Numerical simulations and experimental flexion-extension measurements of human leg joints during squat exercises

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Abstract: In this paper the variations of ankle, knee and hip flexion-extension angles during squat exercises of a healthy male subject were obtained using a complex data acquisition system, based on electro goniometers. Using an acquisition system based on electro-goniometers, measurements of flexion-extension angle for ankle, knee and hip joints during squat movement on a healthy subject are performed. The curves of ankle, knee and hip angles are normalized and the medium squat cycle for each leg joint are determined. The obtained experimental data series were introduced as input data in the joints of the virtual mannequin and a squat simulation was performed in ADAMS environment software. The variations of reaction forces in joints during squat are obtained by virtual simulation. The reactions forces are very useful for simulation and numerical study of stresses for healthy, affected and implanted joints and bones, using Finite Element Method.
Key words: *squat, electro goniometers, virtual mannequin, numerical simulation, reaction forces.*

Introduction

The squatting movement is one of the most frequently used exercises in the field of strength and conditioning, but, also, it has close specificity to many everyday tasks (picking up children, lifting packages). Squatting is considered one of the most functional and efficient weight-bearing exercises for an increased quality of life or for different performance in sport activities (1,2). In (2) the authors examine kinematics and kinetics of the dynamic squat with respect to the ankle, knee, hip joints in order to optimizing exercise performance. The strength and stability of the knee plays an important role in athletics and activities of daily living (3). In rehabilitation and knee exercise prescription, in order to obtain an athlete’s or patient’s success, a good understanding of knee joint biomechanics while performing variations of the squat is useful to therapists, trainers, and athletes (1,3). Squatting is an activity that increase the risk of knee disorders, including arthritis and menisci injuries (4,5). Because the squat is considered a closed kinetic chain exercise, it can also be employed in knee rehabilitation programs, such as an effective exercise during anterior cruciate ligament (ACL) rehabilitation (6-8).

Material and method

Measurements of flexion-extension angle of right leg joints during squat test were performed on a healthy subject. Before the beginning of the final experimental test, the subject repeats for several times the squat test. The study was approved by the Human Ethics Research Committee, University of Craiova, Romania. The experimental measurements were performed for five trials of twenty consecutive squat cycles of a male subject. The subject was pain-free and had no evidence or known history of motor and skeletal disorders or record of surgery to the lower limbs. The experimental data were acquired for the right ankle joint, right knee joint and right hip joint. In Table I the values for anthropometric data of male subject are presented.

Table I. The subject's anthropometric data

Indicator	Age (years)	Weight (kg)	Height (cm)	Leg length (cm)	Hip–knee length (cm)	Knee–ankle length (cm)
	26	72	177	86	45	41

The experimental method used to obtain the kinematic parameters diagrams for the human knee joint is non-invasive, using a Biometrics data acquisition system based on wearable electro goniometers (9-11). Data Log MWX8 is a device used for portable data collection on 8 channels simultaneously in human gait, human performance, medical research, robotics (8).

Figure 1. Subject with mounted Biometrics Data acquisition system

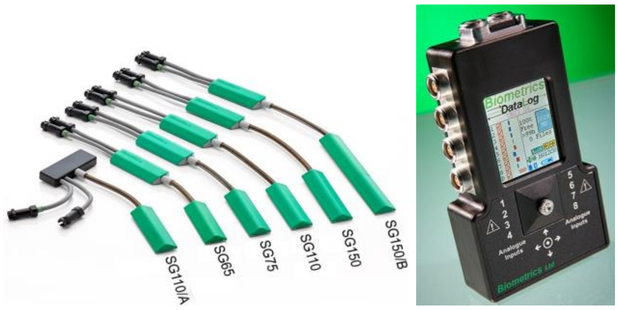


Figure 2. Biometrics flexible goniometers and Data Log data acquisition system (8)

The schema block of Biometrics acquisition data system is presented in figure 3.

