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THE USE OF A 6-DOF ROBOTIC SYSTEM FOR THE FUNCTIONAL ANALYSIS OF ANKLE JOINT LIGAMENTS

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INTRODUCTION

Ankle sprains are common injuries in daily and athletic activities. An epidemiological report indicated that the incidence rate of ankle sprains treated in emergency departments in the USA is more than 2 per 1000 persons a year, and the rate is estimated to be more than double as for ankle sprains in athletic activity [1]. Better understanding of ankle biomechanics is, therefore, important for the improvement of clinical outcome. Many investigators have performed in vitro and in vivo experiments to determine the mechanical roles of ankle structures such as range of motion, contribution of ankle ligaments to joint stability, joint instability due to ligament transection, and so on. In spite of these efforts, tensile forces in ankle ligaments in response to specific loading conditions still remains unclear because of a lack of experimental methodology. Meanwhile, the use of robotic technology for knee joint biomechanics study has been established by Fujie et al [2]. Using the technique, tensile forces in knee cruciate ligaments have been determined by Woo et al [3], Li et al [4], Fujie et al [5], and other groups, while ligament reconstruction technique has been evaluated by many investigators [for example 6-8]. Therefore, the objectives of the present study were to determine the ankle joint instability due to ligament transection and to determine the tensile forces in the anterior tarofibular ligament (ATFL) and calcaneofibular ligament (CFL) in response to anterior-posterior (AP) drawer force to the human cadaveric ankle joints.

MATERIALS AND METHOD

A 6-DOF robotic system consisting of a custom made 6-axis manipulator with a 6-DOF universal force/moment sensor (UFS) (Fig.1) [9] was used. All the actuators attached to the axes of the manipulator were position control-based actuators. In the original system, a LabView-based control program runs on a windows PC to control the displacement of, and force/moment applied to the cadaveric knee joints with respect to the knee joint coordinate system [10]. Kinematic and kinetic calculation in the program was modified to adapt to ankle joints since the joint coordinate system of the ankle [11] used in the present study is similar to that for the knee joint. Detailed information has been presented as regard with the 6-DOF real-time control in the robot system [12]. Briefly, it was assumed that the mass, stiffness and viscosity of an object to be controlled were described as [M], [S], and [C], respectively. When the manipulator applies force/moment $\boldsymbol{F}$ to the ankle, the following equation is derived.

$$[M]\frac{d\boldsymbol{v}}{dt} + [K]\Delta\boldsymbol{x} + [C]\boldsymbol{v} = \boldsymbol{F} \quad (1)$$

Note that the $\boldsymbol{v}$ represents the 6-DOF ankle joint velocity with respect to the joint coordinate system [10]. Under the assumption that the velocity change is small equation (1) can be finally rewritten in a discrete expression as follows,

$$\boldsymbol{v_{n+1}} = \Delta t[M]^{-1}(\boldsymbol{F} - [K]\Delta\boldsymbol{x}) + ([I] - \Delta t[M]^{-1}[C])\boldsymbol{v_n} \quad (2)$$

where Δt represents the iterative time of control, and [I] represents a unit matrix. Based on the current velocity $\boldsymbol{v}_n$, the velocity in the next step $\boldsymbol{v}_{n+1}$ can be calculated from equation (2). The parameters of [M], [K], and [C] were predetermined so that the mechanical response of the force control could be enhanced. The procedure that includes sensing of force/moment and displacement at the ankle, calculation of $\boldsymbol{v}$, as well as manipulator motion at v was repeated at a rate of 200 Hz.

In the present study, human cadaveric ankle joints (n=2) were dissected down to the joint capsule and fixed to the developed system. The anterior-posterior (AP) drawer test was performed for the human ankle joints at 10° of dorsal flexion, and at 15°and 30° of planter flexion, and neutral position. During the AP test, the AP DOF was translated under the displacement control at a rate of 0.1 mm/s up to ±60 N while all the DOFs except the AP and dorsal-planter(DP) DOFs were set under the force control with prescribed force/moment at zero. Six-DOF displacement and force/moment of the ankle joint were measured during the tests. After transection of the CFL, the AP test was performed for the CFL-transected ankle in a manner identical to the tests for intact ankle joint. This allowed to determine joint instability due to CFL transection. Subsequently, the intact ankle motions were reproduced to the CFL-transected ankle joint. This allowed to determine the tensile forces in the CFL in the intact state of the ankle joint. Joint instability due to transection of both the ATFL and CFL, and tensile forces in the ATFL in the intact state of the ankle joint were also determined in a manner identical to the tests for the CFL and ATFL-transected ankle joint.

