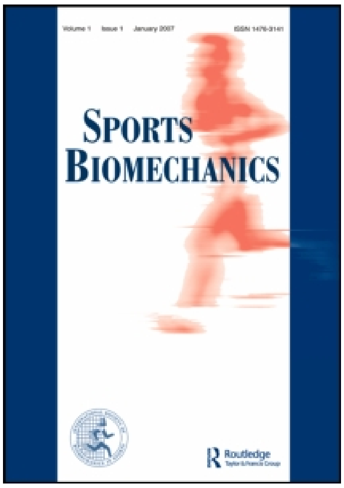

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Kinetic analyses of maximal effort soccer kicks in female collegiate athletes

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Kinetic analyses of maximal effort soccer kicks in female collegiate athletes

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Abstract
To determine the effect of plant leg and approach condition on the torques of the hip, knee, and ankle in soccer kicking tasks, nine female collegiate soccer players performed a series of kicking tasks from three different approach conditions. Kinematic data of the hip, knee, and ankle were recorded and joint torques of the plant leg were calculated. Peak flexor torque of the hip and ankle was greater for the dominant than the non-dominant plant leg for center and off-axis approach conditions ($P < 0.05$), while the opposite was true for peak extension torque for the hip and knee ($P < 0.05$). Similar effects of plant leg dominance emerged for peak internal and external rotation torques as well for peak abduction and adduction torques. In summary, these results indicate that participants use greater pulling torques and smaller braking torques in the dominant plant leg compared with the non-dominant plant leg. Thus, even in collegiate athletes who train to be able to kick efficiently with either leg, differences in peak joint torques emerge between the dominant and non-dominant plant legs, particularly when participants kick from an off-axis approach.

Keywords: *Kinetics, ACL, joint torques, soccer kicking, plant leg*

More opportunities for females to participate in competitive athletics in the United States exist now than ever before, but with increasing participation comes the increased risk of injury (Lopiano, 2000). Consistent with this notion, women's soccer in particular carries specific risks. An annual National Collegiate Athletic Association (NCAA) injury surveillance system found that, over a 15-year period, the frequency of knee injury in female soccer players accounted for 23.6% of all injuries sustained in collegiate sports (Dick et al., 2007). Moreover, Agel et al. reported that non-contact anterior cruciate ligament (ACL) injury in females accounted for 67% of all ACL injuries sustained over a 13-year study of the NCAA injury database (Agel et al., 2005). Studies of biomechanical mechanisms contributing to ACL injury in females have primarily focused on the way that female athletes land from different jumping conditions and perform cutting manoeuvres; however, few studies have characterized or examined female athletic performance in specific sports, such as soccer (McLean et al., 2005; Hewett et al., 2006).

Kicking is a natural fluid motion and a fundamental activity in soccer. Although most of the literature on soccer has focused on the mechanics of the kicking leg, 99% of all ACL

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injuries occur to the limb that is in contact with the ground (Fauno and Wulff Jakobsen, 2006). With respect to the kicking leg, research has focused on the optimal position of the kicking leg to achieve high ball velocities, kicking leg dominance, and kicking accuracy (Isokawa and Lees, 1988; Mognoni et al., 1994; Barfield et al., 2002; Dorge et al., 2002; Nunome et al., 2006). Isokawa and Lees (1988) found that on average maximum swing leg velocity occurred at an approach angle of 30° and peak ball velocity occurred at an approach angle between 30° and 45°, with a maximum velocity at 45°, suggesting that 45° is the optimal approach angle for a maximum velocity instep soccer kick (Isokawa and Lees, 1988). Most research on kicking limb preference or dominance has examined ball speed of the kicking leg. These studies have found that higher ball speeds are achieved when soccer players kick with their preferred or dominant kicking limb as a result of higher foot speed (Isokawa and Lees, 1988; Mognoni et al., 1994; Dorge et al., 2002; Nunome et al., 2006).

Although the mechanics of the kicking leg have been studied extensively to determine factors related to kick performance, few studies have examined the mechanics of the plant leg during soccer kicking (Isokawa and Lees, 1988; Dorge et al., 2002; Nunome et al., 2002; Shan and Westerhoff, 2005). It is known that soccer injuries most often occur to the plant leg during competition; however, an extensive literature search revealed only four studies that examined plant leg mechanics (Barfield, 1998; Kellis et al., 2004; Masuda et al., 2005; Orloff et al., 2008). Orloff et al. (2008) compared the kinetics and kinematics of the plant leg position during instep kicking in male and female collegiate soccer players and found that there was no significant difference in plant leg position; however, females had significantly greater trunk lean, plant leg angle, and medial-lateral ground reaction force during kicking than males.

Kellis et al. (2004) showed that shear forces of the plant leg increase with an increase in approach angle. Large shear forces may cause significant loading of the lower extremity joints and stress to the medial knee. Kellis et al. also reported that higher external rotation displacements and higher knee angular velocities occurred in the plant leg with an increase in approach angle.