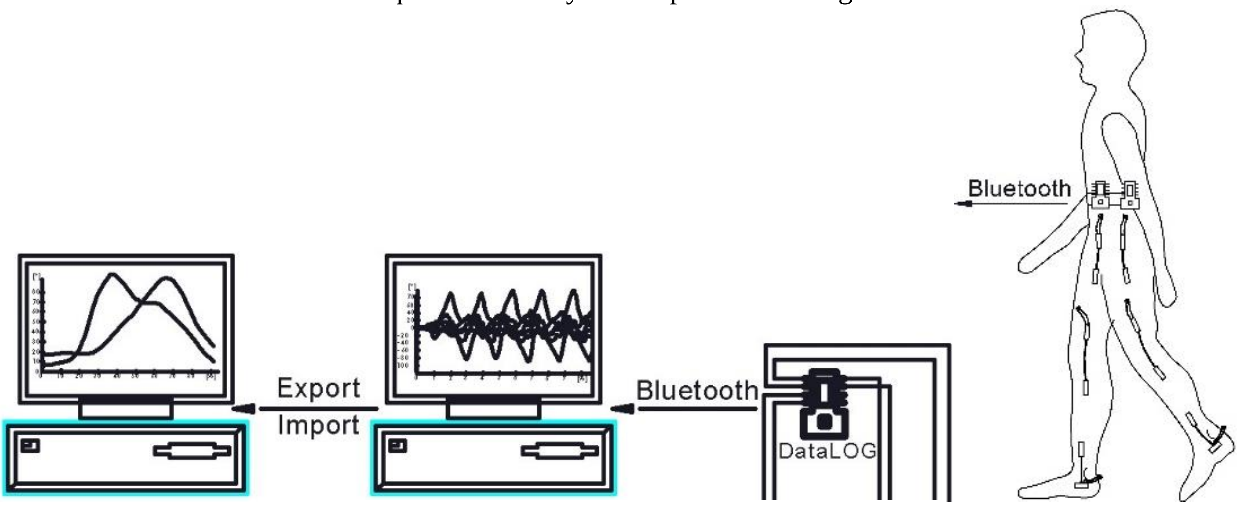


Figure 3. The schema block of Biometrics acquisition system

Results

The flexion-extension angular variations and the angular variation in frontal plane of right ankle, knee and hip joints during squat exercise were obtained from the report, generated as data files, by the acquisition system. In this paper, we are interested to process the variation of the three flexion-extension angles joints. In Figure 4 the consecutive squat cycles diagrams for flexion-extension angle and frontal movement angle of ankle, knee and hip joints collected using Biometrics system and wearable sensors, are presented.

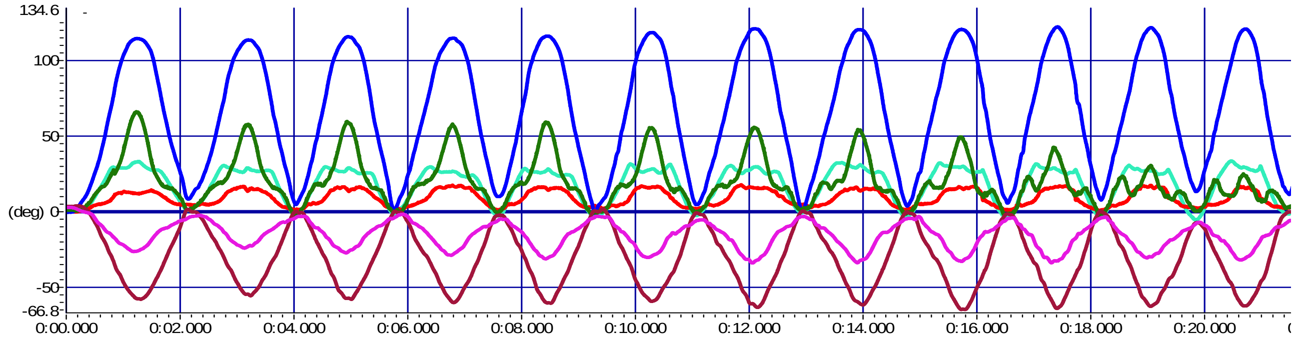


Figure 4. Consecutive squat cycles diagrams for flexion-extension angle and movement angle in frontal plane of ankle, knee and hip joints

