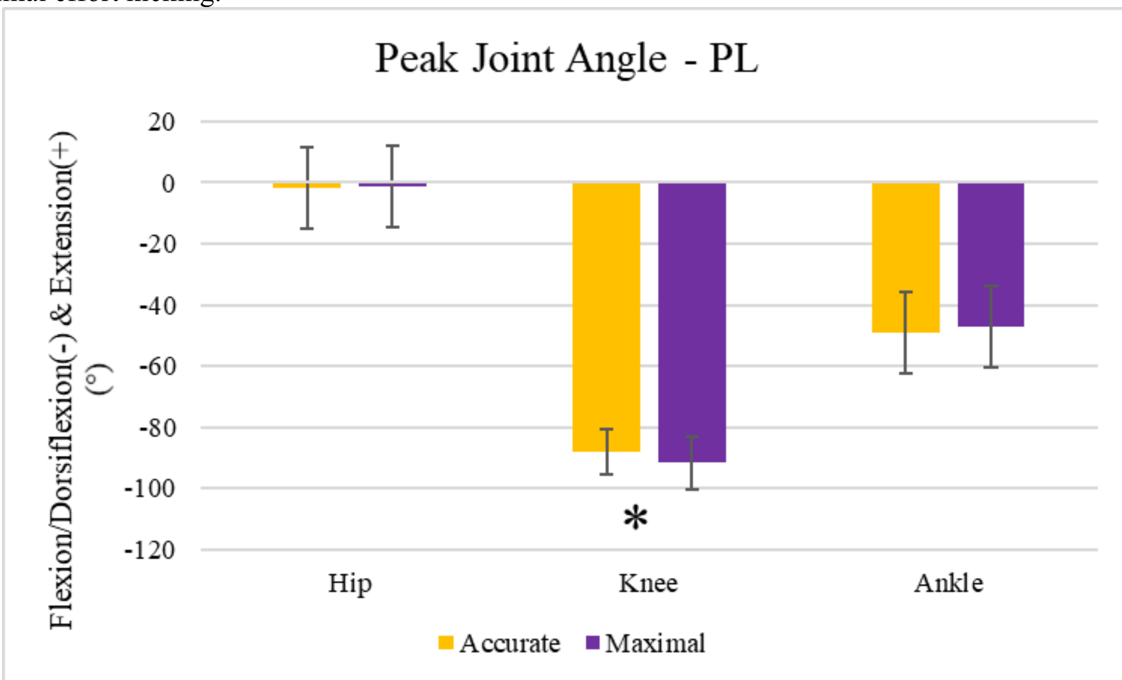
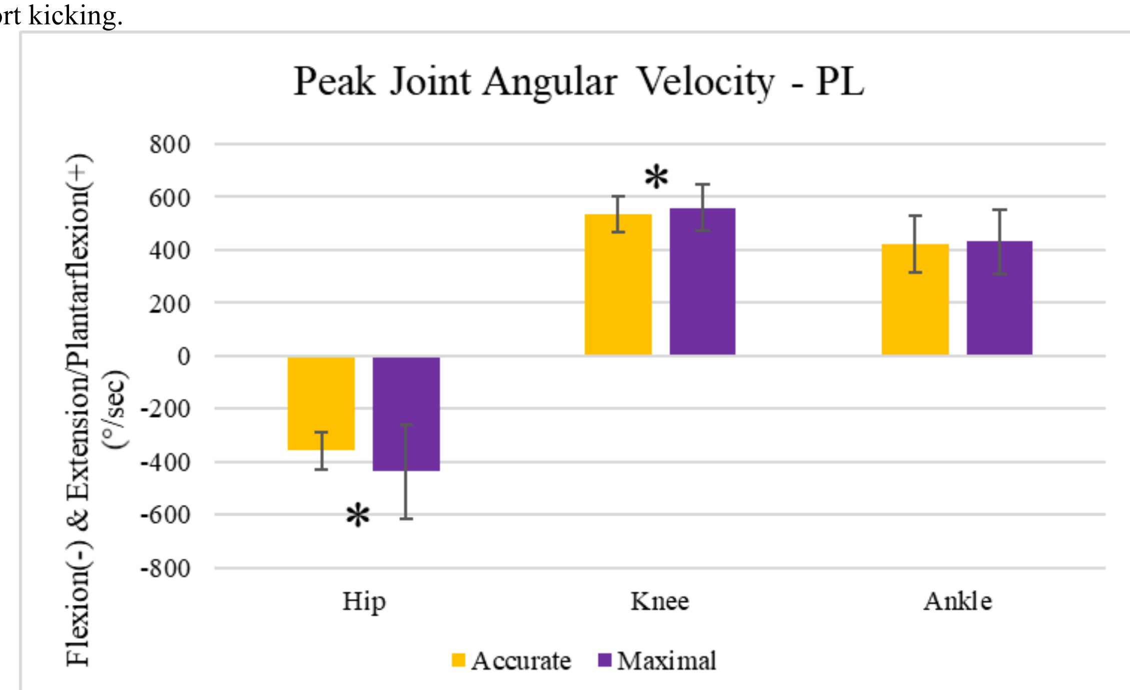
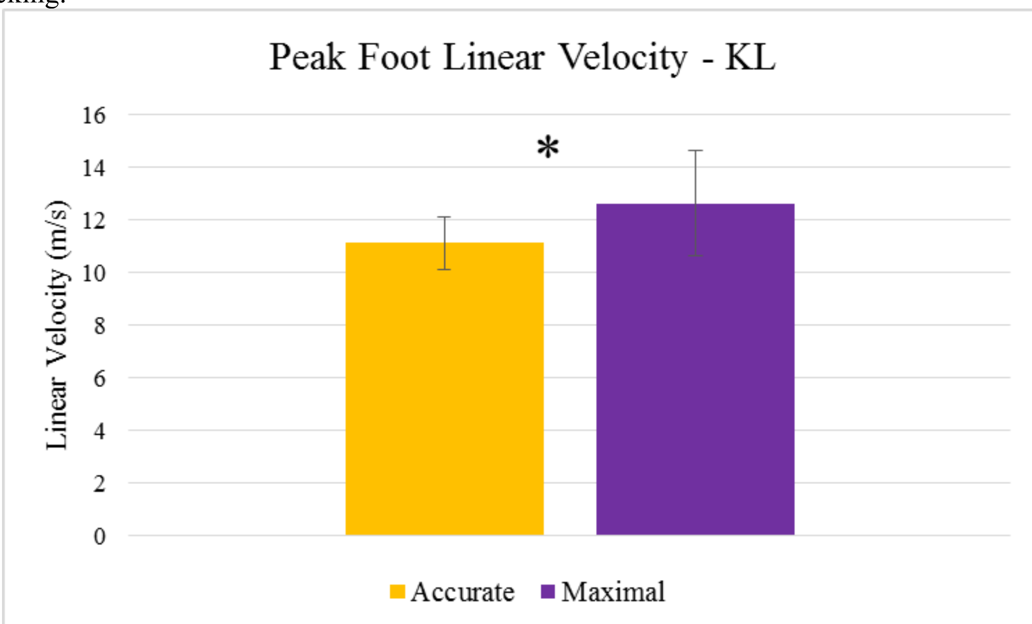


Figure 11. Mean (± S.D.) of peak joint angular velocities of the plant leg between accurate and maximal effort kicking.



