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COMPUTER SIMULATION AND MODELING OF CARTILAGE DEFORMATION DURING ATHLETES' LAND TRAINING: ONE CASE STUDY

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Abstract The objective of this study was to make a computer model of athletes' land training and to determine the real deformation on the knee cartilage. A new algorithm is used for joint motion simulation, which visualizes sport specific motion data in athletes in a specific hip-joint model. Knee pain is a common problem for many sports people in the world. Knee injuries can be either internal (within the joint) or external (outside the joint). The knee is exposed to numerous weight bearing forces and does not cope with both weight bearing and twisting simultaneously, both of which often occur in sport. Anyone wearing boots with long studs will benefit from a better surface grip but this can hold the foot even when the player wants to change direction. The compression and shearing forces can result in menisci tears, knee ligament sprain and ruptures.

Some mechanical properties of cartilage are well characterized, but little is known about its behavior in complex training. A finite element model of porous deformable media for cartilage is implemented [1]. We used our own motion capture system to collect athletes' specific motion data. The system includes a computer, a camera and a number of colored markers. For unilateral gait analysis, 4 markers are attached to the athlete at various positions. Each color is identified by a different number. The computerized camera system captures the exact motion of these markers, which identifies the movement of the body while the athlete is running along a straight line.

The aim of the study was to connect a 3D capture camera system with the estimation of cartilage deformation and stress during football players' standard test.

Key words: cartilage deformation, athletes' land training, motion capture system

INTRODUCTION

The knee is the anatomical spot most often treated by orthopaedic surgeons [2]. Knee problems result in millions of visits to doctors' offices annually. One of the most common knee injuries in sport is tearing. Intensive research has been carried out over the last 30 years to understand the conditions necessary for maintaining healthy cartilage and the mechanical and biochemical environment that leads to disease [2]. Much has been learned about the morphology, biochemistry and mechanics of cartilage, but many of the important questions remain unanswered. For example, what are the dynamic loading conditions to which cartilage is exposed during complex training as well as players' game activity, and how does this environment influence the health of the tissue? The answers are fundamental for sports training as well as diagnosing and treating joint disease, since dynamic loading affects the movement of tissue growth factors, which must be transported into the cartilage layer to keep it healthy. One key difficulty in understanding these issues has been the inability to measure knee movements accurately *in vivo*. Conventional motion capture technologies employ video-based systems to track markers attached to the skin. While these systems are non-invasive, the markers affixed to the skin shift relative to the underlying bone [3]. Skin motion effect can be avoided by using medical imaging techniques such as fluoroscopy. Newer technologies, such as cine magnetic resonance imaging (MRI) and single- and biplane fluoroscopy, are capable of accurately recording 3-D joint motion non-invasively. Cine MRI is limited by the restriction it imposes on the movements that the subject can perform, and it cannot be used to investigate weight-bearing activities such as gait [4].

In order to understand knee injuries we need first to have an appreciation of the anatomy and structures of the knee joint. Basically the knee is a hinge joint and classified as a synovial joint, which means it is surrounded by a capsule filled with fluid. This fluid helps nourish and lubricate the structures within [2].

To diagnose a knee problem, doctors often need to observe knee behavior during the gait cycle. Knee motion simulation provides valuable information for physicians to make correct diagnosis as well as for sports trainers to make better training conditions. Specifically, knee motion simulation should describe the kinematic behavior of tibia, femur, patella, and other elements involved in various knee positions. Three dimensional motion tracking systems capture and measure the motion data by attaching markers to various positions of the knee. This information, along with the knowledge of knee kinematics, can help create subject-specific knee motion simulation [3, 4, 5]. However, it is usually difficult to simulate the motion due to the lack of non-invasive methods to measure the knee motion parameters. The major challenge is the definition of femur and tibia rotation axes.

METHODS

SUBJECT

The average test results are expressed in the stages as it is presented in Table 1. The participant is a male soccer player (Age – 18.0 yrs; BH – 1.84 m; BM 71.0 kg; BMI 21.01 kg/m^2; VO_{2max} – 68.25 ml/kg/min; Anaerobic threshold – 173 bmp). The starting speed is 8 km/h and each minute the speed is increased by decreasing the interval between the beeps.

