IMPACT OF FOOTWEAR BENDING STIFFNESS AND TORSIONAL STIFFNESS ON ANKLE BIOMECHANICS DURING HANDBALL SPECIFIC FAKE-AND-CUT MANOEUVRES

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In this study, the impact of footwear bending stiffness on ankle and foot biomechanics during indoor fake-and-cut manoeuvres was investigated. Footwear, along with torsional and bending stiffness, are hypothesized to influence the risk of ankle sprain injury. In this study, a mobile, pneumatically driven cantilever rig was used to quantify these footwear characteristics. Following this, participants executed fake-and-cut movements wearing their habitual footwear, while motion capture and force plate data were recorded. Utilizing machine learning clustering algorithms, participants were grouped based on their footwear stiffness. Subsequent SPM analysis revealed lower forefoot dorsiflexion and increased forefoot inversion in the stiff group. These findings underscore the need for further research on the interaction between shoe properties and injury risk indicators.

KEYWORDS: footwear, stiffness, mechanical testing, ankle sprains, injury risk

INTRODUCTION: Lateral ankle sprains are the most common injuries in sports, particularly in indoor and court sports. They are characterized by excessive inversion and internal rotation, with or without the presence of plantar flexion (Gribble et al., 2016). Hence, it becomes essential to laterally stabilise the ankle joint to prevent excessive inversion, particularly during movements involving jump landings and changes of direction. The torsional movement of the foot, enabled by the inversion or eversion of the forefoot against the rearfoot, has been identified as critical to adapting to the ground during such movements (Michel et al., 2009). Footwear accounts for an important external risk factor for ankle sprain injuries (Tropp, 2002). It has been suggested that shoes with greater torsional stiffness may lead to greater ankle inversion and external inversion moments, as they restrict the natural movement of the foot and ankle, making the ankle more vulnerable to lateral ankle sprains (Graf & Stefanyshyn, 2013). Torsional and longitudinal bending stiffness appear to be interconnected; however, the extent of their interaction lacks empirical evidence. It can be speculated that there might be a movement- and subject-specific 'sweet spot' for both parameters (Graumann et al., 2007; Ortega et al., 2021). Testing participants and exposing them to different footwear in a lab environment may introduce limitations such as a lack of familiarization. Hence, exploring whether wearing habitual footwear with varying stiffness levels influences cutting biomechanics, and if this correlates with individual characteristics, could provide valuable insights. Therefore, the objective of this study was to examine whether wearing flexible or stiff habitual footwear results in different ankle and foot biomechanics during indoor-specific fake-and-cut maneuvers.

METHODS: This study was part of a bigger project where in-depth biomechanical analyses of cutting technique of 49 female junior elite handball players was performed. Participants were between 15 and 18 years old and from various Norwegian handball clubs (elite, 1st, 2nd, 3rd division).
Mechanical Testing: Prior to the biomechanical investigation, longitudinal forefoot bending stiffness (FFB) and torsional stiffness (TOR) of the participants' shoes were measured using a specially designed cantilever rig. The heel and forefoot were mounted on separate platforms,

with the forefoot platform plate possessing the capability to rotate along the medio-lateral or anterior-posterior axes of the shoe. Through a pulley system, the forefoot platform was linked to the moving arm of a pneumatic actuator. The actuator was equipped with a built-in force transducer that allowed for recording forces. In order to facilitate system mobility, the actuator operated under air pressure. The pressure was adjusted to achieve a flexion angle of at least 40° and a torsion angle of 30°. The average bending velocity was approximately 60°/s; however, slight variations were observed due to pressure dependency. The average stiffness was determined by calculating the slope of the force-deformation curve within the range of 1 to 90% of the maximum deformation. Python's sklearn KMeans clustering was used to categorize shoes into two separate groups, 'flexible' and 'stiff', based on the combined shoe characteristics FFB and TOR. To investigate potential connections between torsional stiffness and forefoot bending stiffness, a linear regression analysis was carried out.
Biomechanics: Handball-specific fake-and-cut movements were performed in front of a passive defender after receiving a pass (Kristianslund et al., 2014). The cutting speed was self-selected but also intended to match game intensity, with players arriving at an angle of approximately 35 degrees. Cuts were performed in both the left and right directions, and three cuts for each side were used for analysis. For three subjects, 2–3 trials had to be excluded. Participants wore their own habitual indoor sports shoes, sports bras, and shorts. A three-dimensional motion capture system (Qualisys AB, Sweden, 23 cameras, 200 Hz) and two force plates (AMTI, USA, 1000 Hz) were used to record the kinematics and kinetics of the players. A full-body marker set with 82 retro-reflective markers was used. The forefoot segment was defined using markers on the shoe upper at the MT1, MT5, and the distal hallux, while markers on the medial, lateral, and posterior parts of the calcaneus defined the rearfoot segment. Their relative movement describes the motion around the metatarsophalangeal (MTP) joint. For details on filtering, joint angles, and inverse dynamics calculations, please refer to previous publications (Bill et al., 2022). Differences in kinematics and kinetics during the ground contact phase were calculated with statistical parametric mapping (SPM) time series analysis using an independent (two-sample) t-test (Robinson et al., 2015). Additionally, the peak external ankle inversion moment was compared between groups using an independent t-test implemented in Python's Pingouin toolbox (www.pingouin-stats.org). The same statistical test was used to check for differences in age, body mass, and body height between groups.

