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FINITE ELEMENT ANALYSIS OF A KNEE JOINT DURING JUMP

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Abstract

Athletes experience high levels of stress during sports activities. One of the most common activities is jumping. This is a very complex activity, which can lead to injuries and long recovery periods. In this research, professional athletes performed jumps in order to obtain ground force values from a force plate. A combination of ground force measurement and inverse dynamics was used to obtain knee joint force values during jumping. The obtained values were then used for the finite element analysis of a knee joint model in order to calculate stress values in the knee joint, with focus on femoral cartilage and menisci. The highest stress values were obtained at the anterior and posterior horn of the medial meniscus, with the highest stress value of 4.894 MPa. Femoral cartilage had lower value, with the maximum stress of 0.391 MPa.

Keywords: inverse dynamics, jump, knee joint, finite element method, stress distribution

1. Introduction

Jumping is one of the most complex, but, at the same time, the most dangerous movements in sports. In order to perform a jump, a high degree of neuromuscular activation and control is necessary. This type of activity consists of a complex range of limb and joint movements, which is necessary to transfer the ground reaction force to the upward jump. During the jump, the jumper needs to engage a number of joints and muscles such as those of arms, abdomen and back as well as the muscle groups and joints of the lower extremities, primarily the knee joint.

Biomechanical analysis of jumping is divided into four phases: approach, take-off, flight and landing. The approach phase represents the positional preparation for the jump, where an athlete tries to take the optimal position for the best possible jump performance. The take-off phase is the most difficult and complex along with the landing. The jumper generates and exerts an explosive force of the foot where the ground reaction force needs to be used before the take-off phase. Acceleration is determined by how fast the mass reaches its maximum speed. The more force the athlete generates and produces, the stronger the jump will be. The landing phase consists of muscular activity that softens the movements during the landing. Better final movement of the landing phase will lead to better preparations for the next movement, which is conditioned by the neuromuscular control and coordination of the athlete.

Athletes experience high levels of stress during sports activities. Based on a study from 2011, professional football players have 2 injuries every season (Ekstrand et al. 2011). It is known that knee injuries are common in sport, especially injuries related to ligament or meniscal tear (Moses et al. 2012). Non-invasive determination of knee deformity (bone and soft tissues) can be a very useful tool for predicting and possibly preventing knee injury.

In this study, ground force measurements from the force plate were used in combination with inverse dynamics. Inverse dynamics has been used for analysis of jumps. The use of inverse dynamics in a known approach for biomechanical analysis (Dziewiecki et al 2013; Holder et al. 2020; Kotsifaki et al. 2021). In this paper, inverse dynamics was used in order to obtain joint force values during different jump segments, based on the values obtained from the force plate. After that, the obtained values have been used for the finite element analysis of a knee joint model.

The aim of this paper was to present a methodology that would be a basis for the development of a practical diagnostic tool that could be used by coaches and experts as a way to better evaluate athletic performance under various training and competition condition.

The paper is structured as follows:

- Section Inverse dynamics describes the experimental setting for determining the reaction force of the ground, which are then used to calculate force values in the joints using the inverse dynamics.
- Section Knee joint finite element analysis presents the knee joint model, material properties as well as the applied boundary conditions.
- Section Results and Discussion presents the results obtained using the finite element analysis and include stress distribution of the knee joint as well as the stress distribution in the cartilage and menisci.

2. Inverse dynamics

2.1. Experimental setting

The goal of the experimental segment of this study was to obtain the ground force values and valuable information about lower joint (ankle and knee) kinematics. The study involved 55 healthy professional male athletes without neuromuscular disorders. Their anthropological characteristics are presented in Table 1.

Characteristic	Arithmetic mean ± SD
Age (years)	28±7
Height (cm)	185.9±5.1
Body mass (kg)	89.1±5.5
SD – Standard deviation	

Table 1. Anthropological characteristics of the participants.