Peak foot linear velocity of the kicking leg significantly increased 14% from 11 m/s when kicking with accuracy to 13 m/s when kicking with maximal effort (Figure 12). This may be the result of the increased loading step ground reaction force during the approach to the ball (Figure 5), leading to significantly increased joint and segment velocities (Figures 8 and 9).

Figure 12. Mean (± S.D.) of peak foot linear velocity of the kicking leg between accurate and maximal effort kicking.



Peak foot medial-lateral velocity of the kicking leg significantly increased 20% from 3.9 m/s when kicking with accuracy to 4.7 m/s when kicking with maximal effort (Figure 13). This may be the result of the significantly greater hip extension of the kicking leg at plant foot ground contact (Figure 14), allowing a further distance for the foot to sweep out a greater arc from the finish of the backswing to ball contact. This longer foot swing will allow more force to be applied over a greater distance, giving the foot more time to accelerate and increase foot velocity.

Figure 13. Mean (± S.D.) of peak foot medial-lateral velocity of the kicking leg between accurate and maximal effort kicking.

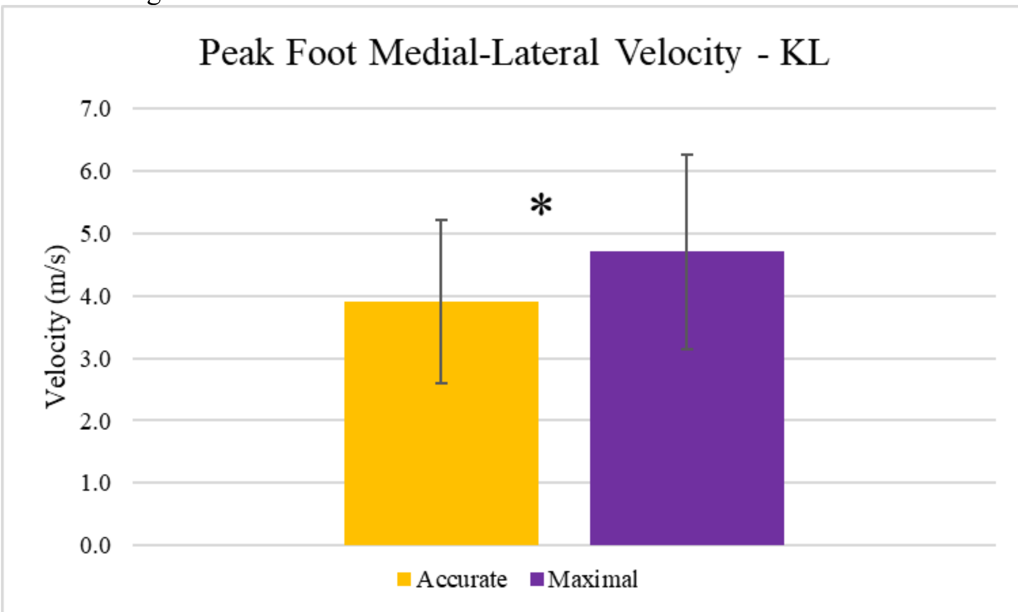
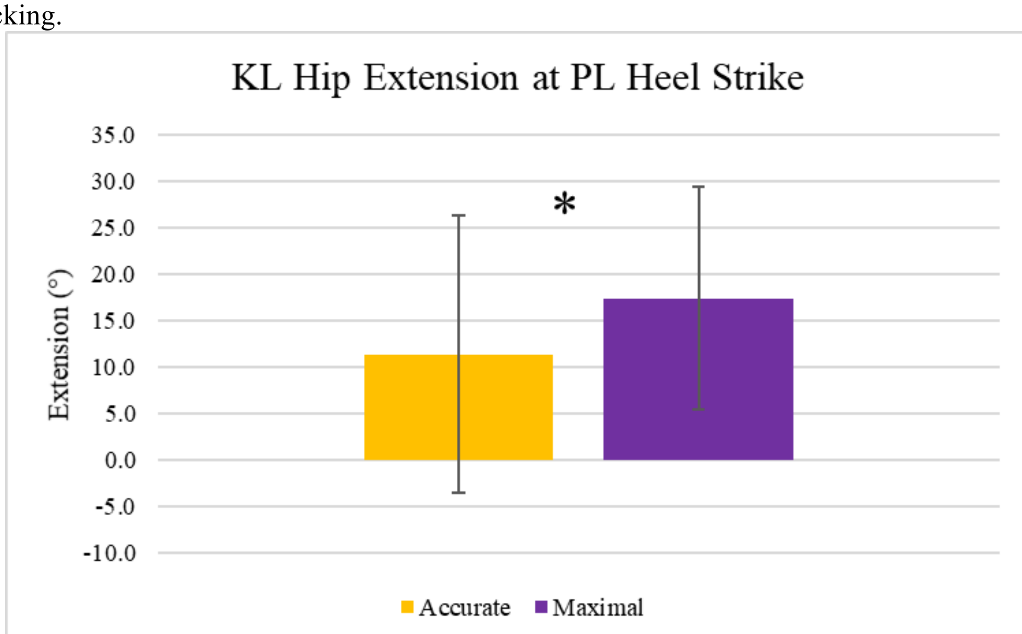
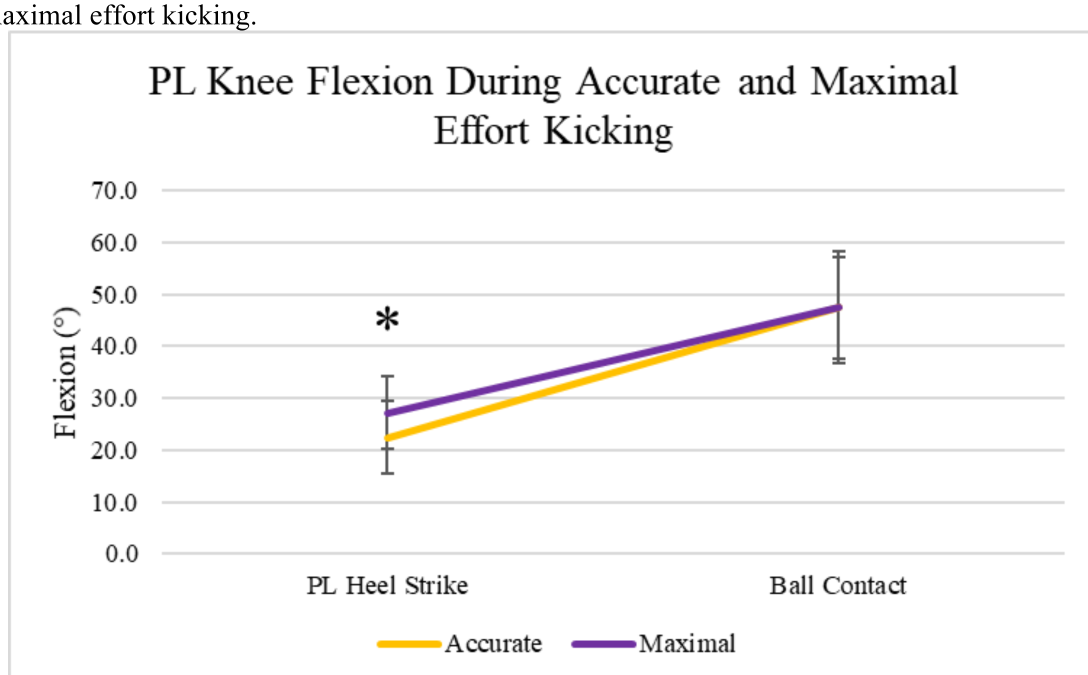


Figure 14. Mean (± S.D.) kicking leg hip extension at plant leg heel strike between accurate and maximal effort kicking.