RESULTS: The total number of shoes that were included was 49, with Adidas (29), Mizuno (16), Asics (2), Puma (1), and Hummel (1) being the brands that were used by the participants. The most popular shoe models were Adidas Crazyflight (15), Mizuno Wave Lightning Z6 (8), Crazyflight Mid (7), and Wave Stealth Neo (3). The shoe sizes ranged from UK 4 to 8, with 6.4 ± 0.9 being the average. The shoes were utilised for an average of 0.76 ± 0.67 years, with a range of 0 to 2.5 years. Two shoes lacked sizing information, while the usage duration of seven shoes remained undisclosed. The KMeans clustering algorithm classified 28 shoes into 'flexible' and 21 shoes into 'stiff'. Participants of both groups did not differ in age, body mass, and body height (Table 1). Linear regression revealed that TOR and FFB were significantly related ($y = 0.6x + 0.001$, $p<0.001$), accounting for 60% of the variation ($R^2 = 0.6$). The SPM analysis revealed significant differences in forefoot inversion (full ground contact, $p<0.001$) and forefoot dorsiflexion (10-75% of ground contact, $p = 0.011$) between groups. No significant differences could be observed in ankle angles or ankle moments. While no significant difference was observed in the peak ankle inversion moment, results approached significance, suggesting increased moments in the 'flexible' group ($p = 0.11$, Cohen's d effect size = 0.45).

Table 1: Mean values and standard deviations of participants' anthropometrics, mechanical shoe properties, and ankle kinetics separated by groups.

Group	Age [years]	Body height [m]	Body mass [kg]	FFB [Nm/°]	TOR [Nm/°]	Peak ankle inv. moment [Nm/kg]
Flexible	16.8 (0.84)	1.72 (0.07)	69.5 (10.0)	0.051 (0.014)	0.083 (0.012)	-0.20 (0.17)
Stiff	16.5 (0.98)	1.74 (0.05)	68.9 (6.7)	0.077 (0.014)	0.123 (0.015)	-0.13 (0.13)

Overall	16.7 (0.9)	1.73 (0.06)	69.2 (8.7)	0.062 (0.019)	0.100 (0.024)	-0.17 (0.16)

DISCUSSION: Differences were observed in forefoot dorsiflexion and forefoot inversion (torsion) between the soft and stiff groups. In the stiff condition, forefoot dorsiflexion was restricted while inversion was increased. The reason for this is unclear, as it was hypothesized that if one plane is restricted due to shoe stiffness, the same restriction would apply to other planes. This discrepancy suggests that participants compensate for limited forefoot dorsiflexion by increasing forefoot inversion, as the latter is potentially easier to achieve during this movement. Visual inspection confirmed this behaviour in athletes. Additionally, individual cutting patterns may vary among participants who prefer stiff shoes. It is assumed that athletes, after wearing a shoe for an extended period, either prefer its properties or have adapted to it. However, participants were not informed about the specific shoe tests conducted with their footwear. Consequently, it can be assumed that their habitual movement pattern was not altered, as it is the case in lab studies where participants are confronted with entirely new footwear conditions. Given that the shoes are used in their typical 'in the field' fashion, a rather genuine effect of that model choice can be assumed. Hence, it could be argued that this approach enhances ecological validity and opens up new perspectives for footwear assessments.