TESTING PROCEDURE

The Shuttle Run determines the maximum aerobic endurance of a player. The test was developed in 1982 by Leger [6]. There are many names now for the Shuttle Run Test: the Beep Test, the Bleep Test, or the YoYo Test. With this test it is possible to run across the gym between two lines twenty meters apart until maximum endurance of the participant, i.e. until testee quitting. The test is performed indoors and the speed of the participants is determined by the interval between two beeps played on a cassette.

During the testing, the pulse is followed through the pulse-meter (HR Polar). The software note from the pulse-meter is entered into the computer and then put to further use for additional diagnostic purposes.

Indirect calculation of the oxygen consumption, expressed in ml per min per kg, is achieved through a pattern: $VO2_{max}$= (5.87 x S)-19.458, where S is running time [11]. The values are directly proportional to the aerobic capacity of the testee.

Table 1. Shuttle Run Test protocol for the maximum aerobic endurance

Stage (min)	Speed (km/h)	Interval (s)	Stage (min)	Speed (km/h)	Interval (s)
1	8.0	9.0	***11***	13.0	5.5
2	8.5	8.5	***12***	13.5	5.3
3	9.0	8.0	***13***	14.0	5.1
4	9.5	7.6	***14***	14.5	5.0
5	10.0	7.2	***15***	15.0	4.8
6	10.5	6.9	***16***	15.5	4.7
7	11.0	6.6	***17***	16.0	4.5
8	11.5	6.3	***18***	16.5	4.4
9	12.0	6.0	***19***	17.0	4.2
10	12.5	5.8	***20***	17.5	4.1

KNEE MOTION CAPTURE

We used our own motion capture system to collect the specific motion data [7]. The system includes a computer, a high-speed camera and a number of colored markers. For unilateral gait analysis, five markers are attached to the subject at various positions, where three were on the subject's dominant leg (at knee, hip and ankle). Each marker was identified by a different color. The computerized camera system captured the exact motion of these markers, which identified the movement of the body while the subject ran in a straight line. The camera was connected /Basler A601fc camera, Graftek Imaging, Inc, USA/ to a computer that collected gait cycle kinematical data. The 3D tracking software [7] of our own design was then used to identify and convert 2D camera information into 3D motion data at different time frames (Figure 1). The result of motion tracking was a series of 3D coordinates for each numbered marker.

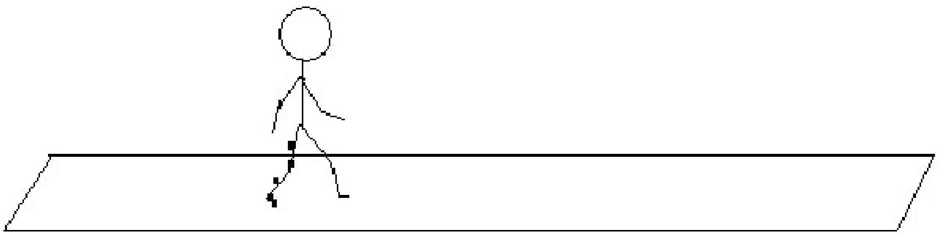

Figure 1. 3D motion capture system

The knee motion involves a series of three rotations (flexion/extension, abduction/adduction, and internal/external rotations) and three translations (anterior/posterior, superior/inferior, and medial/lateral translations). The rotation angles and the translations can be calculated according to the 3D motion data of the stick model recognized from a DVD video movie.

FINITE ELEMENT METHOD

We consider large displacements of a porous deformable body filled with fluid, occupying the whole pore volume. The physical quantities at the material point are: the displacement of solid **u**, relative fluid velocity with respect to the solid (Darcy's velocity) **q**, fluid pressure p, swelling pressure p_c, and electrical potential ϕ.