The flexion-extension data files were exported from Biometrics to Simi Motion software (12), and the normalized curves of flexion-extension angles corresponding to each squat cycle and the medium squat cycle were obtained (Figure 5-7). The mean squat cycle curves of each joint (represented by red color) the mean+ standard deviation envelope cycle (orange color) and the mean - standard deviation envelope cycle (green color) are shown in Figure 3. The maximum values of the ankle angle vary from one cycle to other in the interval [36.73^0; 40.87^0], the maximum values of the knee angle vary in the interval [95.43^0; 110.53^0] while the maximum values of the hip angle vary in the interval the average cycle values vary in the interval [55.67^0; 63.35^0]. The minor differences obtained by comparing the maximum amplitudes of consecutives cycles show a good repeatability of the imposed exercise for subject. The maximum values of each joint cycle determined during the performed trials were compared and tested with a Student *t*-test, considering α=0.05. The *p*-values corresponding to these tests are calculated using ANOVA. The maximum flexion angles for all cycles of each of the three joints were not significantly different ($t_{calc}=2.01<t_{cr}=2.31$ and $p=0.0795>0.05$).

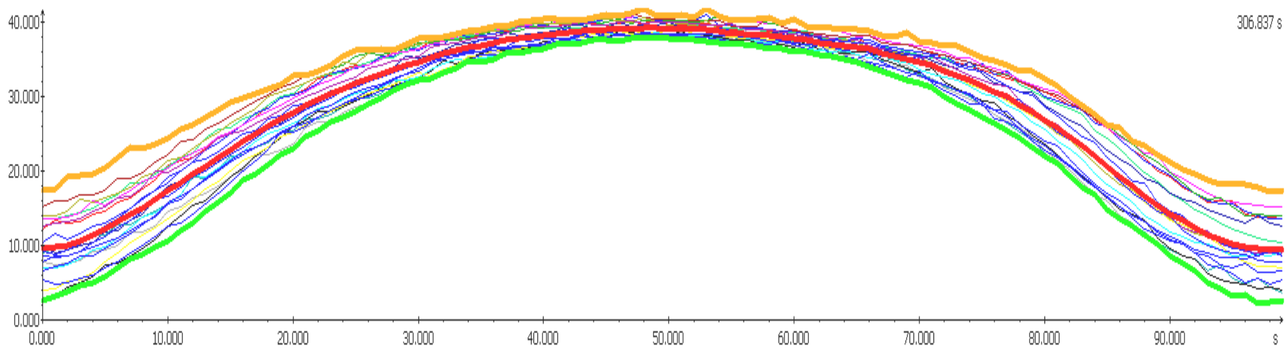


Figure 5. The twenty normalised consecutive squat cycles (deg), the medium cycle (red color) for ankle joint

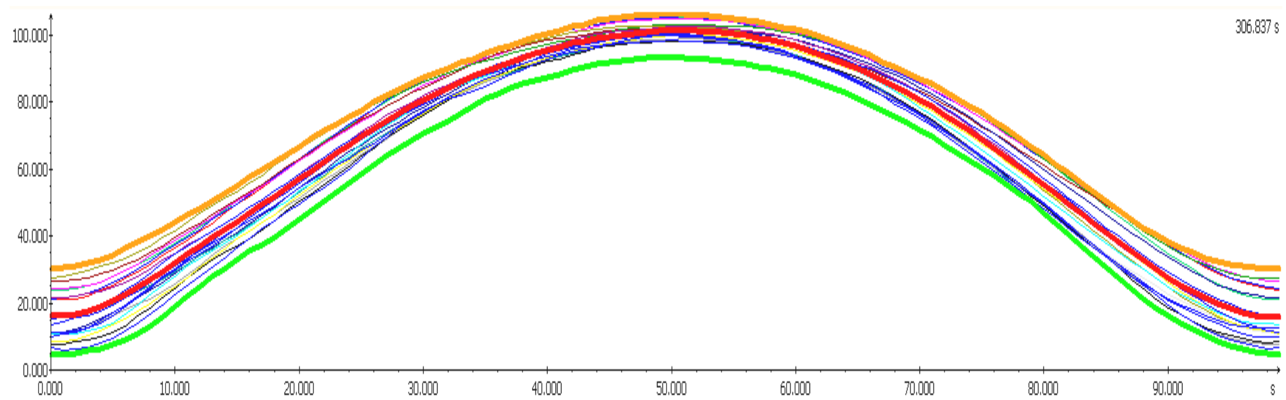


Figure 6. The twenty normalised consecutive squat cycles (deg), the medium cycle (red color) for knee joint