The study by Masuda et al. (2005) of the plant leg examined the relationship between ball velocity, approach angle, and strength of the plant leg. The approach angles used in the study were set so that zero degrees represented the direction in which the ball was kicked. Participants performed a designated number of kicking trials aimed at a target from three approach angles (i.e. self-selected kick or free kick, 90° or 135°). It was found that ball velocity and strength of the plant leg correlated when kicking from a large approach angle (i.e. an approach angle of 135°). Masuda et al. (2005) suggested that greater knee flexor, hip extensor, and hip abductor strength was required to stabilize the body during an off-balance kick and to generate high ball velocities.

While these studies have made important contributions to understanding the mechanics of the plant leg, they only examined the ground reaction forces, joint displacements, and strength of the plant leg. The distribution and magnitude of lower extremity joint torques of the plant leg during kicking remain unknown. Furthermore, there has been no explicit comparison of kicking with dominant versus non-dominant leg on plant leg mechanics, which leaves the question: Do differences arise between the plant legs when kicking with the dominant versus non-dominant kicking leg? Accordingly, the aim of the present study was to determine the influence of plant leg and approach condition on the torques of the hip, knee, and ankle in healthy female athletes during soccer-style kicking tasks. We hypothesized that there would be differences in joint torques of the plant leg when the participants kicked with their dominant versus non-dominant kicking limb and when kicking from an off-axis approach.

Methods

Participants

Nine healthy female collegiate soccer players participated in this experiment, which involved a series of kicking tasks from different approach angle conditions using both the left and right plant legs. Inclusion criteria for the study required the participants to be between the ages of 18 and 25 years, actively participating in intercollegiate soccer within the 12 months before testing, and to have no prior history of ACL injury. The participants recruited had a mean age of 20.4 years ($s = 1.5$), mean height of 1.63 m ($s = 0.09$), mean weight of 61.3 kg ($s = 10.1$), and averaged 12.7 years ($s = 2.9$) of previous competitive soccer experience. Seven of the nine participants reported that their right leg was their dominant kicking limb, thus making their left leg their non-dominant kicking limb. We defined the dominant plant leg as the leg most often in contact with the ground during kicking (i.e. the left leg). The study was conducted in accordance with the current American Psychological Association guidelines for human research and was approved by the Ohio University Institutional Review Board. Before testing, each participant provided signed informed consent.

Procedure

Anthropometric measurements were collected from the participants using an established protocol described in Thomas et al. (2003). Before testing, participants completed two practice kicks from each of the three approach conditions allowing them to measure a comfortable one-step approach to determine their starting position from the ball. For these maximal effort kicks, the participants were barefoot on their plant leg to reduce any variance in the ground reaction forces due to differences in footwear. However, participants did wear a tennis shoe on the kicking limb to ensure a maximum effort kick by eliminating the potential for pain that could be caused by kicking barefoot. The participants were instructed to listen for the sound of a buzzer and then take a one-step approach with the designated plant leg onto a force plate and kick the ball as hard as possible, which we operationally define as a "maximal effort kick". Each participant performed a total of 18 maximum effort kicking trials (9 per plant leg), three from the left approach, three from the center approach, and three from the right approach. An infrared sensor was positioned directly in front of the ball to detect ball contact. A #5 ball size was used in this study for all kicking trials.

Kicking approach conditions

Participants approached the ball from 60° to the left of the ball (left start), 60° to the right of the ball (right start), or from straight behind the ball (center start) (Figure 1). These angles were chosen based on a previous study by Isokawa and Lees (1988), who found that kicking from an increased approach angle (i.e. 30 to 90°) resulted in higher ball velocities and correlated with an increase in rotation at the knee about the vertical axis, and a study by Kellis et al. (2004), who determined that kicking from an angled approach (i.e. 45 and 90°) caused higher knee angular velocities and external rotation displacements compared with kicking from an approach of zero degrees. Higher ball velocities are often favourable during match-play, especially when taking penalty kicks.

Six trial conditions, based on the three start positions (left, center, right) for each plant leg, were defined in this study. Specifically, an on-axis or ipsilateral approach is when the plant leg and approach angle are the same (e.g. left approach to the ball and left plant leg), while an off-axis or contralateral approach is when the plant leg and approach angle are opposite