Players demonstrated a significant 21% increase in plant leg knee flexion at ground contact when kicking with maximal effort (22.4 ± 6.9° vs. 27.1 ± 7.0°, p = 0.000) compared to when kicking accurately (Figure 15). However, knee flexion was the same at ball contact between conditions (47.4 ± 9.8° vs. 47.4 ± 10.7°). This suggests that at ball contact, the plant leg knee angle behaves in a manner that is similar across kicking techniques. Perhaps plant leg knee angle at ball contact contributes to kicks that are both accurate and fast.

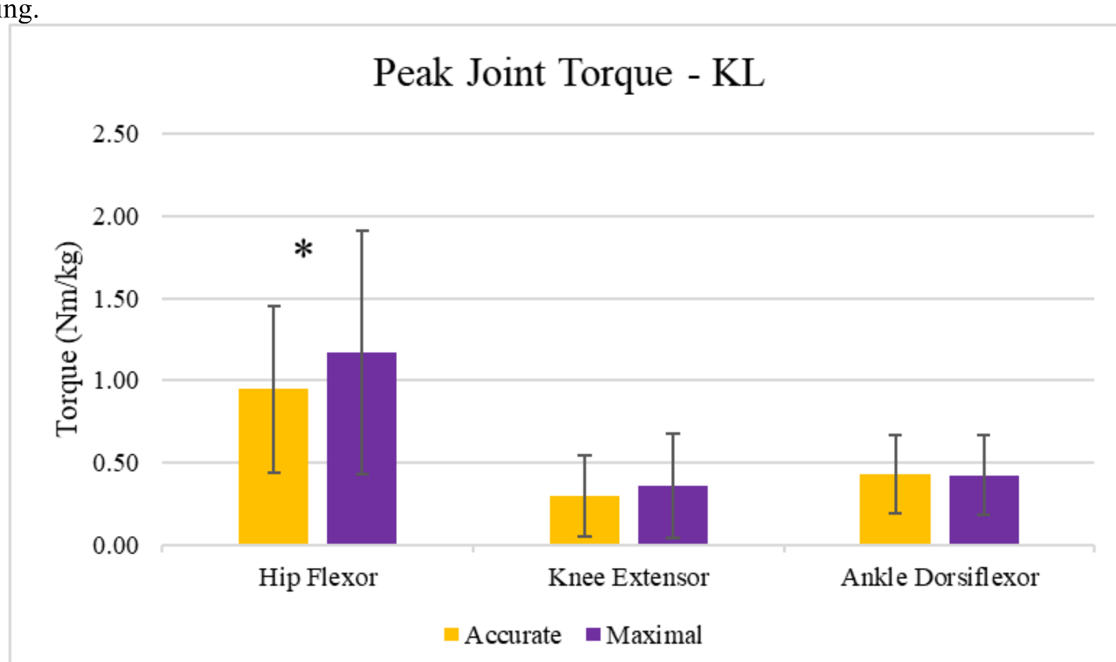
Figure 15. Mean (± S.D.) knee flexion of the plant leg at heel strike and ball contact between accurate and maximal effort kicking.



Joint Torques

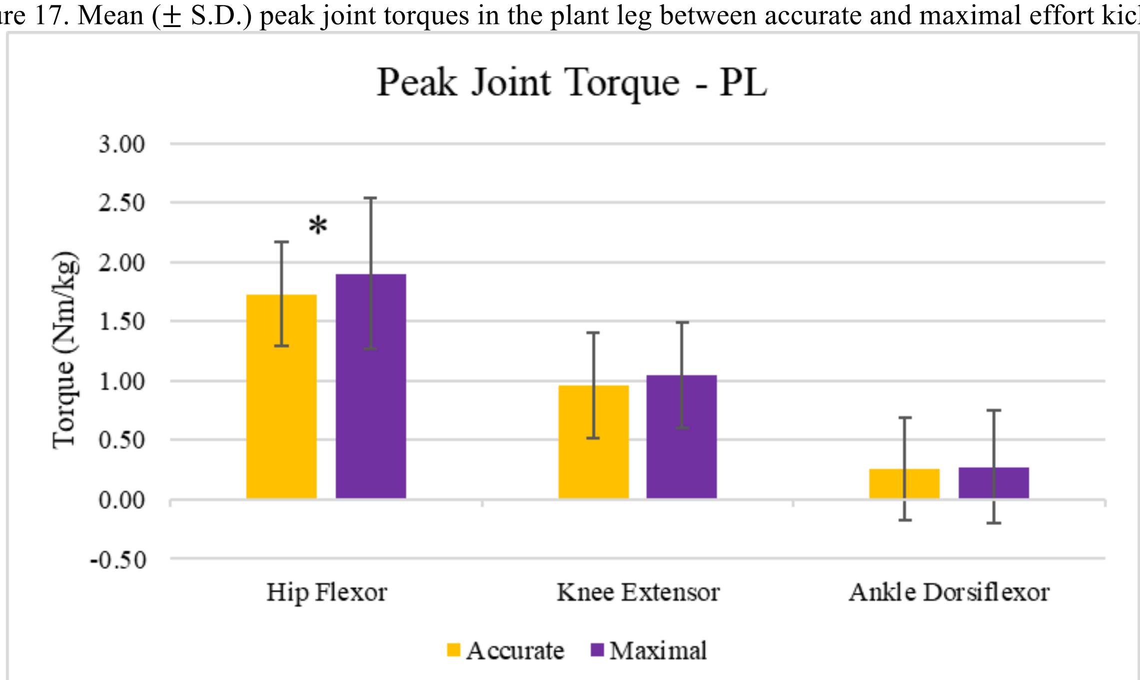
All joint torques are reported as the mean of the peak torques across all participants. The peak hip flexor torque in the kicking leg during accurate kicking was 0.95 ± 0.51 Nm/kg and significantly increased to 1.17 ± 0.74 Nm/kg during maximal effort kicking (Figure 16) which represented a 24% increase and suggests that increasing hip flexor torque may be critical when kicking with maximum velocity. There were no significant differences in the peak knee extensor or peak ankle dorsiflexor torque of the kicking leg between kick conditions. In fact, these variables were very similar across both conditions (0.30 ± 0.25 Nm/kg vs. 0.36 ± 0.32 Nm/kg in the knee and 0.43 ± 0.24 Nm/kg vs. 0.42 ± 0.24 Nm/kg in the ankle). These results indicate that knee and ankle joint torque during the approach may not affect joint angular velocity in the swinging phase as joint angular velocity in the knee and ankle were significantly different between conditions, whereas joint torque was not.

Figure 16. Mean (± S.D.) of peak joint torques in the kicking leg between accurate and maximal effort kicking.



In the plant leg, peak hip flexor torque (± S.D.) during accurate kicking was 1.73 ± 0.44 Nm/kg and significantly increased 10% to 1.90 ± 0.63 Nm/kg during maximal effort kicking (Figure 17). There were no significant differences in peak knee extensor or peak ankle dorsiflexor torque of the plant leg, similar to the results found in the kicking leg, between kick conditions (0.96 ± 0.45 Nm/kg vs. 1.04 ± 0.44 Nm/kg in the knee and 0.26 ± 0.43 Nm/kg vs. 0.27 ± 0.47 Nm/kg in the ankle). This indicates that knee and ankle joint torque may play an equal role in both accurate and maximal effort kicking during the approach to the ball, but that during maximal effort kicking, a greater hip flexor torque is required to produce faster kicks.

