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ASSESSMENT OF A KNEE RESISTANCE BY APPLYING THE COMPUTATIONAL METHODS

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ABSTRACT
In tennis, the complex serving motions produce high mechanical stresses on player's musculoskeletal, tendon and ligament joints. In this paper, different cognitive methods have been integrated in order to non-invasively assess the knee's bone and cartilage resistance at the maximum power tennis serve. The proposed methodology is based on the creation of patient-specific biomechanical model, as well as on the tracking the knee's kinematics, ground force measurement, inverse dynamics modelling and analysis of the knee using the Finite Element Method with aim to assess the knee resistance of a tennis player, considering acute deformations and potential injuries. The main objective of this paper is development of the optimised computational technology and creation of practical diagnostic tool for non-invasive assessment of the knee function during specific moves and motions in tennis. It is expected that this approach can provide prediction and injury prevention in training and competitive tennis to a significant extent.

Keywords: NON-INVASIVE DIAGNOSTICS / PREDICTION OF KNEE INJURY / BIOMECHANICAL MODEL / INVERSE DYNAMICS / TENNIS

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INTRODUCTION

The serve is the most complex stroke in tennis. In order to perform the tennis serve, activation of large number of joints and muscles is needed, going from the forearm, upper arm and shoulder girdle, back musculature, abdominal musculature, to the pelvic muscles, hamstring muscles, lower leg and foot. The serve requires combination of motions needed to transfer all the force from the ground, across the racket up to the hitting the ball. Biomechanical analysis of tennis serve is divided into four phases: preparation, acceleration, impact and follow-through.

The preparation phase of serve is mostly a mental aspect of the stroke where the player is trying to focus on the upcoming actions. The next one, acceleration phase is the most complex phase of the tennis serve. The movements take place through order and pace, where impulse of the muscular and ground reaction force is shaped through the balance and rhythm. Acceleration is determined by how fast mass of the tennis ball reaches its top speed. Third phase is the impact. The more force player applies to the mass of the tennis ball – the greater serve will be. However, this phase requires displaying of player's coordination skills in order to maximize the accuracy of impact, i.e. serve. The last phase, follow-through consists of the player's decelerations and completion of maximum motion amplitude – where player releases all the momentum and power until the next shot. The better the follow-through the easier it will be for a player to get ready for the next shot.

In the case of maximum serving motion very demanding task is to accurately differentiate the forces and torques acting in the human joints, bones, soft tissues and articulation. This task is more challenging if it is related to impact loads on human body that occur during maximum mechanical loads. One of tasks in analysis of such a complex motoric act is the ground contact in the follow-through phase of tennis serve, such as concentric contractions during the landing (Bahamonde and Knodson, 2001). To push it further, we investigated the loads during the case of one leg touch-down after maximum power tennis serve. In this paper, the analysis of mechanical loads on one leg due to the tennis serve was based on kinematic analysis (Elliot and Wood, 1983; Talaat and Attaallah, 2015) of experimental setup for motion. The applied methodology for 3D analysis of tennis player's motion has been presented in the study of Elliot et al. (Elliott, Marsh and Blanksby, 1986). As usual, in a first step of data acquisition, the time dependent ground reaction forces and three-dimensional (3D) positions of leg joints were collected by using the force plate and optical motion capture system. After that, the biomechanical models of human body were applied to experimental data (Filipovic, Vulovic, Peulic, Radakovic, Kosanic and Ristic, 2009). The forces and torques in the leg joints were determined by using inverse dynamics (Gruber, Ruder, Denoth and Schneider, 1998; Payton and Bartlett, 2008). Due to specific serving motion, the stress analysis based on Finite Element Method (FEM) was applied for the cartilage and bones inside the full 3D patient-specific knee model (Vulović, Vukićević, Jovičić, Ristić and Filipović, 2016). The FEM has found a wide application in the prediction and prevention of the fracture occurrence of the bone tissue, as well as of the cartilage damage (Živković, J., Jovičić, Vulović, Stepanović and Živković, M., 2013; Antic, Vukicevic, Milasinovic, Saveljic, Jovicic, Filipovic, Rakocevic and Djuric, 2015; Janovic, Saveljic, Vukicevic, Nikolic, Rakocevic, Jovicic, Filipovic and Djuric, 2015; Sabet, Raeisi, Hamed, and Jasiuk, 2016; Pajic, Antic, Vukicevic, Djordjevic, Jovicic, Savic, Saveljic, Janovic, Pesic, Djuric and Filipovic, 2017).