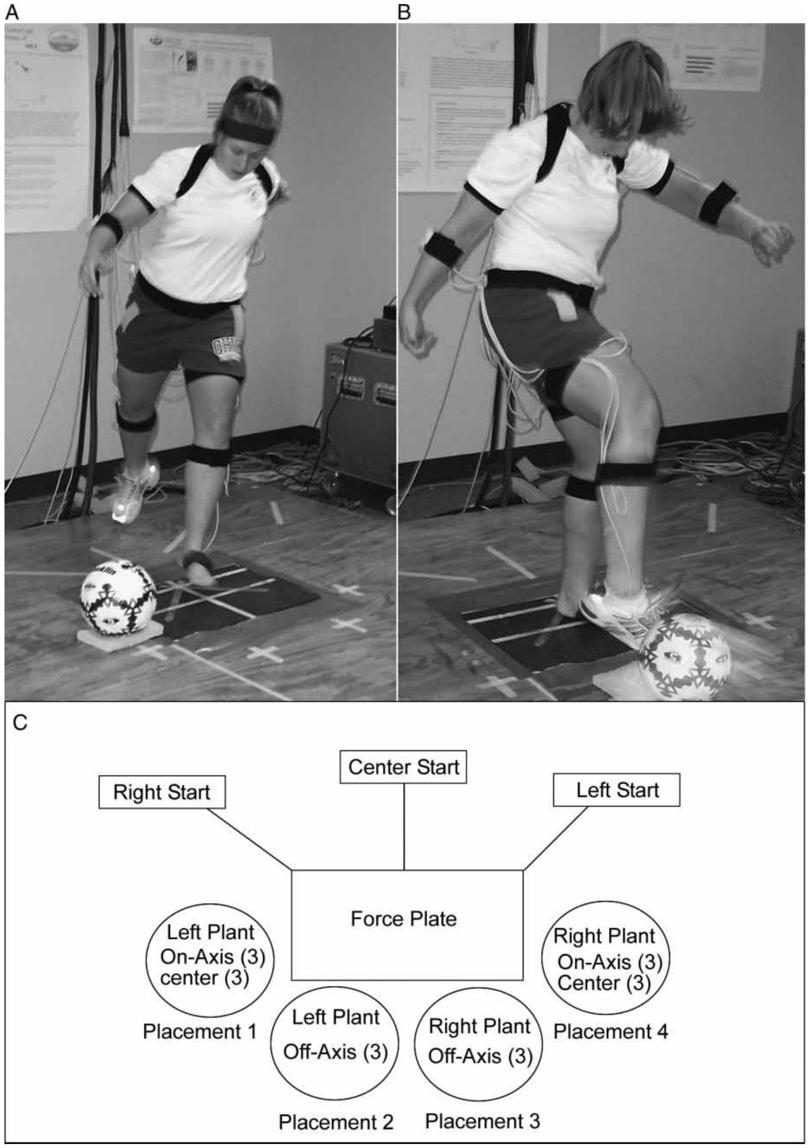

Figure 1. A typical participant performing a maximal effort kick with the dominant plant leg using (A) an on-axis approach and (B) an off-axis approach. (C) Diagram of the ball placement and start positions for the following six experimental conditions: approach (on-axis, center, off-axis) × plant leg (left, right). Note that the data were aligned for plant leg dominance in post-processing.

(e.g. left approach to the ball and right plant leg). An off-axis kicking approach was used in this study to mimic the many variable and unpredictable kicking approaches that often occur in high-level competition. Off-axis kicking approaches have been found to cause high rotational forces around the knee joint of the support leg, which may induce significant loads to the knee (Kellis et al., 2004). A center approach is when the participant approaches the ball from directly behind. An example of a participant kicking using an on-axis and off-axis approach with the dominant plant leg is shown in Figures 1A and 1B. A diagram of the start positions and ball placements for the various trial conditions is provided in Figure 1C. Participants performed three maximal effort kicks at each of the six trial conditions. No specific instructions were given to the participants on how to kick the ball, other than to kick it as hard as possible. In fact, the off-axis approach often required the participants to change their kicking strategy to achieve ball contact; however, most participants used an instep foot position to kick the ball in the on-axis and center approach conditions.

Data collection

Movements of the lower limb segments of the plant leg were recorded using a magnetic based kinematic system (Motion Monitor) that can track the three-dimensional coordinates of sensors with a spatial resolution of 0.03 inch (Ascension^{TM}). Data were sampled at 100 Hz and recorded for 5 s per trial. Data collection began 500 ms prior to the "go signal" (i.e. buzzer). Force plate data were collected using a Bertec (Bertec Corp., Worthington, OH) non-conductive force plate sampled at 100 Hz. Both the kinematic data and force data were collected on the same system using Motion Monitor software to ensure synchronization of the data stream. Sensors were attached with Velcro® straps to the limb segments (pelvis, right and left: thighs, shanks, and forefeet) at the midpoint between two joints.

Local right-handed orthogonal reference frames for the foot, shank, thigh, and pelvis were used to determine joint angles, angular velocities, and joint torques. The ankle joint center was defined as the center point between the medial and lateral malleolus. The knee joint center was defined as the center point between the lateral fibular head and the medial tibial epicondyle. The hip joint center was determined using the method described by Leardini et al. (1999). The local segment axis system was set up such that the longitudinal axis pointed from the proximal to the distal extremities of the segment, the transverse axis pointed from the right to left side, and the sagittal axis pointed from the back to the front of the segment.

Joint torques expressed in anatomic coordinates of the ankle, knee, and hip were derived using Motion Monitor software. The model consisted of four linked segments including the foot, shank, thigh, and pelvis. Segment mass and location of the center of mass for each segment were determined using the regression equations of Zatsiorsky and Seluyanov (1983). Joint angular velocity and acceleration were calculated using a 5-point numerical differentiation technique (Lanczos, 1988). The kinematic data and the ground reaction force data are used by Motion Monitor software to determine the joint torques of the hip, knee, and ankle for each instant in time using a bottom-up approach. The method used by the Motion Monitor software to derive the joint torques was detailed in Appendix A of Gagnon and Gagnon (1992). Timing of the peak joint torques, from contact of the plant leg on the force place to ball contact, were determined but are not presented in this article. For each trial, the kick was defined as the time from force plate contact of the plant leg to maximum hip flexion of the kicking leg. Using custom software written in Matlab (Mathworks, Natick, MA), peak joint torques (i.e. flexion/extension, abduction/adduction, internal rotation/external rotation) were extracted for each trial from the time-series data.