Figure 17. Mean (± S.D.) peak joint torques in the plant leg between accurate and maximal effort kicking.



Summary of Results

PL kinematic analysis revealed a significant increase in peak hip and knee joint angular velocity during maximal effort kicking (Figure 11). Of the peak joint angles in the PL, peak knee flexion angle was the only significant increase in maximal effort kicking (Figure 10). This significant difference in the PL knee angle most likely occurs at heel strike because the average PL knee angle at ball contact did not differ between kick conditions whereas it did at heel strike (Figure 15). In the KL, peak joint angle and angular velocity of the hip, knee and ankle all significantly increased during maximal effort kicking (Figures 8 and 9). These significant increases likely contributed to the significant increases in foot velocities of the KL (Figures 12 and 13). Peak hip flexor torque significantly increased during maximal effort kicking in both limbs whereas knee extensor and ankle dorsiflexion torque did not differ between conditions (Figures 16 and 17). This indicates that peak hip flexor torque may be a critical factor when kicking with maximum velocity.

Peak horizontal GRF in the LS significantly increased during maximal effort kicking which likely led to the significant increase in peak horizontal and vertical GRF in the PS (Figure 5). Peak vertical GRF in the LS did not differ between conditions. Tables 2 and 3 revealed that LS horizontal (propulsive) GRF had strong relationships with foot velocities in both kick conditions compared to PS horizontal (braking) GRF, indicating that increasing LS horizontal GRF in both conditions may be critical in improving kick velocity. PS vertical GRF had a moderately strong relationship with foot velocity whereas LS vertical GRF had no relationship with foot velocity in either kick condition. Correlation coefficients (Tables 2 and 3) revealed a greater amount of strong relationships between GRFs and outcome variables in accurate kicking compared to maximal effort kicking.

CHAPTER V. DISCUSSION

The purpose of this study was to investigate the kinetic and kinematic differences between accurate and maximal effort kicking in female soccer players. It was an attempt to determine how the ground reaction forces during the approach to the ball influence kick performance and which mechanical factors are associated with foot velocity in each condition. Aiming to kick with accuracy or with maximal effort are two important kicking tasks during a soccer game as they increase the chance of scoring of a goal either through accurate placement, surprising the goalkeeper with the velocity of the ball, or both. In the current study, we confirmed these kicking conditions were different in that accurate kicking resulted in significantly slower peak foot velocity compared to maximal effort kicking foot velocity ($p < 0.001$). Previous studies (Barfield et al, 2002; De Witt and Hinrichs, 2011) reported foot velocities between 13 m/s and 14 m/s during maximal instep soccer kicks which values are comparable to our maximal effort kicking foot velocity of 13 ± 2 m/s (Figure 12). In addition, Figure 2 shows shorter LS and PS stance phase time periods during maximal effort kicking indicating this condition was a faster movement. We used this information to confirm our kick conditions were true to the task goal (kicking accurately versus kicking with maximal effort).

Discussion of Ground Reaction Forces

Our results revealed that significant kinetic and kinematic differences exist between accurate and maximal effort instep soccer kicking. In maximal effort kicking, the normalized peak vertical ground reaction force in the plant leg was 2.4 BW, which was less than that previously reported by Ball (2013) who found vertical ground reaction force in the plant leg when kicking with the preferred leg to be 3.0 BW. One possible explanation for this difference is the type of kicking task. In the study conducted by Ball (2013), elite Australian football (AF) players from the Australian Football League performed maximal effort punt kicks. Punt kicking has shown to have greater vertical ground reaction force in the plant leg as AF kickers tend to use a straighter approach into the kick (Ball, 2013), so these greater vertical forces are directed more vertically compared to an instep kick. Ball's vertical forces of three times body weight (BW) were also larger than those previously reported for soccer kicks (Orloff et al, 2008). Interestingly, approach speeds were slower in the kicks performed in Ball's study compared to those reported for soccer (Orloff et al, 2008) even though they demonstrated larger ground reaction forces. It seems that approach speed does not play a factor in producing larger forces, at least during AF punt kicking. Therefore, the larger forces generated in the plant step may be more dependent on the ground reaction forces generated in the approach.

Peak horizontal ground reaction forces in the plant leg of 1.0 BW found in punt kicking (Ball, 2013) were slightly larger than the 0.79-0.93 BW reported for soccer (Orloff et al, 2008; Kellis and Katis, 2004). These forces reported for soccer are more similar to our findings of peak horizontal forces in maximal effort soccer kicking (-0.74 BW), and the slightly larger peak horizontal forces found by Ball (2013) might be explained by the straighter approach used by AF kickers compared to soccer's more angled approach, so greater forces are directed parallel to the line of kick. According to Kellis et al (2004) and Isokawa & Lees (1988), maximum horizontal ground reaction force decreases as approach angle increases from 0° to 90°. Players in the present study used a self-selected and straighter approach of approximately 20° compared to Kellis and Katis (2004) who found horizontal force to be 0.69 BW at a greater approach angle of 45°. Therefore, it is not surprising to see slightly larger horizontal ground reaction forces in the present study compared to those who used a larger approach angle (Kellis and Katis, 2004), and slightly smaller forces compared to those who used a straight approach (Ball 2013).

An angled approach is commonly used by soccer players as it orients the body to gain greater hip and knee flexion range of motion, and enables the kicking leg to be tilted in the frontal plane so that the foot can be placed further under the ball for better ball contact (Lees and Nolan, 1998). Approach angles of 30° to 45° have been found to be optimal, with maximum velocity of the shank achieved with an approach angle of 30° and the maximum ball velocity achieved with an approach angle of 45° (Isokawa and Lees, 1988). In a more recent study conducted by Scurr et al (2009) who investigated the effects of approach angle on kicking accuracy, players used a self-selected approach angle and found ball velocity to be highest in this condition. Therefore, it is logical to assume the self-selected angle of approach used in the present study played a role in the slightly larger vertical ground reaction forces compared to previous reports (Kellis and Katis, 2004).

Orloff et al (2008) also used a self-selected angle of approach when instructing players to kick with maximal effort and found peak vertical ground reaction force in the plant leg to be 2.4 BW for females, which is the same value found in the present study for females. Interestingly, peak horizontal ground reaction force found in males was -0.79 BW, which was the exact same peak horizontal ground reaction force that we saw in our study for females (-0.79 BW) when kicking with maximal effort. However, slightly larger peak horizontal ground reaction forces (-0.93 BW) were demonstrated by females in the study conducted by Orloff et al (2008) which may be explained by the greater number of steps (3 to 5) in the approach, which would allow a greater kicking velocity by the time the player reaches the ball thus a corresponding increase in horizontal ground reaction force. In the present study, players were constrained to use a 2 to 3 step approach to the ball. Nonetheless, our peak vertical and horizontal ground reaction forces in the plant leg follow similar patterns to those previous reported for maximal effort instep kicking.

