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An alternative method of anthropometry of anterior cruciate ligament through 3-D digital image reconstruction

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Abstract

Accurate and flexible measurements of length, area, and volume are important in evaluation of the mechanical properties of soft tissue. Although a number of contact-based and non-contact techniques have been reported in the literature, due to a variety of reasons such as cost, complexity, and low accuracy, the research community has not adopted a standardized technique. In this paper, an alternative method of measuring the geometric parameters of cadaver anterior cruciate ligament (ACL) is presented. In this method, a 3-D scan of the ACL is constructed using a simple, commercially available, scanning system. The 3-D scan is then analyzed using the 3-D Doctor Software to extract important information regarding the length, cross-sectional area, and volume of the ACL. The accuracy and repeatability of measurements obtained by this method are acceptable and comparable to existing non-contact methods. The limitation of the method is that surface concavities cannot be detected. However, the non-contact optical method, described here, has inherent advantages over the existing methods: (1) it is inexpensive; (2) it allows the determination of area at any distance along the length of the tissue of interest; (3) all relevant information including minimum area is extracted from one single application of the method; (4) the volume can be calculated with a simple additional step of length measurement although, for accurate results, condylar blockage must be minimized by coring the ACL out. The entire process of scanning takes less than 30 min. This technique has the potential to become a standard method in anthropometry of soft tissue.
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1. Introduction

The geometric characteristics including length, cross-sectional area, and volume of soft tissues such as the human anterior cruciate ligament (ACL) are important when determining the mechanical properties of the ACL, or comparing the geometrical characteristics of ACL in various populations for instance based on gender, race, or age. The non-destructive techniques used in measurement of soft tissue geometry are divided into contact-based and non-contact categories. The contact-based techniques are the caliper technique (Haut and Little, 1969), area micrometer technique (Walker et al., 1964; Ellis, 1969; Allard et al., 1979; Butler et al., 1986), potentiometer technique (Shrive et al., 1988; Vanderby et al., 1991), and casting technique (Race and Amis, 1996; Muneta et al., 1997). Of the above techniques, the constant pressure area micrometer method is the most readily accessible and most commonly used technique in the literature.

The non-contact methods include the shadow amplitude method (Ellis, 1969), optical microscope method (Gupta et al., 1971), profile width method (Njus and Njus, 1986), laser telemetric system (Lee and Woo, 1988), optical method (Iaconis et al., 1987) and laser reflectance transducer method (Chan et al., 1996). Of the above non-contact techniques, only those developed by Iaconis et al. and Chan et al. have the ability to detect surface concavities in the soft tissue. Generally, the above non-contact methods have shown more accuracy

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than contact methods in determining the geometric characteristics of soft tissues.

Although a number of methods for soft tissue anthropometry exist, there is still a need for an inexpensive, accurate and easy to apply method for measurement of soft tissue geometry. This need is justified because the contact-based techniques, although inexpensive, by their nature, produce inaccurate results. For instance, the accuracy of the area micrometer method depends on the pressure applied on the soft tissue and the operator care. On the other hand, the non-contact techniques are generally highly specialized and require moderately expensive equipment and complex follow-up calculation procedures. None of the published techniques can find the smallest cross-sectional area along the length of the tissue with a single measurement. The published methods cannot produce a 3-D model of the whole tissue and none can be used to measure the volume of the tissue of interest.

In this paper, we present an alternative optical technique of measuring cross-sectional area (at any position along the ACL) and the volume of the ACL based on a single 3-D scan of the tissue. The scanning system is affordable at USD 5000. However, as with most optical techniques, the system cannot detect surface concavities.

2. Materials and methods

A commercially available photographic scanner, 3-D Scantop (Olympus America), was used to construct the 3-D image of human ACLs. The setup consists of a high-resolution digital camera (Olympus 3030-Z), a stand for the camera, motor driven turntable with background, lights, and associated software (Fig. 1). A computer is used to generate the 3-D image from the collection of 2-D images. The system can scan objects less than 250 mm height and 200 mm diameter. Before scanning the actual specimen, the system is calibrated for the relative position between the camera and the turntable using a calibration pattern provided by the manufacturer. The calibration pattern must be similar in size to the actual specimen. The specimen is then placed on the turntable, and the turntable is set to rotate at prescribed angular steps. At the conclusion of each angular step, the camera automatically takes a single picture. The minimum graduation of the angular displacement is 5° which results in a total of 72 images. These images produce an accurate model of the object. The reconstruction quality is set at 1500 voxels (analogous to pixels in a digital 2-D image) and 10,000 triangles (used to define the surface) to produce quality models. The Scanware 1.5 software is then used to construct a 3-D textured model of the specimen. The imaging system does not have the capability of providing dimensions or making area or volume measurements. To achieve this, the 3-D model is exported to the 3-D Doctor software (Able Software Corp., USA), where the model can be virtually sliced by any number of planes passed transverse to the longitudinal axis of the model. The software allows the selection of an imaginary plane at any angle relative to the longitudinal axis. The model is then divided into a desired number of virtual slices of equal thickness. The cross-sectional area of any slice, its position along the length of the object, and the volume of each slice can now be determined. To validate the accuracy of this method, four solid prismatic specimens of circular, square, hexagonal, and triangular cross-sections of known area were scanned and the measured and actual cross-sectional areas were compared (Lee and Woo, 1988).

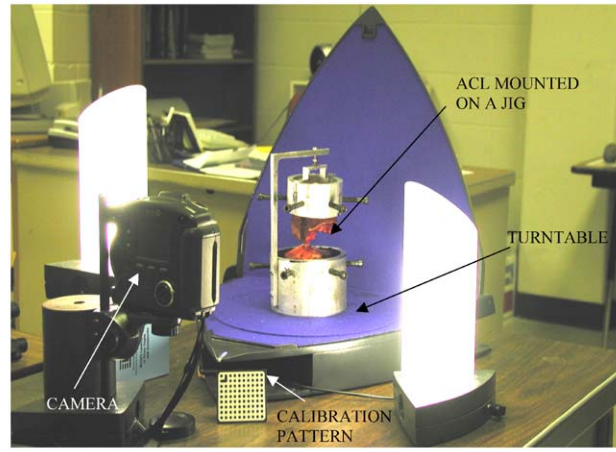

Fig. 1. The 3-D scantop imaging system. The setup consists of computer-controlled turntable and digital camera. The calibration pattern is used by the scanner software to calibrate the position between turntable and camera.

Fifteen knees were then transected from eight unembalmed cadavers and stored with all soft tissues intact at −20°C for approximately 1 month. On the day of test, the knees were thawed at room temperature and the femur and tibia were cut approximately 40 mm proximal to the femoral insertion site and distal to tibial insertion site of the ACL. All tissues around the ACL were carefully removed and the femoral condyles and tibial plateau were partially shaved to provide better exposure to the scanner. The ACLs were hydrated with 0.1 N saline solution. The total length of the ACL was measured by a caliper based on the average length on anterior and posterior sides of the ACL (Noyes and Grood, 1976). The femur–ACL–tibia complex (FATC) was then held in position by a custom made jig (Fig. 1). The remaining unshaved portions of the femoral condyles and the tibial prominences blocked portions of the ACL near both insertion sites. Ligaments were aligned along the longitudinal axis of the tibia on the jig. The ACLs were all loaded to a small load of 5 N to

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