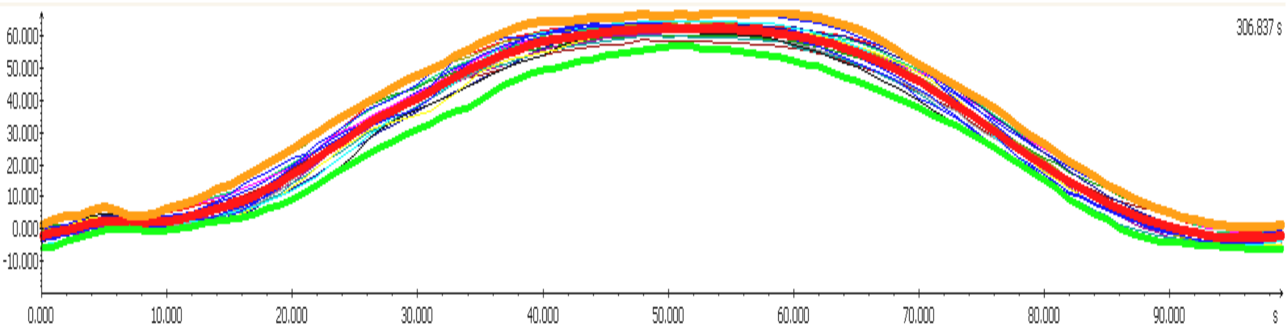


Figure 7. The twenty normalised consecutive squat cycles, the medium cycle (red color) for hip joint

Virtual squat simulation

Based on the average anthropometric data taken from table 1, a virtual model of a mannequin was developed (Figure 8) using SolidWorks software (13). The virtual model was transferred from SolidWorks to ADAMS simulation environment, which is often used for numerical simulation of virtual models of robotic structures (11, 14-18). Kinematic joints of lower limb: hip, knee and ankle, were defined as revolute joints. The curve of final medium cycle and the corresponding data files for the three joints of human leg were taken from experimental results and then the corresponding polynomials were determined by interpolation in MATLAB software (19) and introduced in ADAMS environment, as laws of motion of the mannequin joints. The orthogonal system is defined having x axis – the horizontal walking direction, y axis - along the tibia, and z axis - the knee joint rotation axis. Taking into account the difficulty of obtaining the variation in vivo of the reactions forces developed in the human joints during a squat cycle, it is very important to obtain by virtual simulation, the variation of reaction force in all leg joints, during a cycle movement.
The aim of this study was to obtain, by numerical simulations in ADAMS, the reaction forces in lower limb joints based on experimental measurements of angular variation of joints angles.