Kellis and Katis (2004) used a one-step approach and found peak vertical ground reaction forces of 2.21 BW in the plant leg, which was less than ours of 2.4 BW. It has been reported that increasing the number of steps from one to three increases foot velocity and maximum swinging leg force (Ismail et al, 2010). Therefore, our larger peak vertical ground reaction forces may be explained by this step number difference, and further indicates the importance of investigating factors (i.e., ground reaction forces) during the approach to the ball and its influence on kick velocity. The similarities in plant leg ground reaction forces in these previous reports for soccer kicking can be used to help validate our plant leg ground reaction force data and we can assume that players in our study use similar techniques during the approach to the ball, including factors that are associated in the loading step, specifically peak vertical and horizontal ground reaction forces leading into the plant step.

Discussion of Correlations

Our results show that players propel off the ground with a peak ground reaction force approximately half of their body weight (0.51 BW) when stepping into the plant step which has a counteracting force that is 55% greater (0.79 BW) in the plant step during maximal effort kicking. In accurate kicking, this propulsive force generated by the loading step into the plant step is slightly less (0.42 BW) followed by a 60% greater braking force (0.67 BW) in the plant step. Although players demonstrate greater peak horizontal ground reaction forces in both legs during maximal effort kicking, there is a larger percent increase in peak horizontal ground reaction force from the loading step to plant step in accurate kicking. One possible explanation for this larger difference in accurate kicking would be that players may tend to generate greater force in the plant step to initiate the kicking leg to swing forward when velocity during the approach is lacking. This may be why we see a stronger relationship between ground reactions forces during the approach and kick velocity in accurate kicking compared to maximal effort kicking.

Sinclair et al (2014) found knee extension angular velocity of the kicking leg to be the only significant predictor of ball velocity. While we did not directly measure ball velocity, we can assume ball velocity through foot velocity measurements due to the notion that foot linear velocity ultimately governs the resultant ball velocity (Ball, 2008). The significant relationship found between knee angular velocity and ball velocity in the study conducted by Sinclair et al (2014) supports our finding of the significant relationship between kicking leg knee extension angular velocity and foot linear velocity in both accurate ($p = 0.000$) and maximal effort kicking ($p = 0.002$). Due to the significant positive relationship between loading step peak horizontal ground reaction force and knee angular velocity (R = 0.62*, p = 0.000) in this study, it appears logical to suggest that increasing peak ground reaction forces of the loading step will increase foot and ball velocity through increases in knee angular velocity during accurate kicking. Interestingly, this was not the case in maximal effort kicking. Although loading step peak horizontal ground reaction force is directly related to foot linear velocity in maximal effort kicking, it is not related to kicking leg knee angular velocity (R = 0.20) and is not seen to have a strong relationship with most kicking parameters that were measured in this study (Table 2). Perhaps a reason for this is the fact that hip rotation followed by hip flexion and knee extension have been found to be the primary factors that influence swing limb velocity (Roberts and Metcalfe, 1968). Therefore, knee extension angular velocity is more influenced perhaps by hip angular velocity when the goal is to kick as hard as possible. We found that during maximal effort kicking, peak horizontal ground reaction force in the loading step had a significant relationship with hip extension angular velocity (R = 0.34*). Therefore, rather than knee extension angular velocity, this peak horizontal ground reaction force may play a larger role in rotating and extending the hip to load a more forceful hip flexion angular velocity when the swinging leg comes forward. In support of this is the significant difference we found in peak hip flexor torque (Figure 16) between accurate and maximal effort kicking and the significant relationship between peak vertical ground reaction force in the loading step and peak hip flexor torque (R = 0.29*) (Table 2) during maximal effort kicking. This suggests that in maximal effort kicking, the harder that the loading step pushes off the ground leading into the plant step, the faster the hip extends and the more torque it requires to initiate the forward rotational movement of the swinging phase.

In studies that have examined plant leg ground reaction forces during kicking tasks (Ball, 2013; Orloff et al, 2008), the relationship between ground reaction forces and foot or ball velocity is reported to be strong. Ball (2013) showed that a high initial vertical force (R = 0.69*) and a strong braking force (R = 0.87*) in the plant step are associated with larger foot speeds, indicating that stronger bracing of the plant leg exists about which the kicking leg can swing thus generating greater kicking leg velocity and power. In addition, Orloff et al (2008) showed that higher peak braking forces in the plant leg were associated with higher ball velocities (R = 0.88*). Our results show a weak and non-significant correlation between braking force and foot velocity for females (R = 0.23) in maximal effort kicking. In accurate kicking, although still a weaker relationship than those previously reported, plant leg braking force and foot speed were found to be significantly associated (R = 0.31*). These findings suggest that peak horizontal ground reaction force during the approach to the ball, rather than in the plant step, plays a more important role in foot velocity, especially when aiming to kick towards a defined target versus when kicking solely with maximal effort (Tables 2 and 3).

One aim of this study was to determine how the ground reaction forces in the loading step during the approach to the ball influence kick velocity (as measured by foot linear velocity). Our results reveal that peak ground reaction forces in loading step have a stronger relationship with most outcome variables during accurate kicking compared to maximal effort kicking. In maximal effort kicking, the only strong significant correlation seen is between loading step peak vertical ground reaction force and plant leg ankle angular velocity ($R = 0.44^*$), meaning the larger peak vertical ground reaction force in the loading step, the faster the plant foot makes full contact with the ground from the point of heel strike. However, this relationship did not seem to play a noteworthy role in kick velocity (indicated by the weak correlation between loading step peak vertical force and foot velocity ($R = 0.03$) in Table 2), and peak vertical ground reaction force in the loading step should not be used to predict kick velocity, especially when kicking with maximal effort. Based on these results, it can be suggested that increasing peak horizontal ground reaction force in the loading step, rather than peak vertical ground reaction force, increases foot velocity in both kicking conditions but more so in accurate kicking. One possible explanation for this could be that perhaps players were more consistent in their foot velocities during maximal effort kicking which would reduce the correlation since foot velocity range was less in comparison to in accurate kicking. In other words, players may have been reaching their performance limit for foot velocity when kicking with maximal effort, thus showing weaker correlations for this variable.

Discussion of Kinematics and Joint Torques

Literature has reported differences in angular velocities of the hip, knee and ankle during soccer kicking (Kellis and Katis, 2010; Sinclair et al, 2014; Numone et al, 2002; Lees and Nolan, 2002). Our results for hip and knee angular velocities most closely align with those of Lees and Nolan (2002) who performed kinematic analysis of the instep kick under speed and accuracy conditions. When kicking with accuracy, Lees and Nolan (2002) reported hip and knee angular velocities for the kicking leg to be 413 and 983 °/sec, respectively, which is comparable to our results during accurate kicking (hip = 425 °/sec; knee = 886 °/sec). Joint angular velocities during maximal effort kicking in professional soccer players were reported to be 579 °/sec and 1212 °/sec for the hip and knee, respectively (Lees and Nolan, 2002), which are slightly higher than our values (hip = 536 °/sec; knee = 1095 °/sec) in college club and varsity level players. Numone et al (2002) found an even greater angular velocity in the knee of 1364 °/sec. It is likely these differences are a result of male soccer players (n = 5) used in these previous studies versus females (n = 20) used in the present study. However, it can be suggested that most soccer players use similar instep kicking techniques when kicking with accuracy or with maximal effort. Therefore, the ground reaction forces revealed in this study during the approach are likely to have the same effect across most soccer players during these kicking techniques.