Subjects were instructed to perform different types of jumps in isolated conditions. Their movements were recorded by the Opti Track motion capture system (6 V100: R2 100Hz camera with ARENA software). As a result of this experiment, ground reaction force values were obtained. The ground reaction force was measured on a multi-axis AMTI force plate for measuring force at a sampling frequency of 1000 Hz.

2.2. Data postprocessing

At the end of the experimental stage, several parameters for each jump had to be determined. Those parameters were (Filipovic et al. 2009): a) frame rate, b) duration of the jump, c) the ankle and the knee joint coordinates for each time frame, d) ground forces values measured on the force plate, e) number of jumps and f) maximal velocity that was gained during the landing on the force plate.

The recorded ground reaction forces (both horizontal and vertical) were used to calculate internal forces in the athlete's ankle and knee. Fig. 1 shows the vertical ground force for the first 0.1s of the experiment. Besides the ground force values, the coordinates of the ankle (Fig. 2) and knee joints were required in order to calculate the forces in the knee joint which was required for the finite element simulation of the jump.

Time	Vertical ground force [N]
0	1759
0,01	1725,6
0,02	1692,2
0,03	1658,8
0,04	1625,4
0,05	1592
0,06	1560,2
0,07	1528,4
0,08	1496,6
0,09	1464,8
0,1	1433

Fig. 1. Vertical ground force (0 to 0.1 s).

Time	Ankle y coord [mm]	Ankle z coord [mm]
0	529,46	124,777
0,01	529,434	115,107
0,02	526,834	106,615
0,03	522,792	99,503
0,04	522,893	97,805
0,05	519,027	98,814
0,06	515,24	101,937
0,07	511,461	104,957
0,08	507,126	106,01
0,09	503,054	105,946
0,1	498,674	105,572

Fig. 2. Ankle coordinates (0 to 0.1 s).

2.3. Data postprocessing

Inverse dynamics analysis has been used to calculate joint forces and torques based on the ground force values and necessary joint coordinates measured in the experimental study, explained in the previous section. The human body was considered as a rigid body linked segment model (Fig. 3). In this study, two sections of the linked segment model (section AB and BC) were analyzed.

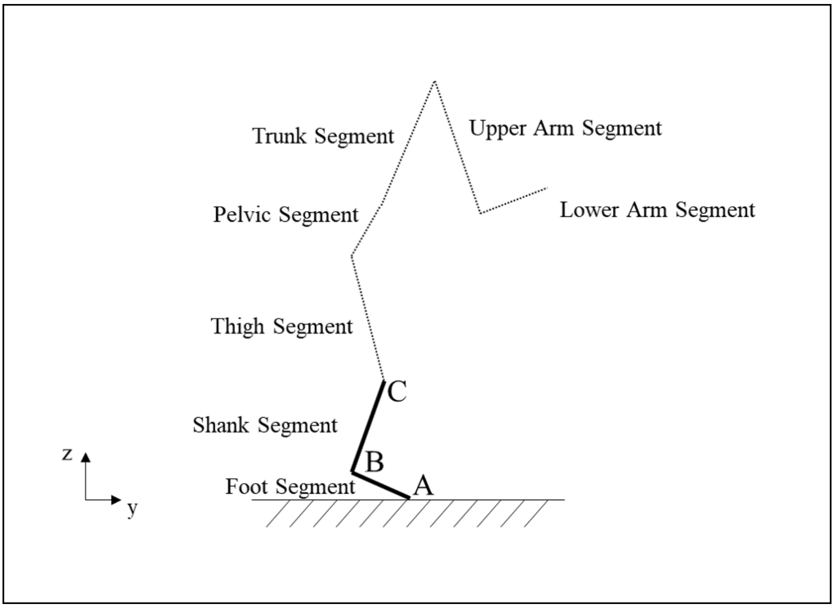

Fig. 3. Rigid body linked segment model.