Bones are hard tissues with highly anisotropic characteristics and, in contrast to engineering materials, they have the ability to regenerate and adapt over time. Moreover, the process of adaptation to dominant muscle and external forces may vary depending on skeletal shape, age, gender, physiologic functions, disease, mechanical stress and type of micro damage, as well as fatigue of biomaterial due to permanent loading. The risk of the bone fracture is increased and lies in the fact that fatigue fracture mechanisms depend not only on the level of a force applied but on the presence of the micro damage, too (Vukicevic, Zelic, Jovicic, Djuric and Filipovic, 2015; Jovičić, Djorović, Vukicević, Djordjević and Filipović, 2019). This is an important fact that, as a chronic factor, increases the risk of injury of athletes and even tennis players. Thus, the injury caused by mechanical stress potentially can occur in the zone of initial micro fractures due to impact of loading which, although within the physiological limits, can be vulnerable at the maximum power tennis serve. It should be underlined that the initial micro damages among professional tennis players can be caused by other permanent loads, not only by tennis serve.

The deformation phenomena of cartilage inside the knee has been subject of various experimental and theoretic studies, where cartilage tissue from the biomechanical aspect is considered as a porous deformable

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body filled with fluid, occupying the whole pore volume. The Darcy's law is a fundamental law which describes cartilage as a porous medium, while more complex analysis of cartilage requires employment of additional laws (Filipovic et al., 2009).

METHODS

The applied methods take place through experimental setup for motion tracking and ground reaction force determination (Bahamonde et al., 2001; Filipovic et al., 2009). This is followed by the inverse dynamics (Gruber et al., 1998; Payton et al., 2008; Filipovic et al., 2009), spring-damper-mass models and finite element model for cartilage and knee bone tissue (Kubicek and Florian, 2009). The stress analysis based on finite element method was applied for the cartilage and bones inside the full 3D knee model for a tennis-specific player who participated in this study. At the end, the goal was to estimate the bone fracture resistance parameters in the case of initial micro damage of the bone and cartilage damage. We used a novel decision support system for the assessment of bone fracture resistance by artificial intelligence algorithms (Vukicevic, Jovicic G., Jovicic N., Milicevic and Filipovic, 2018). The practical application of this study suggests a novel computer tool for every tennis-specific player. This tool enables creation of specific geometry of the knee, application of specific forces which are experimentally measured and correspond to physiology of tennis-specific player. It can be considered as a tool for more accurate prediction of the risk of possible injury (i.e. bone fracture).

Sample of the subjects and experimental setup

Five healthy male tennis players, age between 28±5 years, height 186.2±4.1 cm, and body mass 86.1±5.3 kg (arithmetic mean ± SD), without locomotor system injuries nor neuromuscular disorders participated in the study.

Subjects were instructed to perform ten first (flat) and ten second (spin) serves, with individually precepted maximum power. Their motions were recorded using OPTI Track motion capture system (6 V100:R2 100Hz cameras with ARENA software) and predetermined parameters of the motions were observed in order to create the biomechanical model at the player's ground contact phase immediately after serve. Ground reaction force was sampled from the multi-axis AMTI force plate at the rate of 1000 Hz. All kinematic and kinetic results of the subjects were used to create the biomechanical model parameters of the supporting leg during the serve, where the obtained parameters were included in the calculation of the knee loads during the final phase of the serve.

Acquisition, modelling and data analysis

I. The inverse dynamics solutions were employed to calculate the forces, moments and power of the supporting leg (Figure 1a) (Gruber et al., 1998; Payton et al., 2008). Body segment parameters: moments of inertia of body segments and their center of masses, were calculated by using the literature data (Zatsiorsky, Seluyanov and Chugunov, 1990; DeLeva, 1996). The projection of 3D dimensional cinematographic analysis of the specific tennis serve is shown in Figure 1b.

In case of inverse dynamics approach for biomechanical properties modelling, specific player must be accepted as a first approximation, due to existence of some serious difficulties (e.g. extremely short duration of impact phase) which are described in detail in the work of Filipovic et al. (2009).

II. The finite element method for numerical calculation of bone stiffness allows identifying the zones of possible damage, i.e., the zones where the bone fracture will initially appear as well as the load force which will cause their appearance or appearance of cartilage damage. The accuracy of reliability assessment largely depends on the material properties and ways of formulation of the failure mechanisms. At the level of continuum mechanics, the bone material can be treated as a heterogeneous structure with strongly anisotropic properties. Despite intensive research, the reliability of phenomenological framework for describing the conditions in which the failure occurs in bone structure (cortical and cancellous) is still experimentally tested.