Data analysis

The data were analysed using the SPSS for Windows software package, Version 15.0 (SPSS Inc., Chicago, IL). Separate two-way repeated-measures analyses of variance (ANOVAs) were performed on the peak joint torques of the hip, knee, and ankle. The two factors in these analyses were plant leg (dominant vs. non-dominant) and approach condition (on-axis, center, off-axis). For each joint, we examined the peak joint torques in each plane of motion (i.e. flexion/extension, internal rotation/external rotation, and abduction/adduction) normalized to body weight. Because internal rotation/external rotation, and abduction/adduction torques have different signs for the left and right legs, we had to use the absolute value of these torques in our statistical analyses to determine the effect of dominant versus non-dominant plant leg. The data were averaged across the three trials prior to performing the analyses. For interactions of plant leg and approach angle, we examined simple main effects of plant leg at each level of approach condition (i.e. on-axis, center, off-axis) using a repeated-measures analysis. Statistical significance was set at $P < 0.05$. In the Results section, we provide the absolute values of peak normalized torque data.

Results

Peak flexor and extensor torque

Peak flexor torques of the hip, knee, and ankle of the dominant and non-dominant plant leg for the three approach conditions are illustrated in Figures 2A–C. There was an interaction of plant leg and approach condition on peak flexor torque of the hip ($F = 9.1$, $P = 0.022$) and ankle ($F = 13.2$, $P = 0.040$). Figure 2A illustrates that peak hip flexor torque was greater for the dominant plant leg than the non-dominant plant leg for the off-axis and center approach conditions, but was only significant for the off-axis approach condition ($F = 9.35$, $P = 0.022$). For the ankle, peak flexor torque was greater for the dominant plant leg than the non-dominant plant leg for both the off-axis ($F = 19.6$, $P = 0.004$) and center ($F = 8.7$, $P = 0.026$) approach conditions. There was no significant interaction of plant leg and approach condition on peak flexor torque of the knee; however, Figure 2B shows a similar trend with peak flexor torque being greater for the dominant plant leg than the non-dominant plant leg for the off-axis approach condition. Thus, no significant differences for peak flexor torque were observed between the dominant and non-dominant plant legs in collegiate athletes during the on-axis approach condition. In summary, peak flexor torques of the hip, knee, and ankle of the dominant plant leg were greater than those of the non-dominant plant leg during the off-axis and center approach conditions.

Peak extensor torques of the hip, knee, and ankle of the dominant and non-dominant plant leg for the three approach conditions are illustrated in Figures 2D–F. There was a main effect of plant leg for the peak extensor torque of the hip ($F = 18.1$, $P = 0.005$) and knee ($F = 48.8$, $P = 0.001$). As illustrated in Figures 2D and 2E, peak extensor torque was greater for the non-dominant plant leg than the dominant plant leg right in both joints for all three approach conditions. There were no other main effects or interactions for peak extensor torque.

Peak internal and external rotation torque

Peak internal rotation torques of the hip, knee, and ankle of the dominant and non-dominant plant leg for the three approach conditions are illustrated in Figures 3A–C. There was a significant effect of plant leg on the peak internal rotation torque of the knee ($F = 11.6$, $P = 0.014$). Participants produced greater peak internal rotation torque when using the dominant plant leg than the non-dominant plant leg. There was a small but significant difference between approach conditions for the ankle ($F = 8.6$, $P = 0.024$). Peak internal rotation torque of the ankle was greater during the on-axis approach than the center and off-axis approach.