The joint reaction forces and torques are calculated using Newton's equations of a motion applied to a rigid body segment (Faber et al. 2018). To obtain force and torque values in the knee joint, needed for the numerical simulation of the knee joint, the following simplifications were considered: joints were considered to be pin joints; the body segments were considered to be rigid and the mass of the body segment was concentrated at the center of mass of that segment. The Newton's equations of motion were formulated for the foot and shank segment starting from the foot. The body segment parameters needed for the equations were calculated using available anthropometric characteristics (Zatsiorsky et al. 1990; de Leva 1996; Ethier and Simmons, 2007). The calculated knee joint force values are shown in Fig. 4.

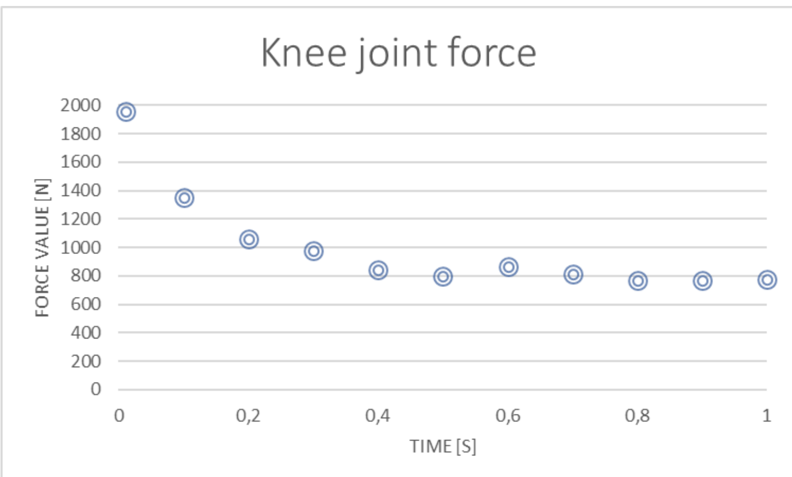

Fig. 4. Knee joint force values obtained by inverse dynamics analysis.

These values were used as loading conditions for the finite element analysis of the knee joint.

3. Knee joint finite element analysis

3.1. Knee joint model

Already developed biomechanical model of the knee joint was used for the finite element analysis (Vulović et al. 2021). A magnetic resonance imaging (MRI) scans of mid-lower thighbone and mid-upper tibiofibular part of the right knee joint in full extension were used to obtain the contours of bone and soft tissue that build the knee joint. The contours of the bones and soft tissues were manually segmented on each MRI scan. Scan resolution was 320 x 320 pixels with slice increment of 0.589 mm.

The knee joint model (Fig. 5) consisted of femur, tibia, menisci (medial and lateral), and articular cartilage (femoral, medial tibial and lateral tibial). Bones, cartilage, and menisci were considered to be deformable.

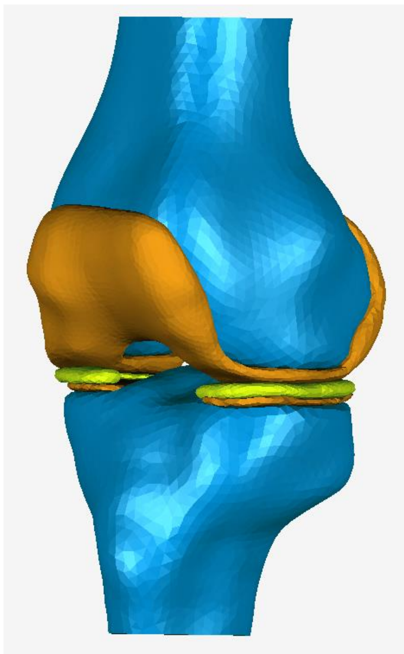

Fig. 5. Knee joint model.

All tissues were meshed using tetrahedral elements. The total number of nodes and tetrahedral elements in the model was 28511 and 117645, respectively.

3.2. Material properties and boundary conditions

The material properties of the bones, cartilage, and menisci are assumed to be linear elastic, homogeneous and isotropic. The considered values are presented in Table 2.

