Calcaneofibular Ligament Rupture Increases Ankle Inversion during Walking in In-Silico Musculoskeletal Dynamics study

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INTRODUCTION: The three ligaments in the lateral side of the ankle joint complex, anterior talofibular ligament (ATFL), posterior talofibular ligament (PTFL), and calcaneofibular ligament (CFL) have important roles in providing stabilities to the ankle joint [1]. Lateral ankle ligament sprain arises due to excessive inversion and internal rotation of the joint, which applies abnormal stress on collateral ligaments, resulting the ligament rupture [2]. Such ankle strains have shown an increased susceptibility to future injuries, making an understanding of ankle joint kinematic changes following ligament injuries a crucial factor in the enhancement of ligament injury treatments. While previous research has employed cadaveric models and motion capture systems to analyze ankle kinematic alterations post-ligament injuries [3, 4], these approaches face limitations in replicating real-world walking conditions and quantifying effects of individual ligament ruptures on joint motion [3, 4]. Consequently, dynamic simulation-based studies have been undertaken to address these challenges. The aim of this study is to quantitatively analyze the impact of individual lateral ankle ligament injuries on kinematics of ankle joint complex. We hypothesized that the absence of the ATFL and CFL would increase ankle inversion motion during walking, thereby increasing ankle joint instability. We also compared the changes of ankle kinematics by individual ruptures of the ATFL and CFL.

METHODS: This research is approved by the Institutional Review Board at Korean Advanced Institute of Science and Technology. A full-body model was developed based on the Rajagopal model [5], incorporating twelve muscles and six ligaments on the right foot. The initial ligament lengths and attachment points were determined according to reference [6], and ligament tension was calculated using a nonlinear strain-tension relationship equation [7]. Each foot was equipped with five collision bodies. A reference motion was generated from experimental data, with a single participant free from musculoskeletal diseases walking on flat ground while wearing 3D reflective markers attached to the body. Inverse kinematics were applied to marker data to calculate joint angles during walking, which served as the reference motion for human walking and were used to train a gait controller responsible for controlling the full-body model. The gait controller was trained to guide the full-body model in following the reference motion, ultimately generating a walking motion for the entire model. After the gait controller had been trained, rotational kinematics of the tibiocalcaneal joint were simulated under three different foot conditions: normal foot, foot with ATFL rupture, foot with CFL rupture. Rotational motion during walking under these different foot conditions was analyzed to assess the variations in motion following ligament rupture. Student t-test was used to check statistical significance.

RESULTS SECTION: The rotational motion of the tibiocalcaneal joint was assessed under four distinct conditions. In the case of ATFL rupture, minimal disparity in rotational motion was observed. Conversely, in the instances of CFL rupture, significant ($p<0.05$) increase in inversion angle was noted during the stance phase. Specifically, the simulation of the foot with CFL rupture exhibited an increase in average inversion angle by 7.9 degrees. Ankle adduction angle also showed a significant ($p<0.05$) decrease of 6.13 degrees The mean adduction angle decreased significantly ($p<0.05$) by 6.1 degrees in the ankle with CFL rupture. Notably, plantarflexion/dorsiflexion motion did not exhibit significant change across all ligament rupture conditions.

DISCUSSION: The simulation results indicated increased inversion motion in the tibiocalcaneal joint following CFL ligament rupture. This observation is consistent with a previous study, which reported a substantial increase in inversion angle following the toe-off phase [4], a result that is supported by the findings of our simulation. Furthermore, Hunt et al. [8] documented that the CFL plays a substantial role in stabilizing lateral ankle motion, whereas the ATFL has a comparatively lesser impact on lateral instability. Our simulations concur with this conclusion, as they reveal that ATFL rupture does not significantly alter the inversion motion of the tibiocalcaneal joint, whereas CFL rupture results in increased average inversion angle of 7.85 degrees, accounting for approximately 25 to 50% of the total inversion range of motion. This study has some limitations. Firstly, the gait controller was trained using kinematic data from a single participant, which may not fully capture the variability in human gait. Secondly, ligament characteristics inherently exhibit subject-specific variations. However, this study relied on ligament characteristics reported in previous research, potentially introducing variability in the kinematic influence of ligaments on the ankle.

SIGNIFICANCE/CLINICAL RELEVANCE: Walking of a musculoskeletal human model was simulated using a deep learning based gait controller to assess the effects of individual ATFL and CFL injuries on ankle kinematics. CFL rupture significantly increases tibiocalcaneal joint inversion angle and significantly decreases tibiocalcaneal joint adduction angle.

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IMAGES AND TABLES:

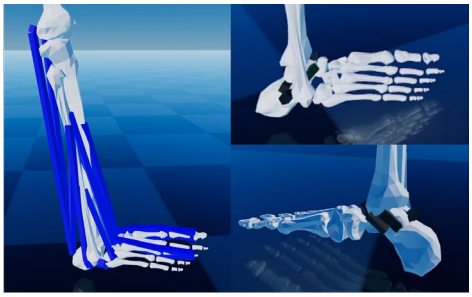

Figure 1. Muscles and ligament attached on right foot. Blue line represent muscles, and dark line represents ligaments.

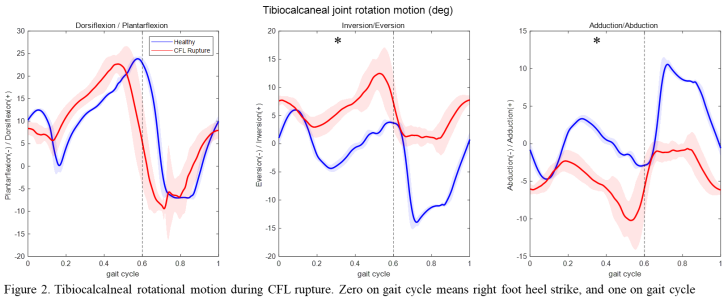

Figure 2. Tibiocalcalneal rotational motion during CFL rupture. Zero on gait cycle means right foot heel strike, and one on gait cycle means next right foot heel strike. Blue line shows motions for healthy situation, and red line shows motions for ligament ruptured situation.