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The in situ force in the calcaneofibular ligament and the contribution of this ligament to ankle joint stability

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A B S T R A C T

Background: Numerous biomechanical studies of the lateral ankle ligaments have been reported; however, the isolated function of the calcaneofibular ligament has not been clarified. We hypothesize that the calcaneofibular ligament would stabilize the ankle joint complex under multidirectional loading, and that the in situ force in the calcaneofibular ligament would change in each flexed position.
Methods: Using seven fresh frozen cadaveric lower extremities, the motions and forces of the intact ankle under multidirectional loading were recorded using a 6-degree-of-freedom robotic system. On repeating these intact ankle joint complex motions after the calcaneofibular ligament transection, the in situ force in the calcaneofibular ligament and the contribution of the calcaneofibular ligament to ankle joint complex stability were calculated. Finally, the motions of the calcaneofibular ligament-transected ankle joint complex were recorded.
Findings: Under an inversion load, significant increases of inversion angle were observed in all the flexed positions following calcaneofibular ligament transection, and the calcaneofibular ligament accounted for 50%–70% of ankle joint complex stability during inversion. The in situ forces in the calcaneofibular ligament under an anterior force, inversion moment, and external rotation moment were larger in the dorsiflexed position than in the plantarflexed position.
Interpretation: The calcaneofibular ligament plays a role in stabilizing the ankle joint complex to multidirectional loads and the role differs with load directions. The in situ force of the calcaneofibular ligament is larger at the dorsiflexed position. This ligament provides the primary restraint to the inversion ankle stability.

1. Introduction

Lateral ankle sprain is one of the most common injury (Waterman et al., 2010). Anatomic structures involved in lateral ankle sprains included the anterior talofibular ligament (ATFL) (85.3% of sprains) and calcaneofibular ligament (CFL) (34.5%) (Swenson et al., 2013). Inappropriate treatment of lateral ankle ligament injury can cause chronic ankle pain, instability, and long-term degenerative osteoarthritis (Valderrabano et al., 2006). Following only non-operative treatment, 70% of ankles with combined injuries of ATFL and CFL were symptomatic (Samoto et al., 2007). For lateral ankle ligament injury with persisting symptoms, many tenodesis methods and repair methods, which are nonanatomical procedures, have been performed (Chrisman and Snook, 1969; Evans, 1953; Gould, 1987). Recently, various anatomical reconstruction procedures have been developed and reported to result in good clinical outcomes (Coughlin et al., 2004; Paterson et al., 2000; Takao et al., 2005). An adequate anatomic reconstructive procedure should restore the biomechanical function of the intact ankle, however, the biomechanical analysis studies of anatomic reconstructive procedures are still insufficient. In such situation, variety types of procedures have been performed from isolated ATFL reconstruction to combined ATFL and CFL reconstruction with inconsistent initial tension at graft fixation. For the purpose of developing a more appropriate anatomical ligament reconstruction procedure, it is important to clearly understand the functions of each ligament alone and in combination.

Regarding the lateral ankle ligaments, many biomechanical studies have been conducted to elucidate the functions of the ligaments and to assess the effects of treatments of the ligaments (Fujii et al., 2010; Johnson and Markolf, 1983; Ringleb et al., 2011; Schmidt et al., 2004). However, the isolated function of the CFL remains unclear. Few studies had been assessed about the CFL in isolation because the isolated rupture of CFL is rare at the actual injury situation. In addition, these studies have some limitations including the accuracy of loads or measurements

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made according to manual procedures or nonphysiological joint motion simulated by an experimental apparatus with a constrained degree of freedom.

In a previous study, we used a robotic system to perform biomechanical tests on the knee to determine the biomechanical characteristics of the anterior cruciate ligament (Fujie et al., 2004). This robotic system allowed unconstrained motion under the application of a load in one direction, which was considered to generate more physiological motions compared with those generated in previous biomechanical studies using devices with a constrained system.

The force within the ligament measured under the physiologic condition is called the "in situ force." In previous studies of the knee ligaments, using the robotic system, the in situ forces in each bundle of the anterior cruciate ligament or the posterior cruciate ligament were clarified, and then, these data were used as information by which the initial tension at graft fixation in the ligament reconstruction surgery was determined (Fox et al., 1998; Fujie et al., 2011; Mae et al., 2008). Considering the advances made in anatomical reconstruction of the lateral ankle ligaments in recent years, it is important to elucidate the functions of not only the ATFL but also the CFL. The in situ force in the CFL has, however, not been completely investigated.

The purposes of this study are to measure the kinematic changes that occur on CFL transection and the in situ forces in the CFL in the loaded ankle and to determine the contribution of the CFL to ankle stability using a robotic system. Our primary aim is to investigate the isolated function of the CFL.

