THE FOOT STRIKE ANGLE PREDICTS THREE-DIMENSIONAL KNEE JOINT MOMENTS IN PREPLANNED AND UNPLANNED SIDESTEP CUTS

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This study investigated if knee joint moments are related to the foot strike angle in preplanned and unplanned handball-specific sidestep cuts performed by n = 51 female handball players. Canonical correlation analysis (CCA) with the foot strike angle as predictor variable was performed on the knee joint moment vector field (M_{xyz}). Subsequently, post-hoc tests using CCA for moment couples and linear regression for individual moment components were performed. In both conditions, the foot strike angle was related to M_{xyz}. However, the relationship remains partially unexplained when the three-dimensionality of the moment vector remains unaccounted for, especially in the unplanned cut. Given the time periods in which correlations exist, the foot strike angle shows potential to reduce multi-plane knee loading associated with ACL injury.

KEYWORDS: ACL, cutting, knee, sidestepping.

INTRODUCTION: Since non-contact anterior cruciate ligament (ACL) injuries occur rapidly after the initial contact of the foot with the ground (Koga et al., 2010), understanding risky kinematics at initial ground contact is key for the development of injury prevention programs. Boden et al. (2009) have suggested that injury situations typically involve the foot firmly planted on the floor when comparing injured athletes to controls. In a study with female handball players, Kristianslund et al. (2014) showed that peak external knee abduction moments can be decreased by 13% when increasing the foot strike angle (FSA), i.e., the sagittal plane foot-floor angle, by one standard deviation towards a forefoot strike ("toe landing"). While external knee abduction moments clearly seem to be a key contributor in the injury mechanism (Hewett et al., 2005), it has been shown that combined loads elevate ACL strain more than single-plane loading (Markolf et al., 1995). Further, based on video analyses of real injury situations, the suggested injury mechanism includes a combination of knee valgus, tibia internal rotation and anterior translation (Koga et al., 2010). Robinson et al. (2015) have previously demonstrated how correlations between kinematics and individual moment components do not account for the complexity of the three-dimensional knee moments. To better understand how FSA affects knee moments associated with ACL injury, this study investigated the relationship between FSA and the overall M_{xyz} moment vector field throughout stance.

METHODS: Data were collected from n = 51 high-level female handball players (mean ± SD: 67.0 ± 7.7 kg, 1.70 ± 0.06 m, 19.2 ± 3.4 years). The study was approved in compliance with the Declaration of Helsinki. As part of a larger study (Mai et al., 2022), players were equipped with a full-body marker set, and kinematics and kinetics were sampled with a 24-camera motion capture system (Qualisys, Gothenburg, Sweden; 200 Hz) and floor-embedded force platforms (AMTI, Watertown, Massachusetts, USA, 600 x 1200 mm; 1000 Hz), respectively. In the present study, a minimum of five valid trials, i.e., following a clean catch of the ball with the foot fully placed within the boundaries of the force platform, of each of the following two conditions was analyzed: 1) a preplanned handball-specific cutting maneuver (PP) in which players were instructed to catch a ball passed by a team mate and subsequently perform a sidestep cutting

maneuver to fake a static human defender, and 2) an unplanned handball-specific sidestep cut (UP) in which players were instructed to catch a ball passed by a team mate to subsequently perform a sidestep cut to pass three variably moving defenders. In this task, the middle defender and one of the outside defenders pressured the player upon catching the ball, and the player was instructed to cut towards the side of the defender that remained static, resulting in an unplanned cutting direction (Mai et al., 2022).
An overall external knee joint moment vector field, M_{xyz}, with M_x representing frontal plane moments, M_y representing sagittal plane moments, and M_z representing transverse plane moments, was created after all data were time-normalized to 201 data points from 100 ms before initial ground contact to toe-off. To test the null hypothesis that FSA and knee joint moments are unrelated, canonical correlation analysis (CCA), the statistical parametric mapping (SPM) vector field equivalent of linear regression (Pataky et al., 2013), was performed. FSA, defined as the angle between the long axis of the foot and its projection to the ground at initial ground contact, served as the predictor variable. Positive angles indicated a forefoot strike. The alpha level was set to $\alpha = 0.05$. CCA was also performed for post-hoc analyses of moment couples (M_{xy}, M_{xz}, M_{yz}), and linear regression was performed as post-hoc tests for individual moment components (M_x, M_y, M_z). To retain a family-wise error rate of $\alpha = 0.05$, Šidák thresholds of 0.017 were adopted for post-hoc tests.