The governing equations for the coupled problem are described above. First, consider the solid equilibrium equation,

$$(1-n)\mathbf{L}^{\mathrm{T}}\boldsymbol{\sigma}_s + (1-n)\rho_s\mathbf{b} + \mathbf{k}^{-1}n\mathbf{q} - (1-n)\rho_s\ddot{\mathbf{u}} = 0 \qquad (1)$$

where $\boldsymbol{\sigma}_s$ is stress in the solid phase, n is porosity, **k** is the permeability matrix, ρ_s is density of solid, **b is** body force per unit mass, **q** is relative velocity of fluid, and $\ddot{\mathbf{u}}$ is acceleration of the solid material. The operator $\mathbf{L}^{\mathbf{T}}$ is

$$\mathbf{L}^{\mathrm{T}} = \begin{bmatrix} \frac{\partial}{\partial x_1} & 0 & 0 & \frac{\partial}{\partial x_2} & 0 & \frac{\partial}{\partial x_3} \\ 0 & \frac{\partial}{\partial x_2} & 0 & \frac{\partial}{\partial x_1} & \frac{\partial}{\partial x_3} & 0 \\ 0 & 0 & \frac{\partial}{\partial x_3} & 0 & \frac{\partial}{\partial x_2} & \frac{\partial}{\partial x_1} \end{bmatrix}. \qquad (2)$$

The Equation (1) and the others that follow, correspond to the current configuration ${}^t\mathbf{B}$ and are essential for the calculation of the change of material properties during deformation (e.g. porosity). In this section we omit every index to indicate configuration, or time. However, it will be necessary to include them in the later development of an incremental-iterative scheme for the solution of the nonlinear finite element equations.

The equilibrium equation of the fluid phase (no electrokinetic coupling) is

$$-n\nabla p + n\rho_f \mathbf{b} - \mathbf{k}^{-1} n\mathbf{q} - n\rho_f \dot{\mathbf{v}}_f = \mathbf{0} \tag{3}$$

where p is pore fluid pressure, ρ_f is fluid density and $\dot{\mathbf{v}}_f$ is fluid acceleration. This equation is also known as the generalized Darcy's law. Both equilibrium equations are written per unit volume of the mixture. Combining Equations (1) and (3) we obtain

$$\mathbf{L}^{\mathrm{T}}\sigma + \rho\mathbf{b} - \rho\ddot{\mathbf{u}} - \rho_f \dot{\mathbf{q}} = \mathbf{0} \tag{4}$$

where σ is the total stress which can be expressed in terms of σ_s and p, as

$$\sigma=(1-n)\,\sigma_s - n\mathbf{m}p \tag{5}$$

and $\rho=(1-n)\rho_s+n\rho_f$ is the mixture density. Here **m** is a constant vector defined as $\mathbf{m}^{\mathrm{T}}=\{1\ 1\ 1\ 0\ 0\ 0\}$ to indicate that the pressure component contributes to the normal stresses only. We have also taken into account that the pressure has positive sign in compression, while tensional stresses and strains are considered positive. In the following analysis we employ the effective stress, σ', defined as

$$\sigma'=\sigma+\mathbf{m}p \tag{6}$$

which is relevant for the constitutive relations of the solid. Using the definition of relative velocity **q** as the volume of the fluid passing in a unit time through a unit area of the mixture (Darcy's velocity),

$$\mathbf{q} = n\left(\mathbf{v}_f - \dot{\mathbf{u}}\right) \tag{7}$$

we transform (3) into

$$-\nabla p + \rho_f \mathbf{b} - \mathbf{k}^{-1}\mathbf{q} - \rho_f \ddot{\mathbf{u}} - \frac{\rho_f}{n}\dot{\mathbf{q}} = \mathbf{0}\,. \tag{8}$$

The final continuity equation using the elastic constitutive law and fluid incompressibility is given in the form [1]

$$\nabla^{\mathrm{T}}\mathbf{q} + \left(\mathbf{m}^{\mathrm{T}} - \frac{\mathbf{m}^{\mathrm{T}}\mathbf{C}^{\mathrm{E}}}{3K_s}\right)\dot{\mathbf{e}} + \left(\frac{1-n}{K_s} + \frac{n}{K_f} - \frac{\mathbf{m}^{\mathrm{T}}\mathbf{C}^{\mathrm{E}}\mathbf{m}}{9K_s^{\,2}}\right)\dot{p} = 0 \tag{9}$$