In the kicking leg, Sinclair et al (2014) found male club soccer players to have an average peak knee flexion of 99° $\pm$ 14° while we found female club soccer players to have a slightly smaller average peak knee flexion of 93° $\pm$ 7° during maximal effort kicking. This is not surprising given that previous reports comparing kinematic parameters between males and females (Orloff et al., 2008; Barfield et al., 2002) have shown little differences in swinging leg mechanics. In addition, peak hip extension was found to be similar between the present study and Sinclair et al (2014) in that our females demonstrated a peak hip extension of 18° compared to males who demonstrated a peak hip extension of 16° when values were reported at plant foot ground contact. These similarities can be used to help validate our kinematic results in the plant leg and we can assume that most soccer players demonstrate the same plant leg mechanics when instep kicking, including the players in our study.

In studies that have examined plant leg kinematics during maximal instep soccer kicking, Orloff et al (2008) found plant knee angle at heel strike to be 23° while Lees et al (2009) found this angle to be 26°. At ball contact, both studies found the knee to be flexed to 42°. We found average plant leg knee flexion to be 27° at ground contact and 47° at ball contact (Figure 12) which indicates that our female players demonstrate similar plant leg mechanics to those previously reported in soccer kicking. Furthermore, our results revealed a significant difference between plant leg knee angle at heel strike between accurate and maximal effort kicking conditions, unlike at ball contact where this angle was found to be the exact same (Figure 12). This suggests that at ball contact, plant leg knee angle behaves in a manner that is similar across kicking conditions. In other words, this variable likely contributes to instep kicks that are both accurate and fast, and the way that players land with their plant foot next to the ball involves significantly more knee flexion during maximal effort kicks. This is likely the result of the significantly greater horizontal and vertical ground reaction forces in the step before the plant step, requiring the plant leg to absorb and cushion these greater forces through greater knee flexion.

In addition to plant leg knee angle at ball contact being similar across kicking conditions, it appears that knee and ankle joint torque in each limb also contribute to kicks that are both accurate and fast because we did not see significant differences seen in these variables between kicking conditions (Figures 16 and 17). However, the significant increase in kicking leg hip torque (Figure 16) may also be the result of the increased horizontal ground reaction force in the kicking leg when it pushes off the ground to load the swing. The significant increase in hip extension angular velocity in maximal effort kicking may explain the significantly greater hip torque required to initiate the more forceful hip rotation to load the kicking leg and kick the ball with maximal effort.

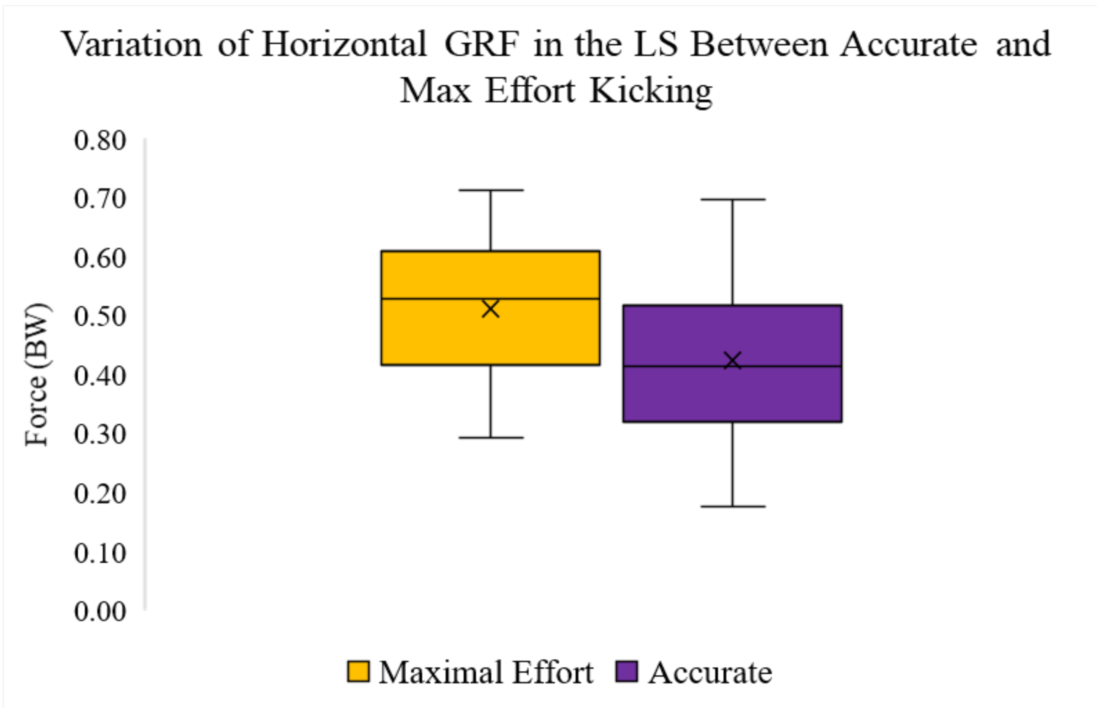
Speed-Accuracy Tradeoff

A substantial amount of evidence exists supporting the speed-accuracy tradeoff, which was introduced by Paul Fitts in 1954 and has been widely accepted for decades. Fitts law (1954) suggests that one can only prioritize velocity or accuracy and not both, thus as accuracy increases, velocity decreases and vice versa. A supported theory to account for Fitts law was proposed by Crossman and Goodeve (1963) which emphasized the feedback control of movement. According to this theory, movements that are longer in distance, or that are aimed at smaller targets, require more movement time because more corrections are required. Therefore, the amount of error or variability in achieving a target is dependent on how fast the movement is performed, which is determined by the number of feedback-based corrections that is required for the individual to make. The Crossman-Goodeve theory suggests that individuals may make as many as five feedback-based corrections in a 900 millisecond movement. However, evidence presented by Schmidt et al (1979) suggest that individuals actually have a hard time processing feedback, meaning individuals require a reaction time of at least 500 milliseconds to make such corrections. Therefore, making up to five corrections in 900 milliseconds seems questionable.

The experiments conducted by Schmidt et al (1979) show how movement time is directly related to impulse variability during rapid (< 500 ms) movements, thus the faster the movement is performed (i.e., less movement time) the less variability in the initial programmed pattern of movement because individuals do not have a long enough reaction time to correct for errors, at least during movements that are faster than 500 milliseconds. This leaves the possibility that fast movements lasting up to approximately 500 milliseconds, such as maximal effort kicks performed in the current study, may too have less variability in the initial programmed pattern of movement and no additional error in direction to which the kick was aimed. More importantly, Figure 2 shows that the loading step lasts approximately 200 milliseconds during maximal effort kicks. Therefore, the initial programmed pattern of movement and its relative force parameters (i.e., ground reaction forces) will not involve feedback-based corrections and players will not change the result of the kick once the first phase is initiated.