A new methodology was applied in this study with aim to represent specific regions of the knee and better assign the material properties, and considering the material structure of the knee is bio-composite, a continuum orthotropic material model was used for predicting the elastic response.

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Geometrical data for Finite Element Analysis (FEA) were obtained from Magnetic Resonance Imaging (MRI) of a specific volunteer. Boundary condition for FEA was taken from inverse dynamics and fitting procedure for spring-damper-mass dynamic model. The MRI images were automatically segmented using a commercial software package such as *Mimics* and a surface stereolithographic (STL) mesh was produced for the bones (cortical and cancellous) and cartilage, including tibia and femur proximally to the knee. The knee-ligament origin and insertion sites were identified directly from the MRI scans. A detailed 3D FE structured volume mesh was generated in the particular region, as well as a combination of generic bone segments.

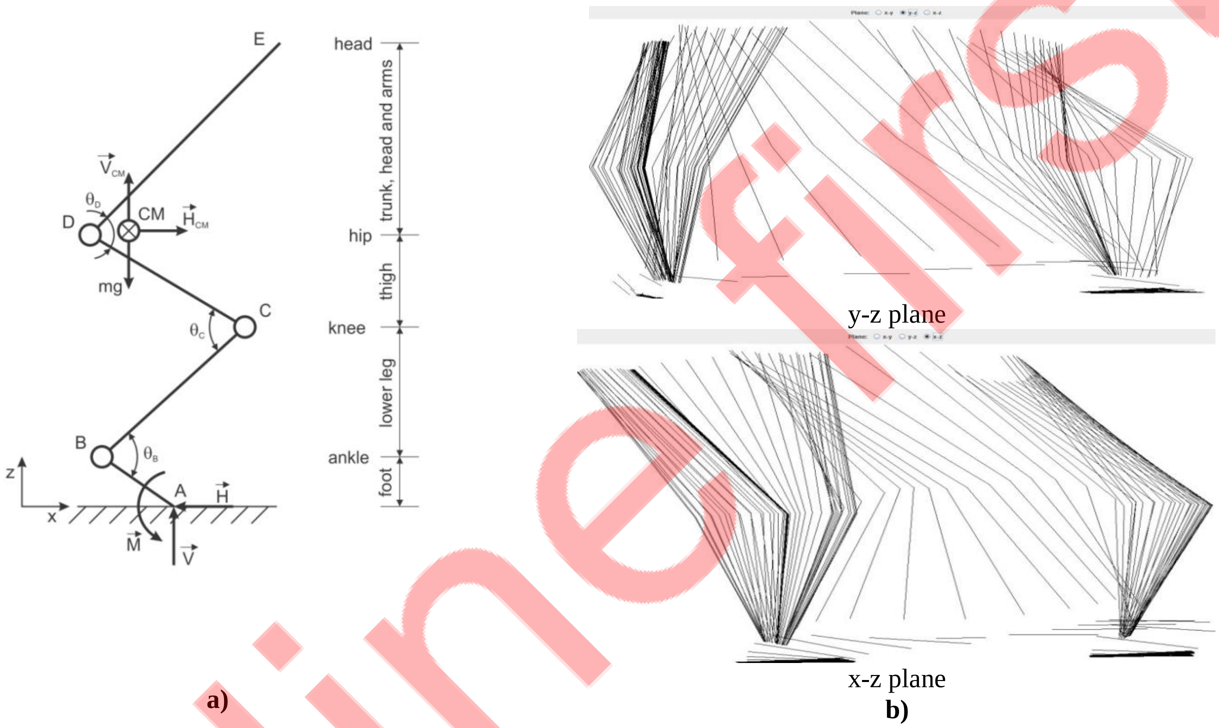

Figure 1. a) Free body model of the human's body and leg segments; b) Projections of leg trajectory in *y-z* and *x-z* plane during tennis serve. Sagittal axis is y, and z is vertical axis.

III. The mechanical properties of knee depend on composition and structure of bone tissue and cartilage. The bone tissue of knee is composed of cortical and cancellous structure (see Figure 2a). Specimen cut from cortical bone under compact tension test for experimental determination of the fracture toughness K_c is presented on Figure 2b. The assessment of bone tissue fracture resistance was based on the linear-elastic fracture mechanics approach, or more precisely, on the formation of fracture resistance curve (R-curve, see Figure 2c). According to the R-curve approach, a crack propagation starts when the stress intensity factor (K) exceeds the value of threshold toughness K_{th} (Jovicic, Vukicevic and Filipovic, 2014). After that, stable crack propagation continues until the K reaches the fracture toughness K_c (Figure 2c). Thus, the corresponding slope of the R-curve is considered as a measure of the crack growth toughness (a bigger slope indicates a bigger resistance to fracture). The crack growth toughness i.e. the slope of the R-curve depends on skeletal shape, age, gender, physiologic functions, disease. It should be underlined that experimental testing of bone fracture resistance (Figure 2b) is not feasible since it represents an invasive method. Thus, in this study was applied the methodology based on artificial intelligence algorithms and neural networks (Vukicevic et al., 2018).