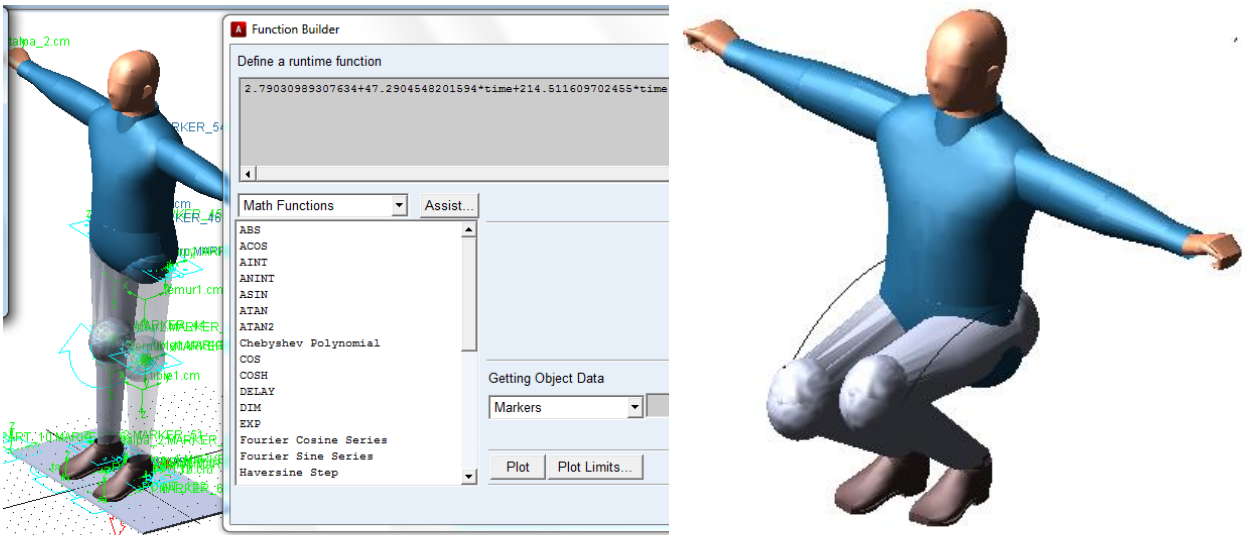


Figure 8. Mannequin virtual model

The resultant force developed in the knee joint is presented figure in 9. Similar graphics are obtained for the variation of the reaction forces developed in ankle and hip joints.
The reactions forces are very useful for simulation and numerical study of stresses for healthy, affected and implanted joints and bones, using Finite Element Method.
The stress analysis allows to study the behavior of a normal or implanted bone (20, 21), the behavior of a normal or affected virtual joint (22-26) as well as a prosthetic joint (27).

In Figure 10 are shown the von Mises stress distribution (top and bottom views) on the femoral cartilage, on the tibia cartilage and on the menisci for healthy knee joint, obtained by using the Finite element analysis applied in ANSYS 14.5 software, a very powerful Computer –Aided – Design software (25).
In a similar manner, the experimental and numerical analysis and virtual simulation can be applied to the joints and the bones of the upper limb (28-32).

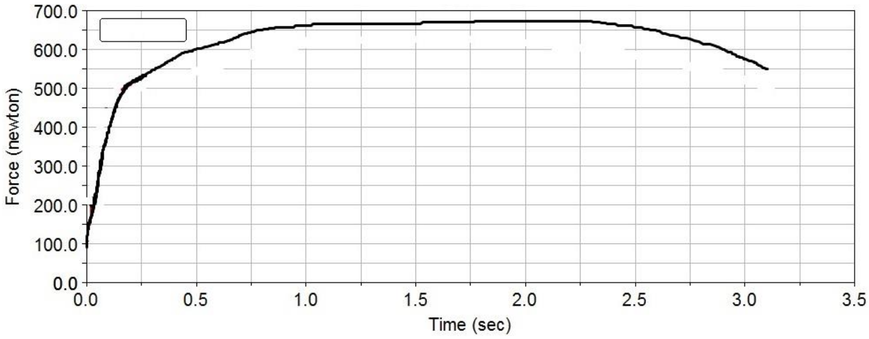
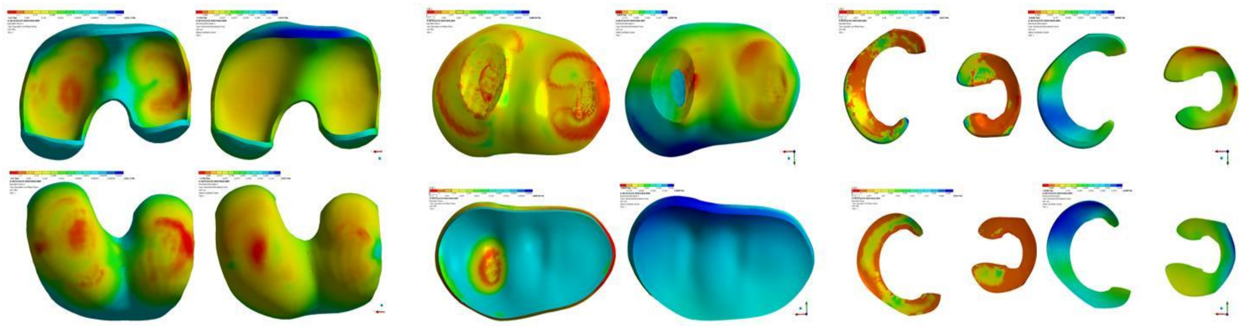