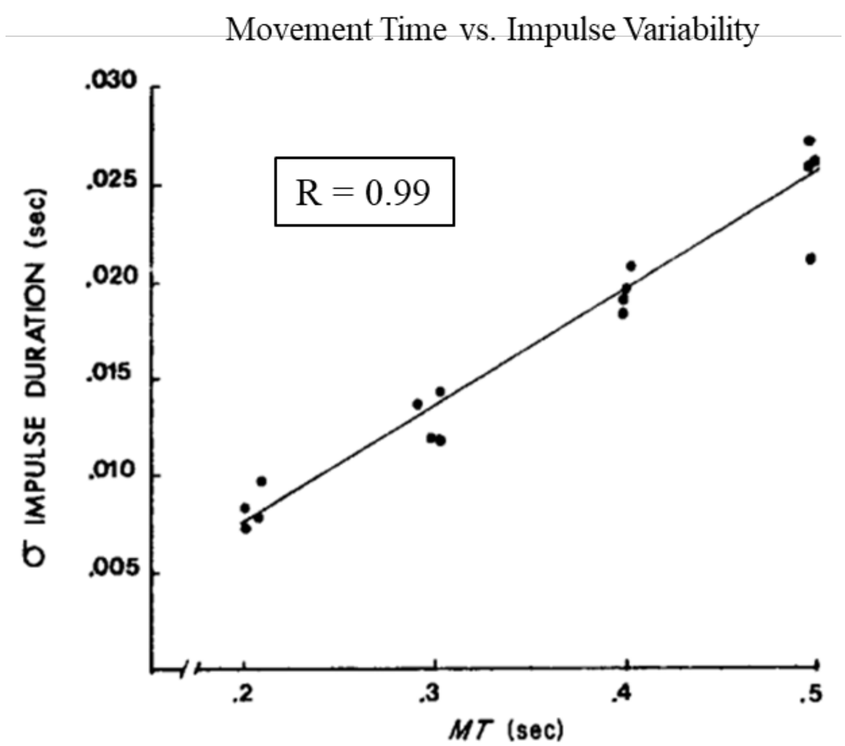
One aim of this study was to gain a better understanding of the speed-accuracy tradeoff in soccer kicking as previous studies have shown conflicting evidence (Hunter et al, 2018; van den Tillaar and Ulvik, 2014). While our data showed a significant increase in peak horizontal ground reaction force of the loading step during maximal effort kicking compared to accurate kicking (Figure 5), this force appeared to have less of an influence on kicking velocity as shown by our reduced correlations (Figures 6 and 7). One possible explanation for the peak horizontal ground reaction force in the loading step to have a stronger relationship with foot velocity in the accurate condition may be due to the less variation in this force in maximal effort kicking compared to accurate kicking as shown in Figure 18 below. This indicates that the faster the kick, the more consistent ground reaction forces and perhaps players were reaching their performance limit for this variable since these forces do not range as much from high to low as they do in accurate in kicking (Figure 18).

Figure 18. Standard deviation of peak horizontal GRF in the loading step (LS) between accurate and maximal effort kicking conditions.



In regards to the speed-accuracy tradeoff, these results appear to fall more in support of the principles described by Schmidt et al (1979). Figure 19 below shows the essential results of the experiments conducted by Schmidt et al (1979) where the average impulse variability is plotted against the obtained movement time and the most striking aspect is the strong linear trend, providing clear evidence in that variability decreases as the movement becomes more rapid. This may explain the reduced variation in horizontal ground reaction force of the loading step as players approached maximum velocity in the current study (Figure 18).

Figure 19. Schmidt et al (1979). Relationship between the average duration of the impulse and average within-subject standard deviation of the impulse length.



It is possible players in the current study were reaching their performance limit for how hard they push off the ground to load the plant step and create maximum foot velocity based on our reduced correlations in maximal effort kicking for those variables. Peak ground reaction forces and foot velocities were significantly greater in maximal effort kicking, so it is clear kicking with maximal effort may be the result of greater peak ground reaction forces thus leading to increases in foot velocity. But ground reaction forces in the loading step and plant step have stronger relationships with foot velocity in accurate kicking, a condition in which the movement was much slower. Another possible explanation for this regards motor programming, a phenomenon in which players program a set of muscle commands that cause movement in the absence of peripheral feedback. Due to the maximal effort kicking condition being a faster movement, there was less time for players to correct for error or deviate from their initial programmed pattern of movement. There was less influence of ground reaction forces in both the loading step and plant step on the kick outcome based on our reduced correlations in this condition, suggesting that players indeed deviated less from their original programmed pattern of movement. This is also in support of the idea that making a movement more rapid would involve applying proportionally more force by each of the muscles for a shorter amount of time. Too much force in one muscle would be counteracted by a proportional amount of force in another muscle, resulting in the movement having a straight pathway and no additional error in direction. Therefore, if players practiced kicking with maximum velocity towards a defined target, the accuracy should increase during fast performances due to the proportional increase in each muscle, thus no deviation from the pathway toward the target.

Although players increase movement force and velocity during maximal effort kicking, the programmed movement sequences during kicking still remain unchanged. This aligns with the idea of the GMP in that relative force may change but the general pattern of movement will remain the same. However, further research is needed to investigate the level of accuracy when the goal of the kicking task is to kick with both maximal effort and accuracy.

Conclusions

There were significant increases in horizontal and vertical ground reaction forces in both legs during maximal effort kicking compared to accurate kicking, with the exception of vertical ground reaction force in the loading step. These significant increases led to significant increases in joint and foot velocities of the kicking leg during maximal effort kicking. However, kick velocity may be best predicted by the peak horizontal ground reaction force of the loading step when players are instructed to kick accurately because when comparing horizontal and vertical forces in the loading step, it appears that peak horizontal ground reaction force has a greater effect on kick velocity (in maximal effort: $R = 75^*$; in accurate: $R = 0.77^*$) than peak vertical ground reaction force (in maximal effort: $R = 0.03$; in accurate: $R = 0.02$) based on the much stronger correlations it has with foot linear velocity. This suggests that the way a players pushes off the ground in the horizontal direction, versus the vertical force that they land with, is more important when aiming to improve velocity, especially during accurate kicking. Therefore, coaches and trainers can utilize these results to help players increase kick velocity by increasing horizontal ground reaction force when the loading step pushes off the ground. In addition, it may be possible to not have to sacrifice velocity for accuracy by practicing kicking fast while aiming at a target to become more accurate in faster performances. In other words, if players continue aiming at a target while kicking with maximum velocity, the number of times that players hit the target should increase because there is less movement variability as the movement approaches maximum velocity.

We identified common mechanical factors between kicking accuracy and kicking with maximal effort. Our results revealed that loading step peak vertical ground reaction force, plant leg ankle dorsiflexion and angular velocity, kicking leg and plant leg knee and ankle joint torque, and plant leg knee angle at ball contact are main factors that play a similar role in both kicking techniques. Therefore, finding ways through strength and conditioning drills to increase these factors should help increase both accuracy and velocity since these factors do not change across kicking techniques. This information may also be used by coaches and trainers when developing training protocols because it highlights focused areas for improvement. Training regimens should include the repetitive practice of kicking both fast and accurately to preserve velocity while kicking accurately. This may lead to an optimal kicking technique as there will not be a speed-accuracy tradeoff.

Limitations and Future Directions

The present study had some limitations. First, the testing environment is not similar to game-like situations or practice fields. The players kicked into a net approximately one meter in front of them and wore their own tennis shoes unlike on a soccer field where players usually kick towards a much further target wearing cleats. Second, the analysis is limited to the accuracy of the motion capture system and force plates. Error in marker placement due to movement on skin surface could skew body segment measurements and movements. However, each participant's accurate kicking condition was compared to their own maximal effort kicking condition. Therefore, marker placements were standardized within participants. Lastly, maximal effort kicking was not validated due to room size constraints. Although instructed to do so, it is possible players did not kick with maximal effort. However, based on foot velocity, it was verified that players kicked significantly harder in the maximal effort kicking condition.