The resulting FE system of equations is solved incrementally [1], with time step Δt. We impose the condition that the balance equations are satisfied at the end of each time step (t+Δt). Hence, we have the following system of equations

$$\begin{aligned}
&\begin{bmatrix} \mathbf{m}_{\mathbf{uu}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \mathbf{m}_{qu} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}
\begin{Bmatrix} {}^{t+\Delta t}\ddot{\underline{\mathbf{u}}} \\ {}^{t+\Delta t}\ddot{\underline{\mathbf{p}}} \\ {}^{t+\Delta t}\ddot{\underline{\mathbf{q}}} \\ {}^{t+\Delta t}\ddot{\underline{\phi}} \end{Bmatrix}
+ \begin{bmatrix} 0 & 0 & \mathbf{c}_{\mathbf{uq}} & 0 \\ \mathbf{c}_{pu} & \mathbf{c}_{pp} & 0 & 0 \\ 0 & 0 & \mathbf{c}_{qq} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}
\begin{Bmatrix} {}^{t+\Delta t}\dot{\underline{\mathbf{u}}} \\ {}^{t+\Delta t}\dot{\underline{\mathbf{p}}} \\ {}^{t+\Delta t}\dot{\underline{\mathbf{q}}} \\ {}^{t+\Delta t}\dot{\underline{\phi}} \end{Bmatrix} \\
&+ \begin{bmatrix} \mathbf{k}_{\mathbf{uu}} & \mathbf{k}_{\mathbf{u}p} & 0 & 0 \\ 0 & 0 & \mathbf{k}_{pq} & 0 \\ 0 & \mathbf{k}_{qp} & \mathbf{k}_{qq} & \mathbf{k}_{q\phi} \\ 0 & \mathbf{k}_{\phi p} & 0 & \mathbf{k}_{\phi\phi} \end{bmatrix}
\begin{Bmatrix} \Delta\underline{\mathbf{u}} \\ \Delta\underline{\mathbf{p}} \\ \Delta\underline{\mathbf{q}} \\ \Delta\underline{\phi} \end{Bmatrix}
= \begin{Bmatrix} {}^{t+\Delta t}\mathbf{f}_{\mathbf{u}} \\ {}^{t+\Delta t}\mathbf{f}_{p} \\ {}^{t+\Delta t}\mathbf{f}_{q} \\ {}^{t+\Delta t}\mathbf{f}_{\phi} \end{Bmatrix}
\end{aligned} \tag{10}$$

RESULTS AND DISCUSSION

Here our goal is to calculate cartilage deformation at the knee joint based on the subject's knee model and classical biomechanical analysis of the shuttle run test, and then we can visualize the change of cartilage deformation during knee motion. The overall forces on the knee joint are presented in Figure 2.

The geometry of the problem is shown in Figure 3. We analyze the knee joint as electrokinetic transduction in charged, homogenous, isotropic, hydrated material. In the analysis we first use the material constants by Frank and Grodzinsky [8, 9]. After that we fit values of the material constants to experimental data by employing our numerical solutions.

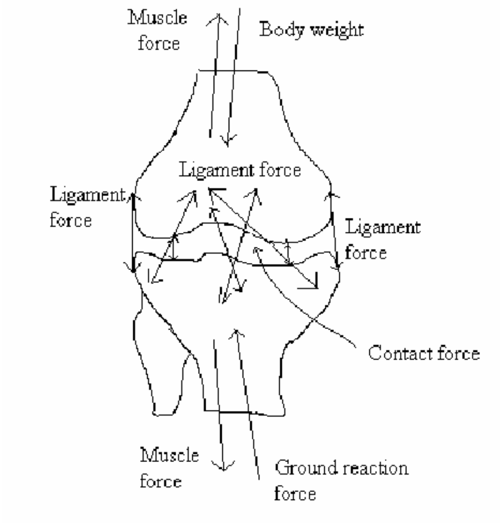

Figure 2. Forces on the knee joint

Figure 3. Geometry of the cartilage model

Following the approach of Frank and Grodzinsky [9], the fluid and the solid are assumed incompressible, and the tissue compression is due to the prescribed force of constant amplitude. The initial result for menisci deformation is presented in Figure 4 [10].