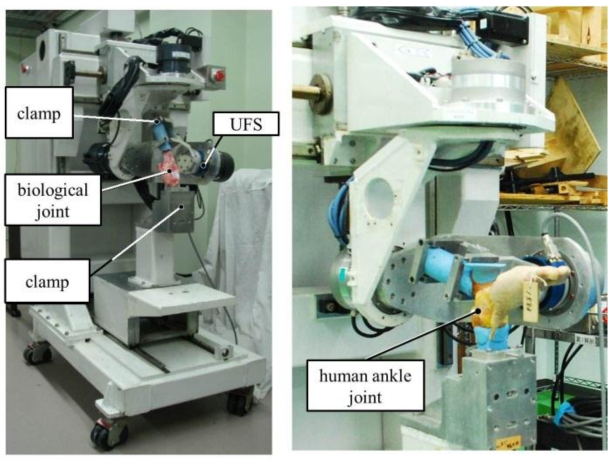

Fig.1 Six-DOF robotic system for the joint biomechanical tests for the ankle joint

RESULTS

An example of the relationship between AP force and AP displacement at 0 degree of dorsi-flexion in the AP test was indicated in Fig.2. The AP laxity between ± 30 N of AP forces was approximately 8 mm in the intact ankle joint. Although the AP laxity remained unchanged in the CFL-transected ankle joint, the laxity tremendously increased to approximately 16 mm in the CFL and ATFL-transected ankle joint. Tensile forces in the CFL and ATFL in intact ankle joint were 15 N, and 55 N, respectively, in response to 60 N of anterior force. With the increase of dorsi-flexion, tensile force in the CFL increased while that in the ATFL decreased (Fig.3).

DISCUSSION AND SUMMARY

The present study is the first one that quantitatively determined joint laxity to ligament transection and tensile forces in ankle ligaments. The joint loading tests have been successfully performed using the 6-DOF robotic system developed in our laboratory. The system consisted of stiff body and structure, and allowed for fast control and easy programming. Making use of these features, it was possible to simulate physiological ankle loadings and motions.

Although the AP instability of the ankle joint was not affected by the transection of the CFL, it was tremendously increased by subsequent transection of the ATFL in planter-flexion. In addition, the tensile force in the ATFL was increased chose to 70 N, while the tensile force in the CFL was around 10 N at planter-flexion in response to 60 N of anterior force. These results suggested that the ATFL is a crucial structure for preventing from ankle sprains in planter-flexion, which indicated a good agreement with the clinical incidence of ankle ligament injuries.

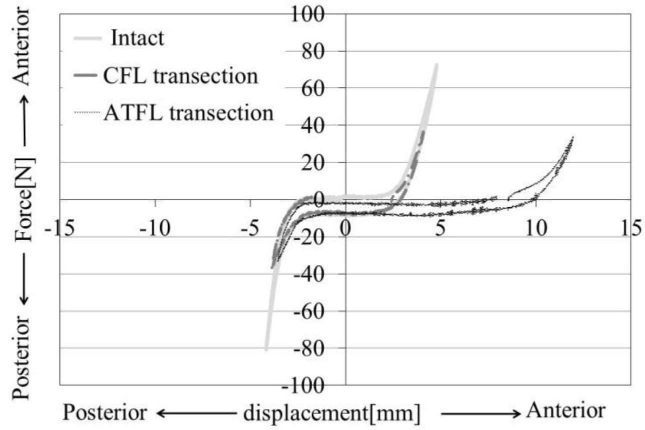

Fig.2 AP force-displacement curves of ligament-transected ankle joints at 0 degree of dorsi-flexion

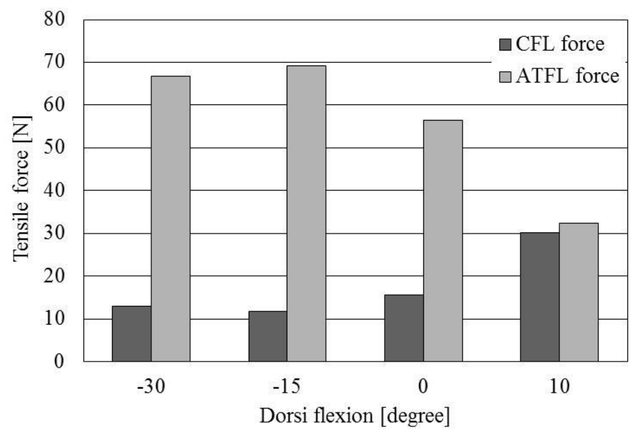

Fig.3 Tensile forces in the CFL and ATFL in response to 60 N of anterior force

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