Material	Elasticity modulus [MPa]	Poisson's ratio	Reference
Femur	16700	0.3	Soni et al., 2007
Tibia	14317	0.315	Soni et al., 2007
Cartilage	12	0.45	Hopkins et al., 2010
Menisci	80	0.3	Hopkins et al., 2010

Table 2. Material properties.

One key moment during the jump was analyzed, and that was the moment when athlete lands on the ground, or, in this case, on force plate. As a result, the following boundary conditions were considered:

- Lower tibia surface was fixed.
- All other nodes were locked in x and y direction and were only able to move along the z axis which was perpendicular to the upper surface of the femoral bone.
- The force was applied as perpendicular to the femur's upper surface and the value obtained with inverse dynamics (Fig. 4) was distributed among all the surface nodes.

Two types of contact boundary conditions have been used – glued and frictionless. Glued contact was used between the following segments: tibia – tibial cartilage, tibial cartilage – menisci, and femoral cartilage – femur. The frictionless contact was used between menisci and femoral cartilage. Analyses were performed using solver NX Nastran 11.4.1.

4. Results and Discussion

The aim of this paper was to calculate the knee deformation and stress during the landing phase of a jump. Fig. 6 shows stress distribution for the knee joint for the highest calculated force (Fig. 4).

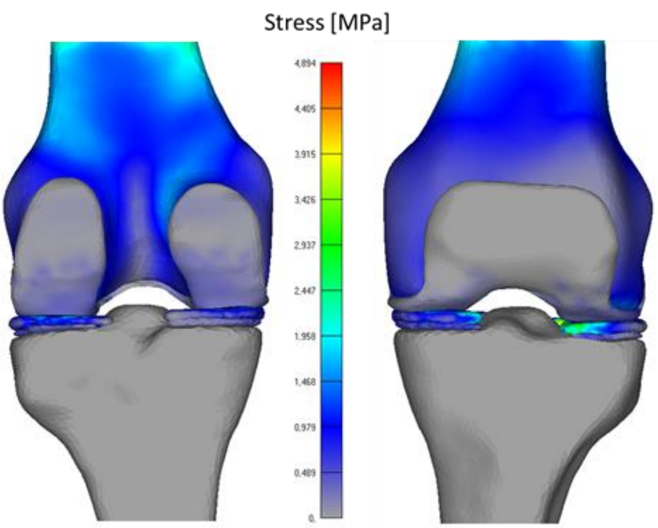

Fig. 6. Knee joint stress distribution.

As it can be seen in Fig. 6, the stress values were in range from 0 to 4.894 MPa. The knee joint segment with the lowest values was tibia. The highest values were calculated in the medial meniscus. Fig. 7 shows the stress distribution in the medial meniscus where the maximum value was calculated. Most of the stress values calculated for medial meniscus were in range from 0.489 MPa to 1.958 MPa. Higher values were calculated at the anterior and posterior horn.

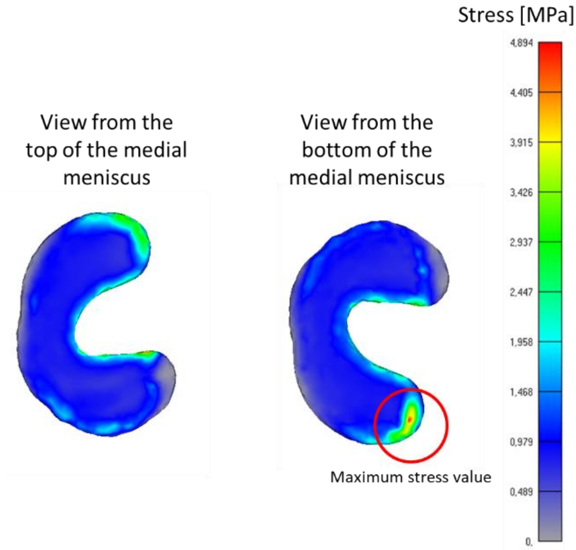

Fig. 7. Medial meniscus stress distribution.