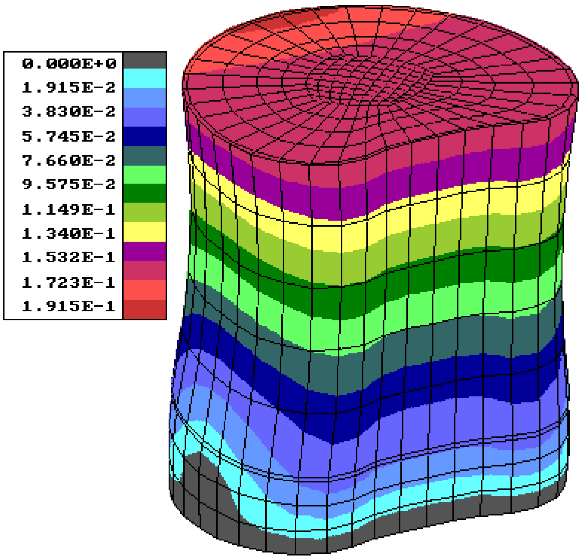

Figure 4. Menisci deformation for a peak force. The units presented in the pallete color for deformation are “cm”[10].

PRACTICAL APPLICATION

Our main goal is to integrate the various steps described above to produce a practical and economical diagnostic tool for non-invasively assessing musculoskeletal function on a subject-specific basis. In summary, virtual biomechanical simulation has phenomenal potential in improving medical science and health care as well as sports trainings. Due to the complexity of medical science and the computer technologies involved in building such simulation systems, there are still a lot of technical challenges in front of us. This work provides solutions to a part of this big problem. Indeed, the 3D reconstruction, motion simulation, and biomechanical visualization techniques presented can be seen as some basic elements of the next generation virtual biomechanical simulation system, a system where all the components of visualization, automated model generation, surgery simulation and surgery assistance come together.

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REFERENCES

1. Kojic, M., Filipovic, N., & Mijailovic, S. (2001). A large strain finite element analysis of cartilage deformation with electrokinetic coupling. *Comput. Methods Appl. Mech. Engrg*., 190: 2447-2464.
2. Donahue, T. L., Hull, M. L., Rashid, M. M., & Jacobs, C. R. (2002). A finite element model of the human knee joint for the study of tibio-femoral contact. *J Biomech Eng*., 124(3): 273 - 280.
3. Reinschmidt, C., van den Bogert, A. J., Nigg, B. M., Lundberg, A. & Murphy, N. (1997). Effect of skin movement on the analysis of skeletal knee joint motion during running. *J Biomech.,* 30: 729–732.
4. Sheehan, F. T., Pappas, G., & Drace, J. E. (2000). In vivo measures of musculoskeletal dynamics using cine phase contrast magnetic resonance imaging. In Skeletal Muscle Mechanics: from Mechanics to Function, ed. Herzog W, pp. 343–363. Wiley & Sons, New York.
5. Wismans, J., Veldpaus, F., Janssen, J., Huson, A., & Struben, P. (1980). A three-dimensional mathematical model of the knee joint. *J Biomech*., 13(8): 677-685.
6. Leger, L. A. & Lambert, J. (1982). A maximal multistage 20m shuttle run test to predict VO2 max. *Eur J Appl Physiol*., 49: 1-5.
7. Filipović, N., Vulović, R., & Kojić, M. (2007). *Software for 3D motion capture system*. University of Kragujevac, Kragujevac, Serbia.
8. Frank, E. H., & Grodzinsky, A. J. (1987). Cartilage electromechanics-I. Electrokinetic transduction and the effects of electrolyte pH and ionic strength. *J. Biomech*., 20: 615-627.
9. Frank, E. H., & Grodzinsky, A. J. (1987). Cartilage electromechanics-II. A continuum model of cartilage electrokinetics and correlation with experiments. *J. Biomech*., 20: 629-639.
10. Filipović, N., Kojić, M., Slavković, R., Zivkovic, M., & Grujovic N. (2001). *Finite element simulation of cartilage deformation*. University of Kragujevac, Kragujevac, Serbia.
11. Radakovic, R. (2005). *Antropometric characteristics and functional abilities in snowboarders.* University of Niš, Niš, Serbia. Tehnical Report. (in Serbian).

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