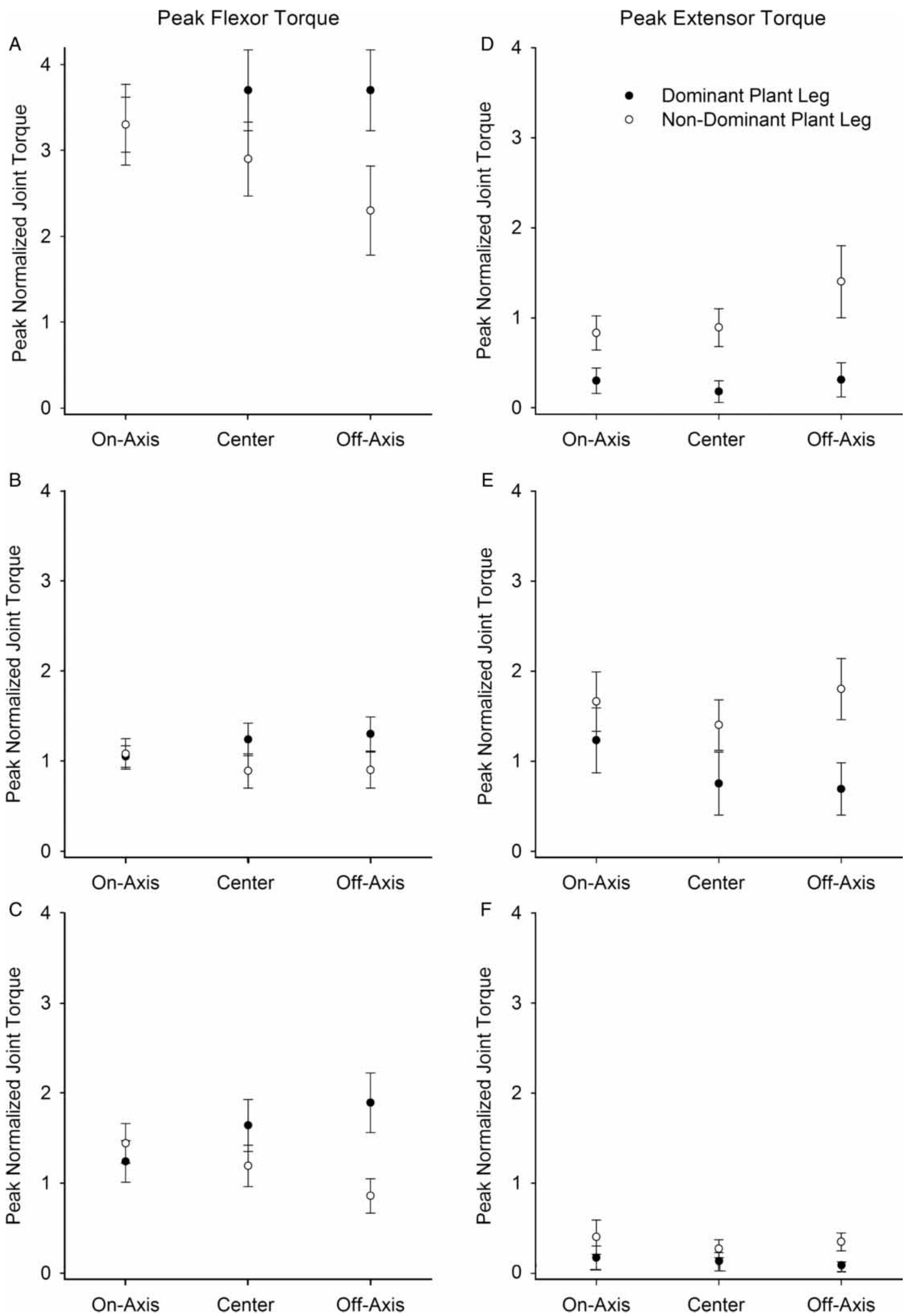

Figure 2. The effect of plant leg dominance on the absolute value of normalized peak flexor torque for on-axis, center, and off-axis approach conditions is plotted for the (A) hip, (B) knee, and (C) ankle. Similarly, the normalized peak extensor torque is plotted for the (D) hip, (E) knee, and (F) ankle. Data are presented in means ± standard errors.