Fig. 8 shows the femoral cartilage stress distribution. As it can be seen, the maximum value for this segment was significantly lower than the medial meniscus maximum value. For the femoral cartilage, stress values were in the range from 0.00000921 MPa to 0.652 MPa. The higher stress values were obtained above the medial meniscus. The area above the lateral meniscus were lower with the highest value being around 0.391 MPa.

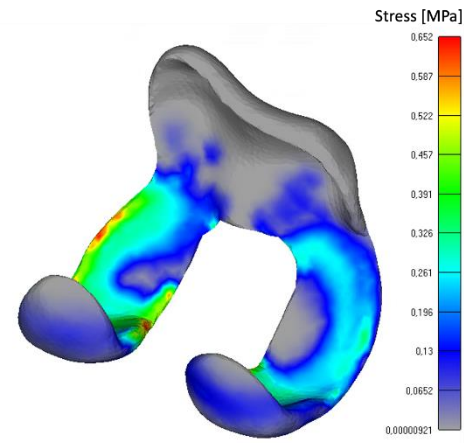

Fig. 8. Femoral cartilage stress distribution.

Fig. 9 shows the maximum stress values that correspond to the forces presented in Fig. 4.

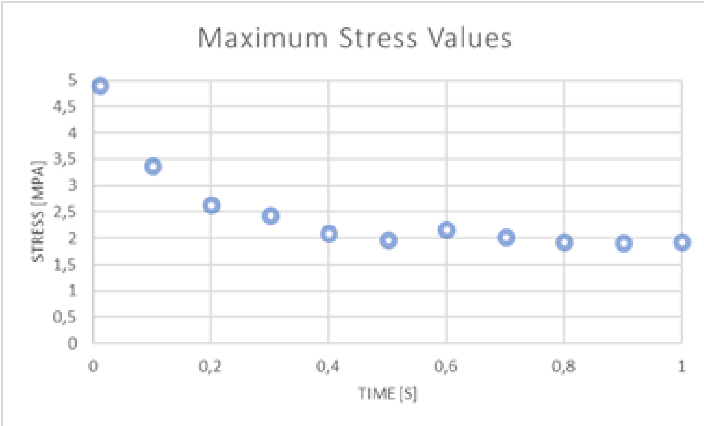

Fig. 9. Change of maximum stress values during time.

By comparing Figures 4 and 9, it can be noticed that the trend of value change is the same. The highest stress value was obtained for the first step for which we have obtained the highest force value. The previously presented values can be used to determine fracture resistance, which can be done with the use of artificial intelligence (Vukićević et al. 2018). By determining the fracture resistance we can possibly predict potential injuries of athletes during maximal jumps performance.

4. Conclusions

A methodology for a practical diagnostic tool for non-invasive assessment of an athlete's knee function is presented. The presented methodology is based on the following elements: creating a knee joint biomechanical model, monitoring the kinematics of the joints, measuring the reaction force of the ground, analyzing the knee model by using the finite element method and assessing the knee resistance. The implementation of such technological achievements in the field of sports science is very important step for top athletes. This approach can potentially be used to gain knowledge that could be useful for better understanding of injuries and their prevention.

In this paper, the stress distribution of the knee joint as well as the soft tissue that includes femoral cartilage and medial menisci were presented. The values were obtained using the finite element method. Results indicate that the most critical area of the knee joint under presented boundary conditions was at the anterior and posterior horn of the medial meniscus. The main limitation of the presented results is related to the defined material properties, especially for soft tissues which are more complex that the properties used.

In the future research, special focus will be on the inclusion of muscular control of human jumping through inclusion of the muscles. Future research plans include the development of computer technology that combine previously described methodology in order to develop a practical diagnostic tool that would allow coaches and experts to better evaluate athletic performance under various training and competition condition.

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