Knee cartilage surface loading during stationary bicycling

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Abstract

Bicycling, either stationary or in the open air, is a common leisure activity. It is known, that this exercise is characterized by relatively low knee loading, thus it is often advised even to elderly people as a recreational activity. However, the knowledge about knee cartilage load distribution during bicycling is limited. The presented method utilizes experimental measurements of forces developed between feet and pedals as well as motion capture of the activity, as an input for a three-dimensional rigid body simulation. The aim of the multibody simulation is to acquire knee forces and angles during stationary bicycling. For this exercise, a human lower body model was created. The model consisted of two feet, two tibias, two femurs and pelvis sections connected via kinematical joints. Lower body muscles were described as 32 PID servo muscles. The results of the multibody simulation were transferred to the detailed finite element model of the knee. The FE analysis allowed estimating the cartilage surface loading during stationary cycling activity. The results were compared with different studies, presenting benefits and limitations of the proposed method. The results can be utilized in optimization of the rider position, crank mechanism as well as in the prosthesis design.

Keywords: biomechanics, dynamics, bone mechanics, finite element methods, multibody dynamics

1. Introduction

Bicycling is a very common physical activity; it can be performed by people of almost any age, thus it is suitable for a recreational activity and an exercise to maintain health. Various publications focus on bicycling from the mechanical point of view, as it can be treated as two-dimensional motion and studied with simple mechanical models, still giving realistic results. Many aspects of bicycling have been studied, for example Dorel Ref. [2] focused on exhaustive conditions influencing muscle coordination in one of his publications, and in another one on force analysis Ref. [2]. Hug Ref. [3] reviewed the exercise using the electromyography approach. There has been, however, little activity in the research of load distribution in the knee joint during bicycling. The load distribution in the knee joint's articular cartilage characterizes the wear of the cartilage material. If the loading is concentrated on a small area of the cartilage, it can lead to osteoarthritis, which represents itself as damage in the cushioning cartilage surface leading to bone-to-bone contact. The aim of this study is to evaluate the stress distribution of the knee articular cartilage during stationary bicycling.

2. Methods

Computational modeling techniques utilized in the current study are based on rigid multibody dynamics Ref. [4] and finite element method Ref. [5]. Rigid multibody dynamics is used to model the lower body of the human and the crank mechanism of a stationary exercise bicycle. Finite element method is used for a detailed knee model consisting of four main ligaments, epiphyses of tibia and femur, menisci and articular cartilage surfaces. In order to reproduce realistic motion pattern and to gather validation data for the multibody model, experimental measurements are conducted.

2.1. Experiment

The experimental measurements were conducted at the biomechanical laboratory of the University of Jyväskylä. A young 29-years old, clinically healthy male subject participated voluntarily in the trial, giving his written consent to the procedure. The subject was 185 cm tall, and weighted 85 kg. The experiment was conducted according to the declaration of Helsinki. A stationary bicycle was used to perform the test. The subject was equipped with 29 reflective markers placed on all body segments, and wore shoes with force sensor pads installed on them. The motion of the subject was captured using four high-speed video cameras, capturing 100 frames per second. Videos were later digitized using Peak Motus in order to extract 3D trajectories of the markers. Contact forces between the feet and pedals were registered with the sampling frequency of 125 Hz.

2.2. Multibody simulation

A three-dimensional subject-specific skeletal lower body model (see Fig. 1a) was built using LifeMod plug-in for MSC ADAMS, version R3. It was equipped with 32 PID controlled muscles. The joints connecting the bones were modeled as spherical. To prevent joints from reaching unnatural positions, joint limits were introduced by progressive stiffness elements. The bicycle crank mechanism was modeled as one rigid body, attached via a hinge joint to the ground. Pedals were separate rigid bodies attached via hinge joints to the corresponding crank arms. Feet were attached rigidly to pedals and forces measured during the experiment were applied to pedals to model the resistance. The pelvis was supported by six general constraints, which were based on trajectories obtained from the motion data.

Computation began with inverse dynamics, where motion data was used to drive the model. Each of the markers registered during motion capture was represented as two rigid massless elements connected via spring. One of the elements followed strictly the trajectory while the other one was rigidly attached to a corresponding body segment. This arrangement leads to the least square fit of the marker trajectories to obtain body segments motion paths constrained by joints. During this step pelvis trajectory together with muscle contraction patterns were recorded. The inverse dynamics was followed by forward dynamics procedure, where pelvis constraints were applied, and passive muscle models were replaced by their active PID controlled versions. The over-actuation problem is solved by the algorithm, which minimizes the muscles forces needed for joint torque production. Muscles can be divided into groups responsible for flexion/extension/abduction/adduction of a specific joint, because each muscle can only produce force to shorten itself. The force division within the functional muscle group is determined by taking into account the maximum force that each muscle can produce as well as muscle activation levels. The output of the simulation was knee forces and knee angles measured with respect to the femur. This data was transferred to finite element model in order to compute stress distribution of the knee articular cartilage.

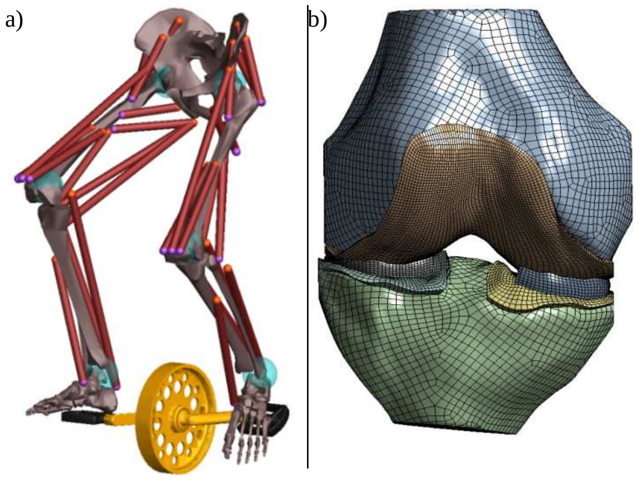

Figure 1: Multibody model (a), knee finite element mesh (b).

2.3. Finite element analysis

The knee joint was modeled using the commercial finite element method software Abaqus, version 6.10.1. The geometrical data for the knee joint was obtained from [6-7]. The four main ligaments were described as nonlinear spring elements. The material properties for the meniscus and cartilage were obtained from [8]. The epiphysis of tibia and femur were considered as rigid bodies, as the material stiffness of the bones is approximately 30-times higher than the stiffness of the soft tissues of the knee. Menisci-articular cartilage and articular cartilage-articular cartilage contacts were formulated based on augmented Lagrangian method. The finite element mesh is presented in the Fig. 1b.

3. Results

Two sets of results are presented in this work. First set represents the data obtained from the multibody simulation. It contains knee forces and knee angles for both legs expressed as a function of time. The second set represents the results from the finite element analysis which contains cartilage contact stresses.

4. Discussion and conclusions

The peak knee forces during the bicycling were 1552 N and 1467 N for left and right leg, respectively. The 5.8% higher force in the left knee is justified by higher pedal-foot reaction force for the left leg comparing to the right leg. Knee force values are comparable with the knee forces obtained from knee flexion exercise, described in [9], where the peak force is between 1500 N and 1600 N depending on the speed of movement.

The average knee forces for left and right knee were 680 N and 485 N, respectively. The 40% difference between legs can be explained by 28% difference in the average contact forces measured during experiment. The results show that pedaling can be asymmetric in terms of loading when the rider position is not fixed.

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