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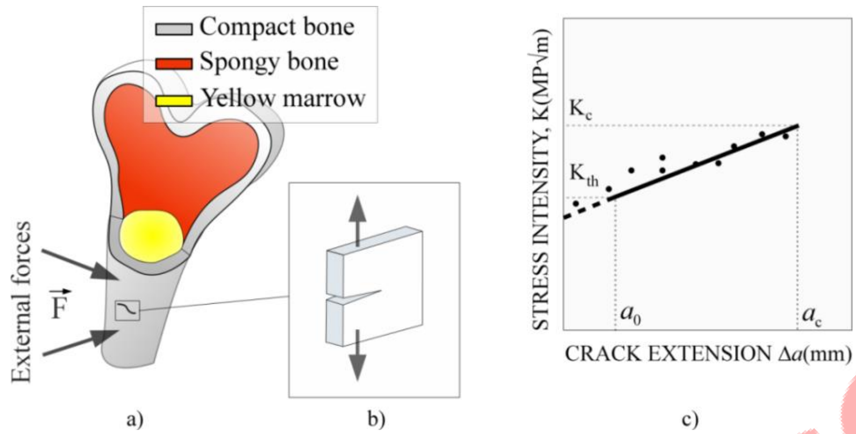
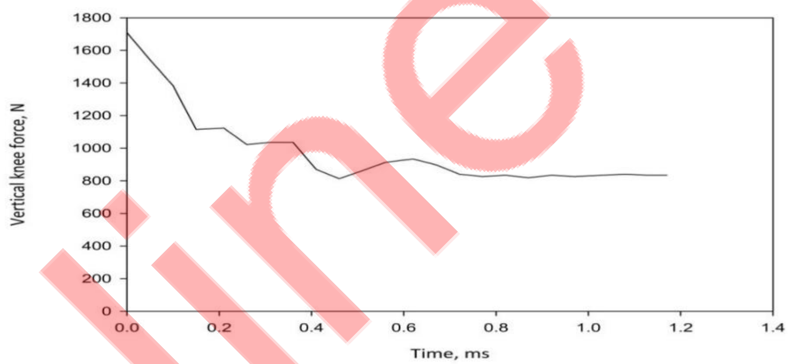


Figure 2. Sketch of the considered methodology: a) Cortical tissue (Compact) of tibia bone with the initial crack; b) Specimen cut from cortical bone under compact tension test; c) R-curve with specific values of crack size and stresses intensity.

RESULTS AND DISCUSSION

In this paper we used dynamic model to prescribe forces obtained from the inverse kinematics and dynamic analysis. Resulting force, acting on the knee during landing on one leg in tennis serve, is shown in Graph 1. Solid line represents force calculated by using inverse dynamics procedure.



Graph 1. Knee force obtained by inverse dynamics model (Filipovic et al., 2009).

The numerical simulation of knee model, presented in Figure 3, showed that maximum stress (1.15 MPa) is present in some parts of the cartilage. The suggested methodology allows simultaneously prediction of joint kinematics and stress distributions, using also the force and moments from a rigid-body model simulation (kinematic model simulation).

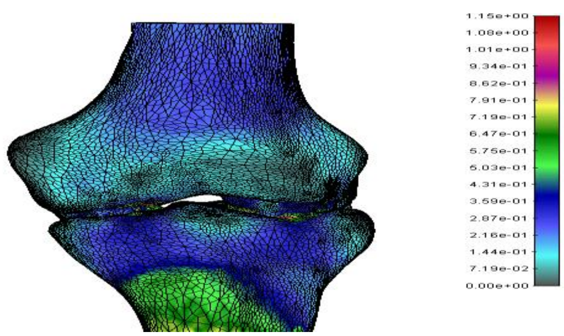


Figure 3. Finite element analysis of the knee model. Effective stress distribution in the tibia bone as well as in the cartilage; Units for stress [MPa].