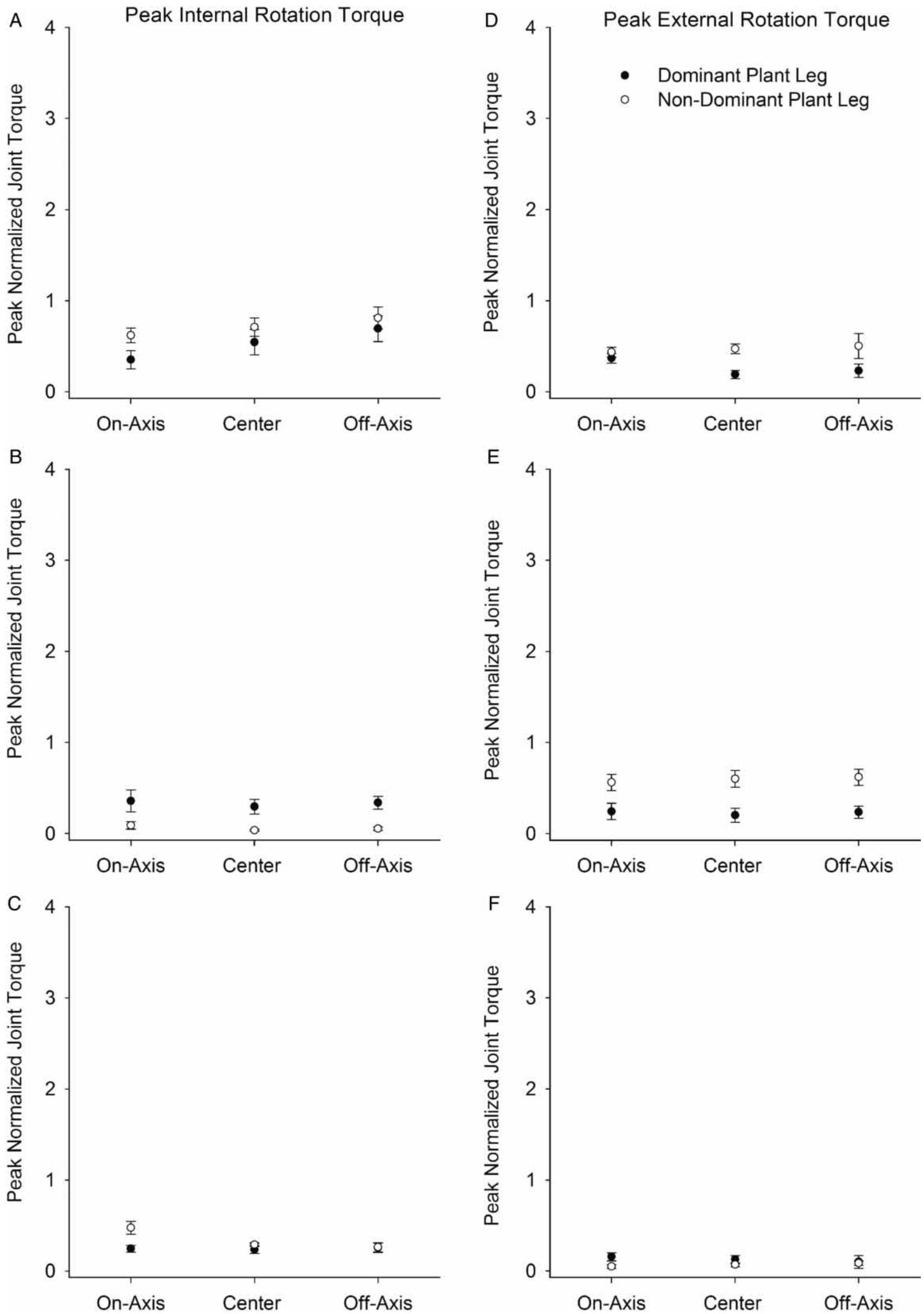

Figure 3. The effect of plant leg dominance on the absolute value of normalized peak internal rotation torque for on-axis, center, and off-axis approach conditions is plotted for the (A) hip, (B) knee, and (C) ankle. Similarly, the normalized peak external rotation torque is plotted for the (D) hip, (E) knee, and (F) ankle. Data are presented in means ± standard errors.

Peak external rotation torques of the hip, knee, and ankle of the dominant and non-dominant plant leg for the three approach conditions are illustrated in Figures 3D–F. There was a significant interaction of plant leg and approach condition for the hip ($F = 13.3$, $P = 0.011$) with significant simple main effects for the center ($F = 22.6$, $P = 0.003$) and off-axis approaches ($F = 12.5$, $P = 0.01$). As illustrated in Figure 3D, when kicking from a center or off-axis approach condition, participants had greater peak external rotation torque when planting with the non-dominant limb. For the knee, participants had significantly larger peak external rotation torque when planting with the non-dominant limb than the dominant limb regardless of the approach condition ($F = 116.1$, $P = 0.001$). There were no effects of plant leg or approach condition for the ankle.

Peak abduction and adduction torque

Peak abduction/adduction torques of the hip, knee, and ankle of the left and right plant leg for the three approach conditions are illustrated in Figures 4A–F. There were no interactions of plant leg and approach condition on peak abduction or adduction torque of the hip, knee or ankle. For all three approach conditions, participants had greater peak abduction torque of the hip ($F = 57.3$, $P = 0.001$), knee ($F = 528.8$, $P = 0.002$), and ankle ($F = 53.8$, $P = 0.001$) for the non-dominant plant leg compared with the dominant plant leg (Figures 4A–C). In contrast, peak adduction torque of the hip ($F = 26.9$, $P = 0.002$), knee ($F = 29.6$, $P = 0.002$), and ankle ($F = 102.5$, $P = 0.001$) was greater for the dominant plant leg than the non-dominant plant leg for all three approach conditions (Figures 4D–F).

Discussion

This is the first kinetic analysis of the hip, knee, and ankle of the plant leg during naturalistic soccer kicking tasks in collegiate female athletes. Overall, the results of this study show that, even at the collegiate level, when planting with the non-dominant leg, participants had greater amounts of braking torque (i.e. extension, external rotation, and abduction) than when planting with their dominant leg. In contrast, the acceleration torques (i.e. flexion, internal rotation, and adduction) are less for the non-dominant plant leg. These differences are especially evident in the off-axis conditions, which suggests that approach condition, as well as plant leg dominance, influenced kicking strategy when planting with the dominant versus non-dominant leg.

One of the main findings from this study is that differences emerged between the dominant and non-dominant plant legs in collegiate athletes when they kicked with their dominant limb from an off-axis approach. When the participants kicked with their non-dominant limb, they were more cautious or guarded when planting the non-dominant leg. Previous studies that have examined athletes' dominant and non-dominant kicking limbs during soccer tasks have primarily found that athletes produce greater ball velocities when kicking with the dominant limb (Mognoni et al., 1994; Barfield, 1995; Dorge et al., 2002). Our data are consistent with these findings. If participants use larger braking torques and smaller acceleration torques with the non-dominant plant leg, maximum ball velocity would naturally be less.