RESULTS: For PP, FSA was significantly related to M_{xyz} during early ($p = 0.006$ at 0% – 13.2%) and late stance ($p = 0.029$ at 67.7% – 74.6%; Figure 1A). Post-hoc analyses of moment couples revealed that the non-sagittal (M_{xz}; $p = 0.003$ at 0% – 12.0%; Figure 1C) and sagittal-transverse (M_{yz}; $p = 0.002$ at 0% – 12.8%; Figure 1D) moment couples explained most of the results found during early stance while results for the frontal-sagittal (M_{xy}) moment couple were also significant ($p = 0.015$ at 0% – 3.1%; Figure 1B). Individually, the transverse plane moment (M_z; Figure 1J) explained most of the results found during early ($p = 0.007$ at 3.6% – 12.4%) and late stance ($p = 0.016$ at 73.8% – 6.6%, Figure 1G). Results for the frontal (M_x; Figure 1H) and sagittal plane moment (M_y; Figure 1I) also yielded significance during a brief early portion of stance ($p = 0.017$ at 0% – 0.8%; Figure 1E and $p = 0.013$ at 0% – 3.8%; Figure 1F, respectively).

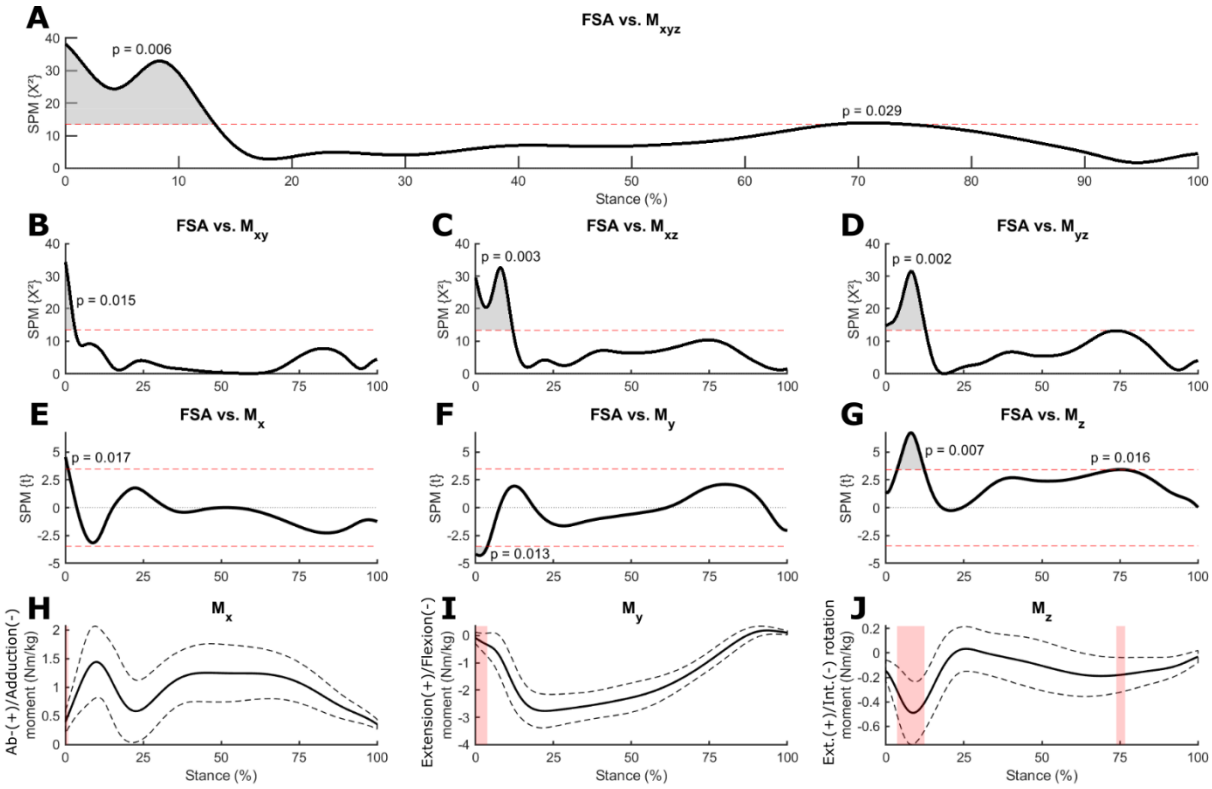

Figure 1: Results for the preplanned cutting maneuver. A) Trajectory level SPM analyses for the relationship between the foot strike angle and the overall M_{xyz} vector field. B – D) Trajectory level SPM analyses for the relationship between the foot strike angle and the moment couples M_{xy}, M_{xz}, and