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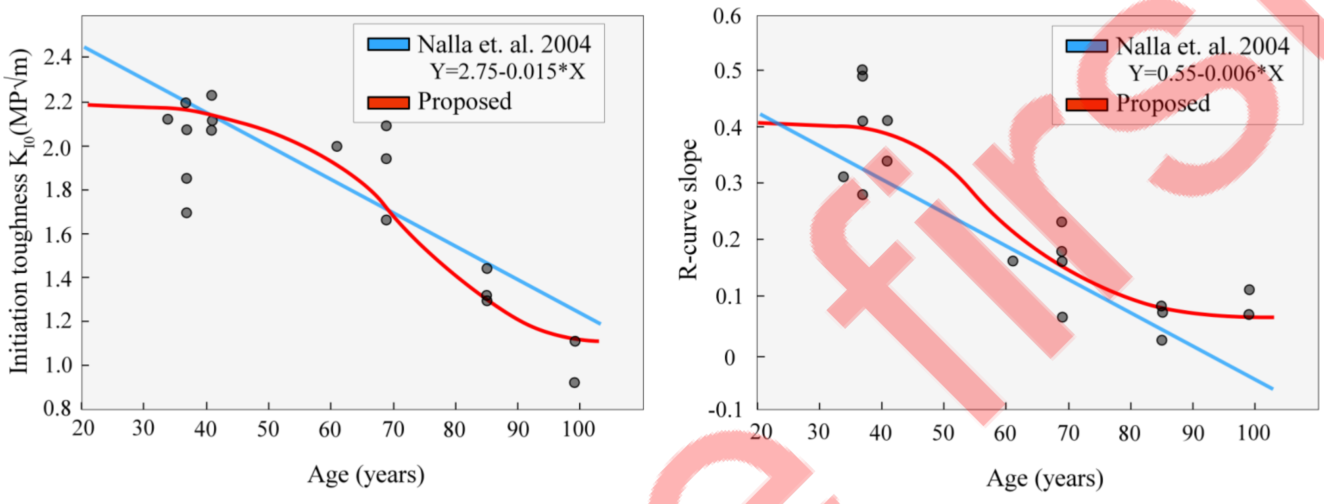
Numerical assessment of the knee structural integrity was based on detection of the zones of possible failure. For this case-specific player, the effective stresses in cortical tissue are in range from 0.28 to 0.719 MPa. Obtained maximum value of effective stress was used for numerical calculation of K. The fracture resistance of bone is satisfied if obtained maximum K is less then fracture toughness (see Graph 2). In this paper, the fracture toughness of cortical bone for tennis-specific player was determined by using the methodology based on artificial intelligence algorithms (Vukicevic et al., 2018). The fracture resistance of bone varies depending on the skeletal shape, age, gender, physiological functions, disease, etc.

The assessment of cortical bone fracture resistance depending on subject's age (Graph 2) was performed by applying artificial intelligence algorithms and neural networks (Vukicevic et al., 2018).



Graph 2. The assessment of cortical bone fracture resistance depending on subject's age (years) (Nalla, Kruzic, Kinney and Ritchie, 2004). a) Initiation toughness vs Age (years); b) R-curve slope vs Age (years).

According to proposed values (red line) presented in Graph 2, it can be concluded that cortical bone fracture resistance parameters have constant values in case of tennis-specific players aged between 28±5. The adopted input parameters for assessment of cortical bone fracture resistance for tennis-specific player aged 28 (Graph 2) were used for calculation of cortical bone critical stress value that was 2.85 MPa. Comparing this value with maximal stress value in cortical bone (Figure 3), it can be concluded that the cortical bone of tennis-specific player will not be damaged during the maximum serving motion. Therefore, the presented methodology can be preventively applied in order to prevent and predict eventual injuries of tennis player during the individual maximum serve power.

CONCLUSIONS

In this study, the implementation of computer technology was presented in order to create a practical diagnostic tool for non-invasive assessment of the knee function. The suggested methodology was based on the acquisition and analysis of data obtained by measurement and calculation, as following: forming the biomechanical model of the specific tennis player, tracking of the joint kinematics, force ground measurement, finite element analysis of the knee model, bone resistance assessing of the player knee. A rigid body model was used to calculate the force and momentum reactions in the leg joints. The effective strength of knee cartilage and bone during maximum serve power for ground contact of tennis player was determined by finite element analysis. Bone fracture resistance assessment of the knee was based on numerical calculation of effective stress. A novel decision support system for the assessment of bone fracture resistance was used by fusing various artificial intelligence algorithms.

The main aim was development of the computer technology which integrates the various steps described above to produce a practical diagnostic tool for non-invasive assessment of the knee function for a tennis-specific player.

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