In addition to ball velocities, Barfield (1995) examined variability of ground reaction forces of the plant leg and kinematic measures of the dominant and non-dominant kicking limbs during in-step soccer kicking tasks in collegiate athletes. Barfield (1998) found that when the athletes kicked the ball using their non-dominant limb, they demonstrated more variability of the measures that correlated with ball velocity, especially angular position,

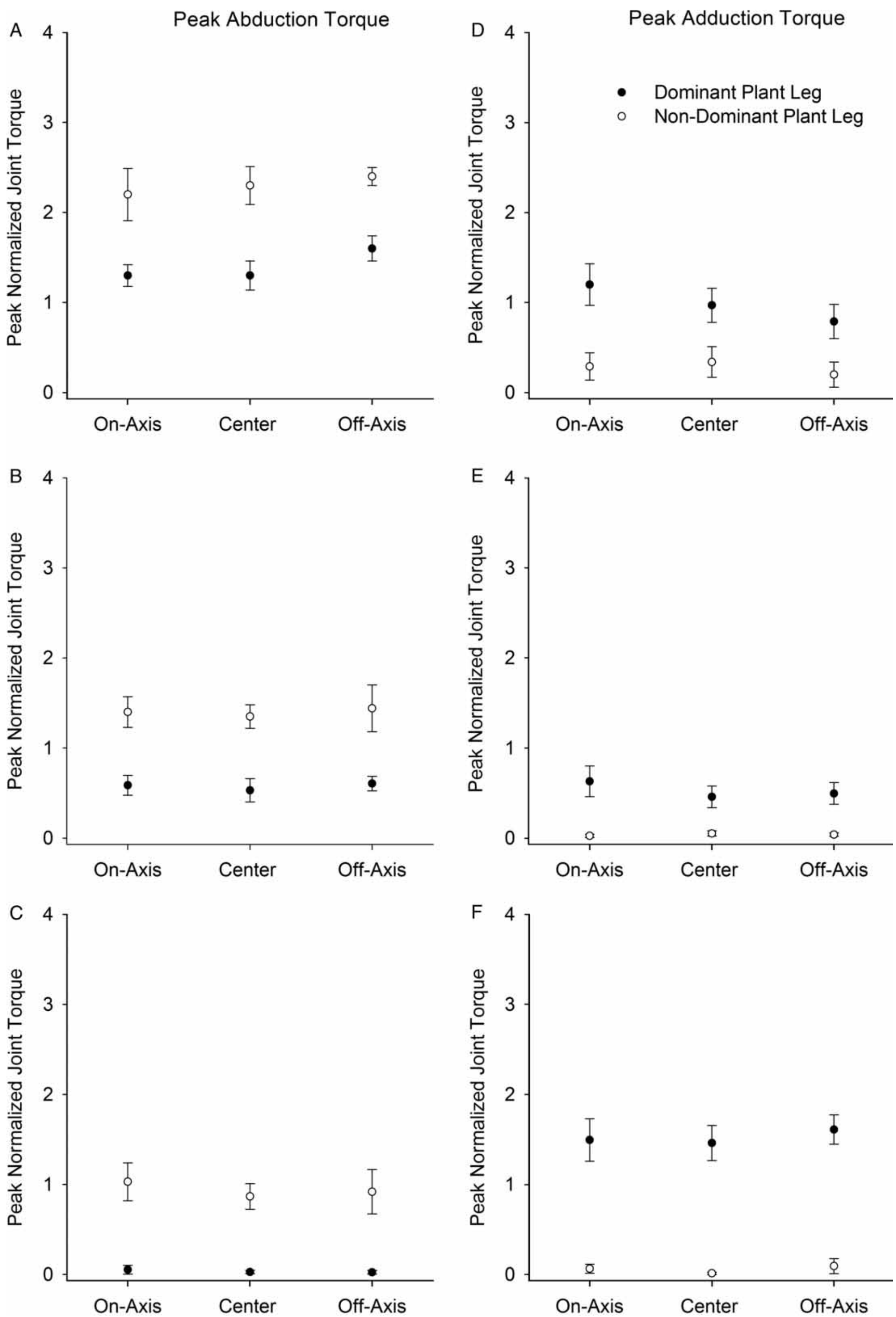

Figure 4. The effect of plant leg dominance on the absolute value of normalized peak abduction torque for on-axis, center, and off-axis approach conditions is plotted for the (A) hip, (B) knee, and (C) ankle. Similarly, the normalized peak adduction torque is plotted for the (D) hip, (E) knee, and (F) ankle. Data are presented in means ± standard errors.

compared with the dominant limb. Some of the measures that were associated with ball velocity included linear velocity of the big toe at ball contact, maximum angular velocity at the knee, maximum angular position at the knee, maximum knee flexion and extension torque, and angular position of the ankle from support foot (i.e. the foot of the plant leg) contact to ball contact. The increased variability may indicate a difference in the control of the non-dominant plant leg and is consistent with the differences we observed in plant legs, particularly during the center and off-axis approach conditions.