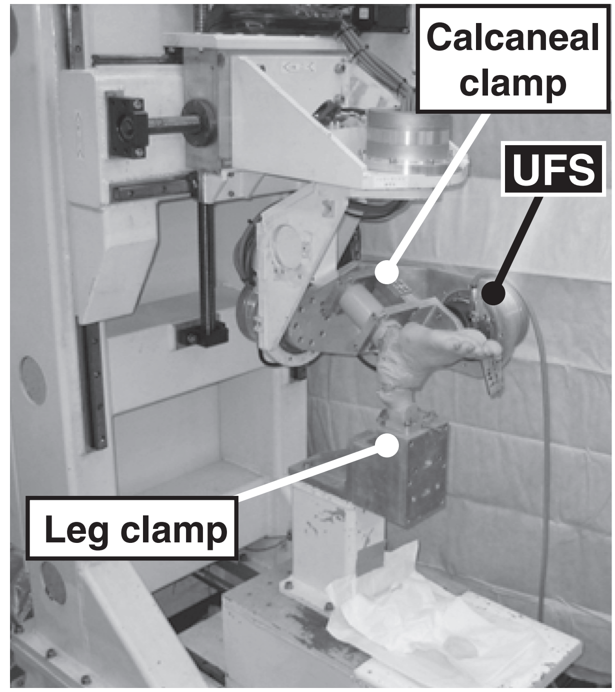

Fig. 1. Six-DOF robotic system. UFS, Universal Force/Moment Sensor.

2. Methods

2.1. Specimens

Seven male cadaveric lower extremities were obtained from donors with a mean age of 81 (SD 4) years. The Institutional Research Ethics Committee reviewed and approved the study protocol. The specimens were preserved at −20 °C and thawed for 24 h at room temperature before testing.

We obtained X-ray images of the specimens to identify those had no sclerosis and no osteophyte formation, so we had ensured that none of the specimens was affected by significant degenerative joint disease (Takakura et al., 1995). (After the tests performed, we confirmed macroscopically that the ATFL was intact in the specimens.) The tibia and fibula were cut to 15 cm in length from the lateral malleolus, and the soft tissues of the leg were carefully removed to up to 3 cm from the ankle joint. The soft tissue around the body of the calcaneus was removed, but the CFL was not exposed. Therefore, the soft tissues around the ankle joint remained intact. Distal tibiofibular syndesmosis was fixed with screws and acrylic resin (Ostron II; GC Corporation, Tokyo, Japan) with the ankle joint complex, which was composed of the ankle and the subtalar joint, in neutral position (Wu et al., 2002). The ends of the tibia and the fibula were inserted into cylindrical molds of acrylic resin. Steinmann pins and screws were inserted into the calcaneal tuberosity, and the posterior part of the calcaneus was inserted into cylindrical molds of acrylic resin while preserving the CFL. The lower leg and calcaneal cylinders were secured to the clamps of the robotic system described below (Fig. 1).

2.2. Testing device

The mechanical testing system consisted of a 6 degrees of freedom (DOF) manipulator, servomotor controllers, and a control computer (Fujie et al., 2004). The 6-DOF manipulator consisted of three translational actuators and three rotational actuators. The 6-axis manipulator is consisted of three translational actuators (SGMP series, Yasukawa, Fukuoka, Japan) and three rotational actuators (FHA series, Harmonic Drive Systems, Shinagawa, Tokyo, Japan). The manipulator had a positional accuracy of <120 nm under the application of 500 N to the clamp and had a clamp-to-clamp stiffness of >312 N/mm. Control and data acquisition were accomplished with a Lab View-based program (Lab View version 8.6.1; National Instruments Corp., Austin, USA). Bone positions and motions were described relative to the previously published coordinate system of Wu et al. (2002) (Fig. 2). The leg clamp was fixed to the lower mechanism, and the calcaneal clamp was fixed to the upper mechanism with a universal force/moment sensor (UFS) (IFS-40E, 15A100-I63-EX; JR3, Inc., Woodland, USA). Iteration of data acquisition, kinematic and kinetic calculation, and motion of actuator was performed at a rate of 17–20 Hz. The maximum clamp-to-clamp compliance of the robotic system is 3 μm/N (The robotic system is deformed for 3 μm at the maximum when a force of 1 N was applied to the clamp), while force control fluctuations are 10 N in force and 0.4 Nm in moment (Fujie et al., 2004). The neutral position was set according to the technique used by Wu et al. (2002).

2.3. Tests

There were two parts of the study. In the first part, we performed multidirectional loading test to the intact ankle joint complex and acquired the data of motions and forces of intact ankle joint complex. After testing the intact joint complex, the CFL was transected. Then, to the CFL-transected ankle joint complex, the robot system reproduced the acquired motion from the intact joint complex and the new forces were recorded by the UFS. We acquired the data of the in situ force and the contribution of the CFL. In the second part, we performed multidirectional loading test to the CFL-transected ankle joint complex and acquired the data of motions of the CFL-transected ankle joint complex.

The anterior-posterior (AP) forces, inversion (IV) and external rotation (ER) moments were applied for the intact ankle joint complexes at 30° and 15° of plantarflexion (30°PF, 15°PF), at the neutral position (0°) and at 10° of dorsiflexion (10°DF). During the AP test, the AP DOF was translated under the displacement control up to 60 N at a rate of 1 mm/s, whereas the remaining 4 DOFs except