M_{yz}. E) – G) Trajectory level SPM analyses, depicting the strength of positive (+) and negative (-) correlation between the individual moment components (M_x, M_y, and M_z) and the foot strike angle. H) – J): Resultant external knee joint moments M_x, M_y, and M_z.

For UP, FSA was significantly related to M_{xyz} during early ($p < 0.001$ at 0% – 22.9%) and late stance ($p = 0.048$ at 98.0% – 100%; Figure 2A). Post-hoc analyses of moment couples revealed that the non-sagittal (M_{xz}; $p = 0.002$ at 0% – 15.3%; Figure 2C) and sagittal-transverse (M_{yz}) moment couples ($p = 0.003$ at 0% – 12.5%; Figure 2D) partially explained the results found during early stance while results for the frontal-sagittal (M_{xy}) moment couple were also significant ($p = 0.016$ at 0% – 1.6%; Figure 2B). The non-sagittal moment couple (M_{xz}) partially explained the results during push-off ($p = 0.017$ at 99.3% – 100%; Figure 2C). Individually, it was mainly the transverse plane moment (M_z; Figure 2J) that explained the results found during early stance ($p = 0.007$ at 3.2% – 12.8%, Figure 2G) while results for the sagittal plane moment (M_y; Figure 2I) also yielded significance ($p = 0.015$ at 0% – 2.9%; Figure 2F). However, moment couples and individual moment components failed to provide a complete explanation of the results.

