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A novel physiological testing device to study knee biomechanics *in vitro*

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ABSTRACT

Background: To properly study knee kinetics, kinematics and the effects of injury and surgical treatment *in vitro*, the knee should be constrained as little as possible, while imposing physiological loads. A novel dynamic biomechanical knee system (BKS) is presented here. The aim of this study was to test the feasibility and reproducibility of the system and demonstrate its features with an Anterior Cruciate Ligament (ACL) lesion model.

Methods: Six goat knees were used in the current study. Flexion and extension simulating gait was imposed by a servo-motor, while normal joint load was applied by two artificial muscles. Intra-class correlation coefficients (ICCs) were assessed for inter-test measures, while paired t-tests were performed for comparison between intact knees and knees with ACL-lesion.

Results: The ICC's for inter-test measures based on all six goat knees were excellent: varus/valgus: ICC = 0.93; rotation: ICC = 0.94 (all $p < 0.01$), and translation in frontal (x)-, side (y)- and upward (z)-direction (ICC = 0.90, 0.88 & 0.94) (all $p < 0.01$). A significant increase in joint center movement was found in knees after creating an ACL-lesion ($p = 0.018$): translation increased more than two-fold in frontal ($p = 0.016$), side ($p = 0.004$) and upward ($p = 0.018$) direction.

Conclusions: Five degrees of motion were reproducibly assessed in the intact joint, suggesting that the goat knee may find its natural pathway when loaded in the BKS. The novel five-degrees-of-freedom knee system allows a detailed study of the effect of a diversity of defects and surgical treatments on knee biomechanics under physiological loading conditions.

1. Introduction

The knee is probably the most vulnerable joint in the human body and, with the hip, the most affected joint by osteoarthritis (OA) in the elderly [1,2]. The worldwide incidence and prevalence of traumatic knee injuries, mainly affecting the menisci or Anterior Cruciate Ligament (ACL) is large. Incidences for hospital admission after sustaining meniscal injuries vary between 0.35 and 0.7 per 1000 person-years [2], besides a number of 100,000–200,000 ACL ruptures per year, in the United States alone [3]. These

Abbreviations: OA, osteoarthritis; ACL, Anterior Cruciate Ligament; BKS, biomechanical knee system.

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numbers are accompanied by an expected increase in the worldwide burden of knee OA, over the next decade(s) [4]. Developments to prevent or reverse knee pathologies are therefore ongoing [2,5,6].

Injuries such as meniscal tears or ACL ruptures cause altered contact mechanics in the knee, including increased loading and motion [7]. In patients with knee OA, the knee kinematics and kinetics change as well, although this is a more delicate process. The general aim of surgical treatment in knee pathologies is to re-establish a healthy biomechanical environment for the articular cartilage in the knee.

Current biomechanical parameters of interest for predicting the onset of knee OA are the knee adduction moment, knee flexion moment, usually combined with the kinematics of the knee in general [8–11]. Experimentally recreating the natural biomechanical characteristics of the knee remains challenging since there are as yet no ambulant measurement devices available for measuring kinetic parameters *in vivo*, and there are as yet no testing devices which combine natural knee kinematics with physiological loading conditions *in vitro*. With the growing numbers of knee-OA patients and surgical treatments, such as total knee arthroplasty, unicondylar knee prosthesis and novel developments in unloader devices, the need for better knowledge on functionality and longevity of implants becomes apparent.

With this study, we present a novel *in vitro* biomechanical knee system (BKS), which allows unconstrained movement conform the natural pathway under physiological loading conditions. In our BKS only flexion–extension and dynamic joint loading are imposed, leaving five degrees of freedom in motion for the knee to find its own natural pathway during normal gait. The first objective of this study is to assess whether it is feasible to create a regular knee movement pattern by solely applying the flexion–extension movement and physiological loading, comparable to a knee gait pattern, measured *in vivo*, obtained from the literature. Secondly, we investigate the repeatability of the outcome parameters regarding the five degrees of freedom that can be obtained with this system, Third, we demonstrate its features with a complete anterior ACL lesion model to confirm the significance of functional tension supplied by peri-articular ligaments, and whether these outcome parameters show significant differences after sustaining injury as would be expected [12–14]. This paper presents our first-generation BKS, demonstrate its features with an ACL lesion model.

2. Materials and methods

2.1. Biomechanical testing device

The novel physiological knee-testing device was developed to allow unconstrained motion under physiological loading conditions during knee testing *in vitro*. Minimum requirements to recreate a physiological gait pattern are the application of the flexion/extension movement and an according loading pattern. Apart from this, the knee is allowed to follow its natural track during the flexion/extension movement, including possible varus–valgus deviation, axial rotation and translation.

The tibia part of the knee is fixed to the ground as a reference. The femur is grabbed by a frame driven DC servo-motor (Parker Hannifin RS440GR1031, Mayfield Heights, Ohio, USA), controlling the flexion/extension angle. The servomotor is driven by an amplifier (AMC 20A20), has a gearbox (Wittenstein alpha precision planetary gearbox with ratio 7, type TP010S-MF1-7-0C0) and is equipped with an encoder (K9).

Loading is applied using two pneumatic muscles (Festo Fluidic Muscle DMSP diameter 20), placed along both sides (medial and lateral) of the knee. These pneumatic muscles are attached to the frame by spherical joints located at the center of rotation of the femur shackle and have compliant properties (Figure 1). The maximum force generated by these muscles is 1500 N each.

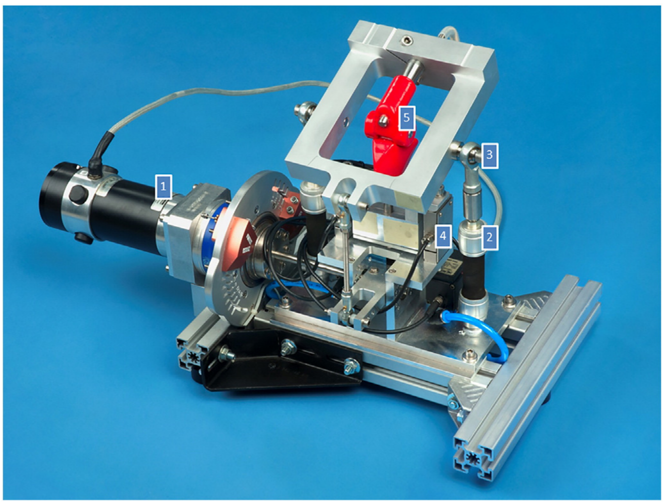

Figure 1. The dynamic biomechanical knee system. With: 1. DC servo-motor, 2. Pneumatic muscle(s), 3. Spherical joints, 4. Force sensors, 5. Knee (in this picture a 3D printed model of a goat knee).

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