To date, no studies have looked at the effect of approach condition on peak lower extremity joint torques of the plant leg. We found that an off-axis kicking approach affected the lower extremity joint torques of the plant leg. In general, the off-axis approach resulted in increased flexion joint torques of the hip, knee, and ankle of the dominant plant leg compared with the on-axis approach. The increase in flexor torque may have been needed to rotate the body forward from an awkward position. Masuda et al. (2005) found that ball velocity was correlated with strength of the plant leg when kicking from a large or unnatural approach angle and that greater hip and knee strength of the plant leg was required to stabilize the body during an off-balance kick in collegiate athletes. Masuda and colleagues' findings provide evidence that an off-balance kick may change the mechanics of the plant leg and requires increased strength and stability compared with a kick from a straight approach (Masuda et al., 2005).

A second study that compared muscle strength and flexibility between the preferred and non-preferred kicking leg in elite and sub-elite players found that the knee flexors of the preferred kicking leg were weaker than those of the non-preferred leg (Rahnama et al., 2005). Rahnama and colleagues suggest that the difference in muscle strength could be explained by the fact that the knee of the plant leg is flexed during kicking, and the plant leg's flexor muscles are required to stabilize the knee joint, support the weight of the body, and resist the reaction of the torque produced by the opposite limb. Thus the knee flexors of the non-preferred limb (i.e. normally the plant leg) become stronger over time (Rahnama et al., 2005). Although we did not measure leg strength, it is possible that one of the factors influencing differences in joint torques between the non-dominant and dominant plant legs could be differences in strength as observed by Rahnama et al. and/or activation levels of the muscles of the lower leg used during the kicks.

In the present study, differences in peak joint torques between the dominant and non-dominant plant leg suggest differences in kicking strategies when participants performed the maximal effort kicking task. These differences in peak joint torques emerged even in elite collegiate athletes who train to be proficient in kicking with both legs.

The differences in peak flexor and extensor torques of the plant leg suggest that when the participants kicked with their dominant kicking limb they produced a larger pulling force, indicated by increases in peak hip, knee, and ankle flexor torque compared with the non-dominant plant leg. The differences in peak torques may reflect a difference in control or in turn be related to strength of the plant leg.

Peak internal rotation torque of the knee of the dominant plant leg was greater than that of the non-dominant plant leg for all three approach conditions, while peak external rotation torque of the hip and knee was greater in the non-dominant plant leg. Even stronger findings emerged with respect to peak abduction and adduction torques. Peak abduction torque of the hip, knee, and ankle was greater for the non-dominant plant leg than the dominant plant leg, while the opposite was true for peak adduction torque.

Overall, these findings suggest that when participants kicked with their dominant kicking limb they produced a larger pulling force, indicated by an increase in hip, knee, and ankle flexion, internal rotation, and adduction torque of the dominant plant leg compared with the non-dominant plant leg; however, when the participants kicked with their non-dominant kicking limb they demonstrated greater peak extensor, internal rotation, and abduction torque of the non-dominant plant leg, indicating a larger braking force to control the movement. The increased braking force suggests a more novice kicking strategy on the non-dominant plant leg (i.e. the leg not usually in contact with the ground during kicking).

It is known that ACL injury occurs during foot contact with the ground. As no studies have specifically addressed the risk of ACL injury or the strain on the ACL of the plant leg during kicking tasks, it begs the question of whether increased strain on the ACL occurs during rapid deceleration or quick stops prior to kicking in soccer (Boden et al., 2000; Fauno & Wulff Jakobsen, 2006). A case study by Cerulli and colleagues (2003) found that peak strain of the ACL occurred at the point of foot contact during a hopping manoeuvre and confirmed that the ACL will be in high stressful conditions during sport. The results of our study demonstrate that collegiate soccer players without prior injury display different flexor and extensor joint torque strategies in the dominant and non-dominant plant legs, particularly during off-axis kicks. If differences emerge in the mechanics of off-axis kicks in healthy participants, it would be beneficial to determine if differences also occur in those who have suffered an ACL injury to further explore the association of biomechanical variables to predict injury and further identify exact mechanisms of ACL injury in soccer.

Conclusion

Based on our results, minimal differences in peak flexor and extensor joint torques emerged between the dominant and non-dominant plant legs in collegiate female athletes when kicking from an on-axis approach; however, even at collegiate level, differences in peak flexor and extensor joint torques emerged between the dominant and non-dominant plant legs when participants kicked from a center or off-axis approach.

It is known that female athletes suffer non-contact ACL injuries of the leg that is in contact with the ground (Arendt et al., 1999; Fauno & Wulff Jakobsen, 2006). The findings from this study provide insight into the mechanics of the plant leg during maximal effort kicking tasks, including differences between plant legs and approach conditions. Collegiate soccer players display very different joint torque strategies in the dominant and non-dominant plant legs. It remains to be determined whether differences in the mechanics of off-axis kicks exist between healthy participants and those who have suffered an ACL injury, as well as to further examine the influence of plant leg dominance and approach condition on kicking strategy and control.

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