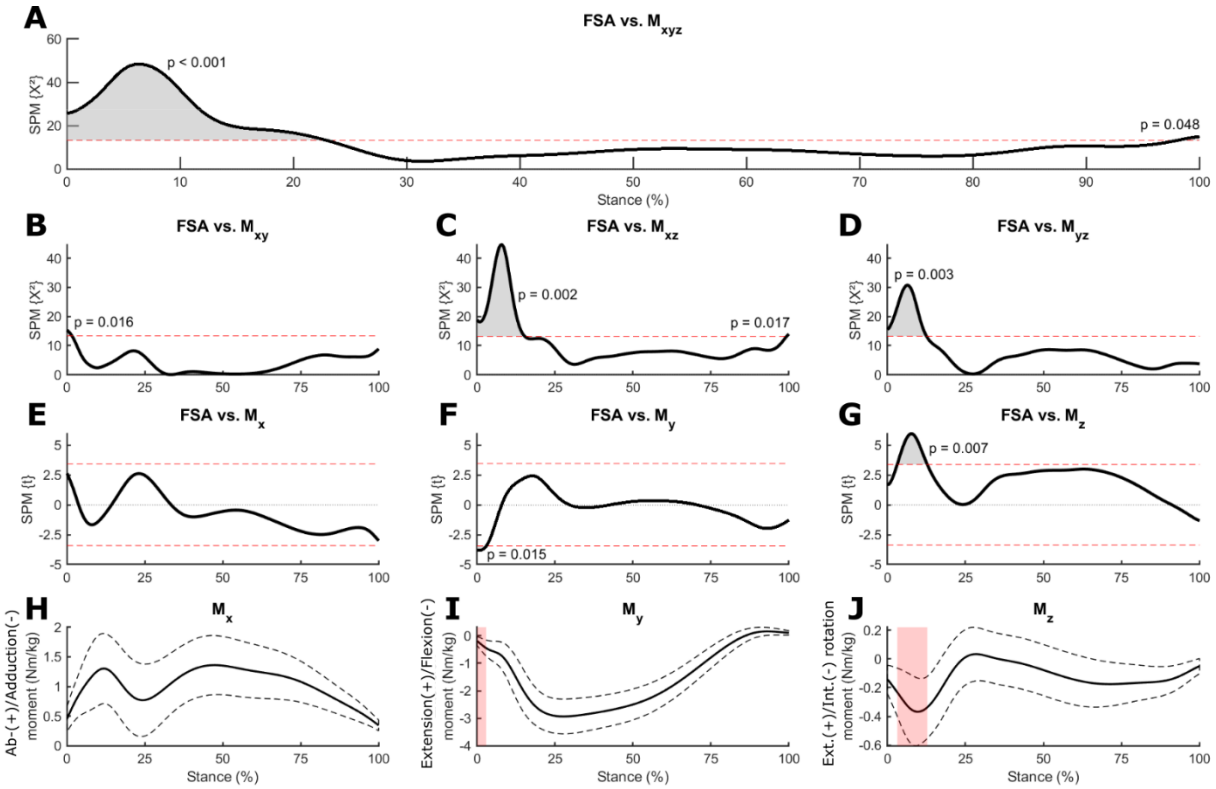

Figure 2: Results for the unplanned cutting maneuver. A) Trajectory level SPM analyses for the relationship between the foot strike angle and the overall M_{xyz} vector field. B – D) Trajectory level SPM analyses for the relationship between the foot strike angle and the moment couples M_{xy}, M_{xz}, and M_{yz}. E) – G) Trajectory level SPM analyses, depicting the strength of positive (+) and negative (-) correlation between the individual moment components (M_x, M_y, and M_z) and the foot strike angle. H) – J): Resultant external knee joint moments M_x, M_y, and M_z.

DISCUSSION: The study revealed that FSA is significantly correlated with the M_{xyz} vector field in PP and UP. Correlations were found during both early and late stance, with the latter correlations not existing when decomposing the overall vector field into moment couples and individual moment components. In both cutting scenarios, it was the frontal-transverse and the sagittal-transverse moment couples M_{xz} and M_{yz}, respectively, that best explained the results. Individually, the transverse plane moment M_z showed the highest correlation with FSA.

However, moment couples and individual moment components failed to fully explain the correlations found for the overall M_{xyz} vector fields. This discrepancy is more evident in UP scenario and can be attributed to the complex three-dimensional nature of knee moments, which is captured in the M_{xyz} vector field analysis but overlooked when examining individual components. Given that the non-sagittal plane moments are highly relevant for ACL injury (Koga et al., 2010; McLean et al., 2004), and FSA is related to multi-plane knee moments with a particularly strong correlation in the non-sagittal plane combination, FSA shows potential to modify ACL injury risk. Precisely, an increase in FSA (i.e., towards a forefoot strike) seems to be inversely related to knee abduction (Figure 1E,H; Figure 2E,H) and internal rotation moments (Figure 1G,J; Figure 2G,J) in the phase of peak loading. These insights enhance our understanding of the biomechanical implications of initial ground contact kinematics on knee loading patterns, shedding light on factors influencing ACL injury risk.

CONCLUSION: FSA is a predictor for three-dimensional knee moments in both PP and UP. While moment couples and individual components provide a comprehensive understanding in PP, the overall M_{xyz} vector field offers a broader perspective, particularly in the UP scenario. The correlations identified during early stance indicate that employing a forefoot strike might be beneficial in mitigating ACL injury-relevant joint loads. Therefore, incorporating forefoot strike techniques into injury prevention programs could be a strategic approach to reducing ACL injury risk.

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