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Artificial Knee Joint and Ski Load Simulator for the Evaluation of Knee Braces and Ski Bindings

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Abstract

Introduction: Epidemiological studies show that severe knee injuries are prevalent in alpine skiing. Their incidence is related to ski boot and ski binding concept – both designed to prevent tibia fractures. To reliably protect the knee, ski bindings need a release mechanism which follows different release principles. Therefore, attempts are made to develop mechatronic concepts implementing additional criteria and to release the foot when critical loads at the knee are reached. One possibility to systematically manipulate external loads and to investigate the resulting stresses in the joint are experiments using an artificial leg. This paper describes the development and the evaluation of such kind of model ("leg surrogate") including a complex artificial knee joint. The evaluation includes tests concerning the reliability, sensitivity and plausibility of the surrogate.

Method: Tibia and femur consist of an aluminum bone imitate and are reconstructed based on human computerized tomography data. Human endoprosthesis are used as articulating surfaces for the tibial plateau, the femoral condyles, the trochlea as well as the patella. Ten steel ropes connected to a force measuring cell are incorporated simulating the muscle. The muscle volume is imitated by a three layer coat of thermoplastic. The artificial knee ligaments are instrumented with custom made elongation and force sensors. Leg surrogate presetting's can be varied trough the knee angle, hip angle, varus or valgus position, tension of the muscle and pretension of the ligaments. A test rig enables t quasi static application of external loads to the leg surrogate in any combination about the x, y and z-axis.

Results: The leg surrogate delivers reproducible measurements with a maximum variation of 2.7%. It allows to simulate different conditions like muscle tension or hip angles and to record their influence on the knee ligaments. The plausibility checks performed indicate, that the leg surrogate represents the behavior of the human knee to a large extend.

Conclusion: The new leg surrogate allows to simulate not only alpine skiing injury but also other load situations. It therefore can be used to systematically investigate critical load situations to the knee and the prevention effect of safety devices such as mechatronic ski bindings or knee protection devices like preventive knee braces.

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Keywords: knee joint, load simulation, skiing, leg surrogate, knee injury, ACL

1. Introduction

The most injured body part in alpine skiing is the knee [1]. Above all, injuries of the anterior cruciate ligament and the medial collateral ligament are prevalent [2]. Because of the ski acting as a lever, the knee loads in skiing are higher than in most other sport disciplines. The high injury rate is also related to the ski bindings that are based on a mechanical design and developed to prevent tibia fractures. Their release mechanism and release value fail to protect the knee reliably [2, 3]. Therefore concepts of mechatronic ski bindings were developed. Their release algorithms however need understanding of the relationship between forces and moments at the ski binding, kinematics of the knee and hip joint in interaction with the leg's muscle activation and the

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resulting loading of relevant knee structures, such as the ACL. As ethical reasons make it impossible to apply critical loads to the human being, the application of biomechanical leg models is a logical approach to determine the responses of the knee structures according to sport specific loading situations. In this publication a biomechanical leg model for testing ski specific loading situations is presented.

2. Former and current knee surrogates

Since the early Nineties a variety of leg surrogates were presented. They can be classified in two categories. One measuring the occurring forces in the knee ligaments [4–6] and the others analyzing the range of motion of the tibia and femur [7–10]. The surrogate of France et al. [6] is the most sophisticated one. Besides the upper and lower leg, it integrates a rudimental upper body, pelvis, hip and ankle. The surrogates of Liu et al. [10], Mitternacht [11] and Hochmann [9] consist of the upper and lower leg only, neither simulating the knee joint nor any corresponding structure. Each of the surrogates [4–8] incorporate anterior (ACL) and posterior (PCL) cruciate ligament, the medial (MCL) and the lateral (LCL) collateral ligament, simulated by Nylon, Teflon or other polymers. France et al. [6] measure tension force in all four ligaments whereas the other surrogates are limited to recording MCL force. Only France's and Cawley's [8] model disposes the patella femoral joint, the others either neglect it or represent it rudimental. The test rig of some of the artificial legs only allow an extended knee position [4, 5, 10], while the others permit the application of different knee flexion angles. Four of the surrogates have mechanical or actuator controlled muscles made of steel ropes [4, 6–8]. Two surrogates are able to control the muscle volume with a pneumatic system [9, 11].

Most of the above mentioned surrogates where developed to investigate the protection potential of knee braces, which are used in American football to prevent players from MCL injuries. With these surrogates however it is not possible to apply multi-directional loads as they occur in alpine skiing thus they cannot simulate typical skiing injury mechanisms. Further the existing leg surrogates have implemented ligaments as a single bundle only, even though many studies have shown, that the individual bundles of a ligament have different functions [13, 14]. It is well known and many studies [i.e. 17-20] report that muscles have significant influence on the knee stiffness. However with a maximum of four implemented muscles the referred surrogates cannot simulate muscle influence properly. Even if the position of the upper body plays an important role in the injurie mechanisms, only France et al. [6] and Daley et al. [5] modeled the hip joint. All the referred surrogates are neither able to systematically analyze knee injuries in alpine skiing nor to proof the effect of safety equipment like ski bindings or knee braces.

With the aforementioned limitations of existing leg surrogates in mind, the aim of this study was to develop and evaluate a novel knee surrogate that overcomes the restrictions and which is able to measure loads in knee ligaments under skiing typical loading situations [15].

3. Technical realization

3.1. Design & construction

The surrogate simulates an artificial right leg (Fig 1b). It incorporates the bones of thigh and lower leg, the hip, six knee ligaments, ten muscles and the muscle volume.

Tibia head, femur head and the head of the fibula are made of cast aluminum (Fig 1c). The geometries of these bones are based on CT-data of a 35 year old man with healthy knee. The data-set is scaled to a 50-percentile German man between 30 and 40 years. Aluminum hollow shafts model the femur shaft and the tibia. The articulating surfaces involve the tibio femoral joint and the patella femoral joint and are realized by prosthetic components (Genesis UNI and Journey, Smith & Nephew, London, UK). The patella is made of two components, with a medical implant acting as articulating surface fixed to an aluminum shell. This shell enables the attachment of the muscle ropes and the patella tendon made of polyethylene (KoSa® hochfest, telos, Marburg, Germany). An alloy "pelvis" is pivot-mounted on a shaft providing to set hip angle within a range between -20° to + 90°. A negative value corresponds to a backward position of the upper body and vice versa.

In total ten muscles are modeled. Eight of the thigh (m. biceps femoris, m. semimembranosus, m. semitendinosus, m. vastus lateralis, m. vastus intermedius, m. rectus femoris, m. vastus medialis longus, m. vastus medialis obliquus) as well as two of the calf (m. gastrocnemius lateralis, m. gastrocnemius medialis). The insertion- and attachment points as well as the lines of action are implemented in the anatomical correct position. The muscles are imitated by 2.5 mm thick steel ropes and are instrumented with force sensors (0-5 kN, K-100 ATP Messtechnik, Ettenheim, Germany). Muscle force for each muscle can be set independently by a tensioning unit.

The ligament apparatus of the knee for which synthetic ligaments made of polyester (LARS Ligaments, Arc sur Tille, France) are used, includes the ACL, PCL, MCL and LCL. Further the two functional bundles of the ACL (posterolateral (PL) and anteromedial (AM)) and the PCL (anterolateral (AL) and posteromedial (PM)), are realized. All ligaments are inserted according to anatomical landmarks and attached to a screw to set its preload according to literature data [16–19]. The AM ACL, PL ACL and the MCL are instrumented with custom made tension force sensors integrated in the bone (range: up to 1.5 kN for the ACL