We investigated the kinetic and kinematic differences between accurate and maximal effort kicking in soccer players. To our knowledge, we are the first to examine ground reaction forces in the step before the plant step and how these forces influence plant leg and kicking leg mechanics in accurate and maximal effort kicking. In addition, the evidence about error corrections and feedback processing contradicting the speed-accuracy tradeoff led us to search for a way to preserve accuracy while kicking with maximal effort or vice versa. This study lays the foundation for further investigation into this area. One possible area of research would be to examine the influence of ground reaction forces during the approach to the ball with the goal of kicking both accurately and fast. Measurements of accuracy and effort level could be obtained to provide direct insight into ways to kick without a speed-accuracy tradeoff. Experimental conditions that have varying kicking distances should be included to investigate effects of target distance on these measures during instep soccer kicking. These types of studies would add to the current literature pertaining to the speed-accuracy tradeoff in sport-specific movements by identifying principles that may help optimize performance techniques.

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APPENDIX A: INFORMED CONSENT

East Carolina University

Informed Consent to Participate in Research

Information to consider before taking part in research that has no more than minimal risk.

Title of Research Study: Kinetic and Kinematic Analysis of the Phases of Kicking during Accurate and Maximal Effort Conditions in Female Soccer Players

Principal Investigator: Patrick Rider (Person in Charge of this Study)
Institution, Department or Division: Department of Kinesiology
Address: 360 Ward Sports Medicine Building, NC 27858
Telephone #: (252) 737-2370

Researchers at East Carolina University (ECU) study issues related to society, health problems, environmental problems, behavior problems and the human condition. To do this, we need the help of volunteers who are willing to take part in research.

Why am I being invited to take part in this research?
The purpose of this research is to determine the changes that occur in the lower extremities during different landing tasks and different kicking conditions. You are being invited to take part in this research because you are a healthy, female volunteer who plays club level soccer. The decision to take part in this research is yours to make. By doing this research, we hope to learn the changes that occur in the lower extremity during different landing conditions and different soccer kicking tasks.

If you volunteer to take part in this research, you will be one of about 40 people to do so.

Are there reasons I should not take part in this research?
I understand I should not volunteer for this study if I am, under 18 years of age, or I am recently injured and would not be able to complete the different tasks required for this study, such as jumping and kicking.

What other choices do I have if I do not take part in this research?
You can choose not to participate.

Where is the research going to take place and how long will it last?
The research will be conducted at Ward Sports Medicine Building. You will need to come to the Biomechanics Laboratory on the third floor of the Ward Sports Medicine Building 1 time during the

study. The total amount of time you will be asked to volunteer for this study is 30-45 minutes the day of the protocol.

What will I be asked to do?
You will be asked to do the following:

- Step on a scale to measure your height and weight
- Answer a survey questionnaire about your soccer playing history
- Stand so that we may place reflective markers on your body to track your movements
- Perform two different landing tasks and two different kicking tasks. One landing condition requires you to jump and land on the force plates. In the second landing condition you will be asked to jump and tap your head on a soccer ball that is suspended from the ceiling. One of the kicking conditions requires you to kick a soccer ball with maximum effort into a net. For the second kicking condition, you will kick a soccer ball into the net as accurately as possibly, aiming at a target on the net. You will be allowed to practice each task until you are comfortable performing the task in the lab environment.

What might I experience if I take part in the research?
We don't know of any risks (the chance of harm) associated with this research. Any risks that may occur with this research are no more than what you would experience in everyday life, including your normal soccer practice activities. We don't know if you will benefit from taking part in this study. There may not be any personal benefit to you but the information gained by doing this research may help others in the future.

Will I be paid for taking part in this research?
We will not be able to pay you for the time you volunteer while being in this study.

Will it cost me to take part in this research?
It will not cost you any money to be part of the research.

How will you keep the information you collect about me secure? How long will you keep it?
Your data will be encrypted and stored on a password-protected computer for 6 years. Additionally, no identifying information will be stored electronically.

What if I decide I don't want to continue in this research?
You can stop at any time after it has already started. There will be no consequences if you stop and you will not be criticized. You will not lose any benefits that you normally receive.

Who should I contact if I have questions?
The people conducting this study will be able to answer any questions concerning this research, now or in the future. You may contact the Principal Investigator at (252) 737-2370 (Monday-Friday, between 9:00-5:00)

If you have questions about your rights as someone taking part in research, you may call the Office of Research Integrity & Compliance (ORIC) at phone number 252-744-2914 (days, 8:00 am-5:00 pm). If you would like to report a complaint or concern about this research study, you may call the Director of the ORIC, at 252-744-1971.

I have decided I want to take part in this research. What should I do now?
The person obtaining informed consent will ask you to read the following and if you agree, you should sign this form:

- I have read (or had read to me) all of the above information.
- I have had an opportunity to ask questions about things in this research I did not understand and have received satisfactory answers.
- I know that I can stop taking part in this study at any time.
- By signing this informed consent form, I am not giving up any of my rights.
- I have been given a copy of this consent document, and it is mine to keep.

____

Participant's Name (PRINT) **Signature** **Date**

Person Obtaining Informed Consent: I have conducted the initial informed consent process. I have orally reviewed the contents of the consent document with the person who has signed above, and answered all of the person's questions about the research.

____

Person Obtaining Consent (PRINT) **Signature** **Date**

____

Principal Investigator (PRINT) ***Signature*** ***Date***

APPENDIX B: INSTITUTIONAL REVIEW BOARD APPROVAL

EAST CAROLINA UNIVERSITY
University & Medical Center Institutional Review Board
4N-64 Brody Medical Sciences Building· Mail Stop 682
600 Moye Boulevard · Greenville, NC 27834
Office **252-744-2914** · Fax **252-744-2284** ·
www.ecu.edu/ORIC/irb

Notification of Initial Approval: Expedited

From: Biomedical IRB
To: Patrick Rider
CC:

Patrick Rider
Date: 9/29/2017
Re: UMCIRB 17-001991
Biomechanics of Soccer Kicking and Landing

I am pleased to inform you that your Expedited Application was approved. Approval of the study and any consent form(s) is for the period of 9/28/2017 to 9/27/2018. The research study is eligible for review under expedited category #4,7. The Chairperson (or designee) deemed this study no more than minimal risk.

Changes to this approved research may not be initiated without UMCIRB review except when necessary to eliminate an apparent immediate hazard to the participant. All unanticipated problems involving risks to participants and others must be promptly reported to the UMCIRB. The investigator must submit a continuing review/closure application to the UMCIRB prior to the date of study expiration. The Investigator must adhere to all reporting requirements for this study.

Approved consent documents with the IRB approval date stamped on the document should be used to consent participants (consent documents with the IRB approval date stamp are found under the Documents tab in the study workspace).

The approval includes the following items:

Name	Description
Biomechanics of Soccer Kicking and Landing Informed Consent (1).doc	Consent Forms
Biomechanics of Soccer Kicking and Landing Study Questionnaire.docx	Surveys and Questionnaires
Research Protocol	Study Protocol or Grant Application

The Chairperson (or designee) does not have a potential for conflict of interest on this study.

IRB00000705 East Carolina U IRB #1 (Biomedical) IORG0000418
IRB00003781 East Carolina U IRB #2 (Behavioral/SS) IORG0000418

APPENDIX C: STUDY QUESTIONNIARE

Kinetic and Kinematic Analysis of the Phases of Kicking Between Accurate and Maximal Effort Conditions in Female Soccer Players Study Questionnaire

1. How old are you?
2. What is your preferred kicking leg?
3. What is your preferred stance leg?
4. What is your primary playing position?
5. How many years of soccer experience do you have?
6. Do you have any previous injuries?
7. How much time do you spend training each week?
8. How much match time do you get each week