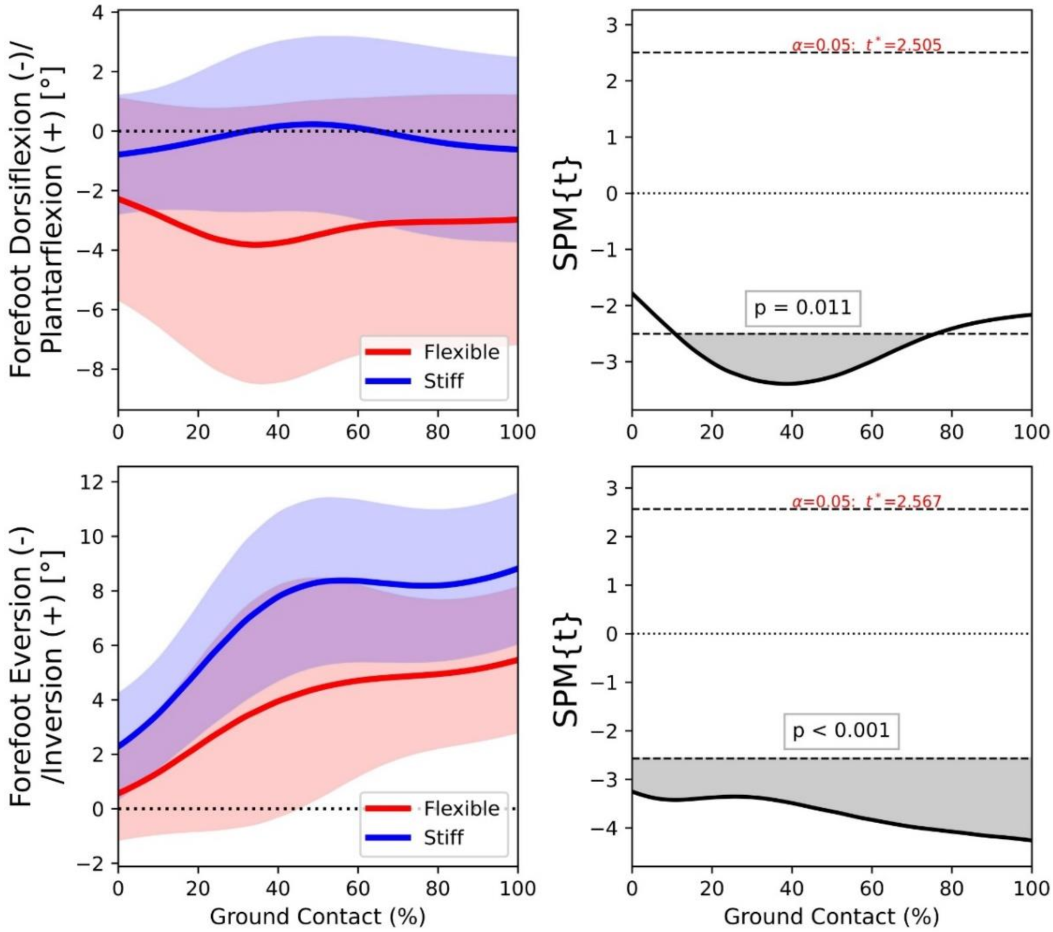

Figure 1: Average values (bold line) and standard deviations (shaded area) for both shoe groups. The right-hand graphs display the results of the SPM analysis, with grey-shaded areas indicating significant differences between the groups during these specific periods.

It is intriguing to note that these cutting movements do not involve a significant degree of forefoot movement. Participants appear to maintain their MTP joints in a dorsiflexed or neutral position during ground contact. The majority of movement occurs in the frontal plane, underscoring the importance of enabling torsional movements in the foot during cutting maneuvers, which supports previous research (Graf & Stefanyshyn, 2013; Michel et al., 2009).

The current study was not designed to answer whether the observed difference indeed poses an injury risk. However, despite the absence of a significant difference in ankle inversion moment as indicated by the SPM analysis, a low p-value and an effect size close to medium strength suggested a potential implication of peak inversion moments. This would suggest a potentially higher load at the ankle joint. Conversely, an indication for higher peak values was observed in the 'flexible' condition, making it challenging to reconcile with the observed kinematic results. In absolute terms, the average stiffness of the 'stiff' group is not high when compared to very rigid or carbon-reinforced models. This may account for the absence of effects at the ankle similar to those observed in previous studies (Graf & Stefanyshyn, 2013). Nonetheless, there were considerable differences across the shoe groups, which mirrored a spectrum of available shoes on the market. The findings highlight the importance of footwear characteristics, even when their differences may seem minimal on an absolute level.
The placement of markers on the upper material of the shoes provides limited insight into the detailed movement of the foot inside the shoe. Recent research has demonstrated that external shoe markers underestimate foot movement within the shoe (Alcantara et al., 2018). Assuming this holds true for the current study, dorsiflexion and inversion values of the foot would likely be higher, but differences between shoe conditions presumably remain systematic.

CONCLUSION: The novelty of this study lies in conducting footwear tests in combination with game-specific athlete testing. Analysing the kinematics and loads of athletes executing cutting movements in habitual footwear of varying stiffness levels resulted in significant differences in forefoot inversion and forefoot dorsiflexion. This study contributes to a better understanding of the interaction between mechanical shoe properties and biomechanical outcomes. Further research is essential to deepen the knowledge of how footwear properties influence the risk of ankle sprain injuries.

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