Figure 9. Reaction force variation in virtual knee joint during squat exercise



a) b) c)

Figure 10.Von Mises stress distribution (top and bottom views) on the femoral cartilage a), on the tibia cartilage b) and on the menisci c) for healthy knee joint (25)

Conclusions

In this paper the variations of ankle, knee and hip flexion-extension angles during squat exercises of a healthy male subject were obtained using a complex data acquisition system, based on electro goniometers. The squat movement presents interest because is considered one of the most functional and efficient weight-bearing exercises whether an individual's goals are sport specific or are for an increased quality of life. When comparing the maximum values of the consecutives cycles for each of the three joints: ankle, knee and hip, we observe that the minor differences obtained by this comparison show a good repeatability of the imposed exercise for male subject. There were not big differences in the shape of the flexion angle. Based on the average anthropometric data taken from Table 1, a virtual model of a mannequin was developed using SolidWorks software. The virtual model was transferred to ADAMS simulation environment and numerical simulation of squat movement was performed. The variation of reaction forces in the leg joints were obtained by numerical simulation.
Determination of reaction forces in lower limb joints is useful in order to study the joint stresses and bones stresses using Finite Element Method applied on the virtual three-dimensional models.
The results obtained can be used as a reference for the normal knee joint movement for further studies of abnormal movement.
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References

1. Escamilla RF (2001). Knee biomechanics of the dynamic squat exercise. *Med. Sci. Sports. Exerc*; 33: 127–141.
2. Schoenfeld BJ (2010). Squatting kinematics and kinetics and their application to exercise performance. *J. Strength. Cond Res;* 12: 3497–3506.
3. Gullett JC, Tillman MD, Gutierrez GM, Chow JW (2008). A biomechanical comparison of back and front squats in healthy trained individuals. *J. Strength. Cond Res*. 23(1): 284–292.
4. Jensen LK, Enberg W (1996). Occupation as a risk factor for knee disorders, *Scand J. Work Environ Health*; 22: 165-175.
5. Dahaghin S, Tehrani-Banihashemi SA, Faezi ST, Jamshidi AR, Davatchi F (2009). Squatting, sitting on the floor, or cycling: Are life-long daily activities risk factors for clinical knee osteoarthritis? Stage III results of a community-based study. *Arthritis & Rheumatism*; 61(10): 1337–1342.
6. Yack HJ, Collins CE, Whieldon TJ (1993). Comparison of closed and open kinetic chain exercise in the anterior cruciate ligament-deficient knee. *Am. J. Sports Med*; 21: 49-54.
7. Toutoungi DE, Lu TW, Leardini A, Catani F, O'Connor JJ (2000). Cruciate ligament forces in the human knee during rehabilitation exercises. *Clinical Biomechanics*; 15 (3): 176-187.
8. Escamilla RF, Fleisig GS, Zheng N, Lander JE, Barrentine SW, Andrews JR, Bergemann BW, Moorman CT (2001). The effects of technique variations on knee biomechanics during the squat and leg press. Med. Sci. Sports Exerc; 33: 1552–1566
9. Tarnita D (2016). Wearable sensors used for human gait analysis. *Rom J Morphol Embryol*; 57(2): 373-382.
10. Tarnita D, Catana M, et al (2013). Experimental measurement of flexion-extension movement in normal and osteoarthritic human knee. *Rom J Morphol Embryol*; 54(2): 309–313,
11. Tarniţă D, Geonea I, Petcu A, Tarnita DN (2016). Experimental Characterization of Human Walking on Stairs Applied to Humanoid Dynamics. *Advances in Robot Design and Intelligent Control, Springer*; pp293-301.
12. SIMI Reality Motion Systems: Manual, www.simi.com
13. www.solidworks.com
14. MSC.ADAMS 2013 User Manual
15. Tarnita, D., Tarnita, D.N., Bizdoaca, N., Popa, D. (2009). Contributions on the dynamic simulation of the virtual model of the human knee joint, *Materialwissenschaft und Werkstofftechnik, Materials Science and Engineering Technology,* 40(1-2): 73-81.
16. Dumitru N, Copilusi C, Geonea C, et al. (2015). Dynamic Analysis of an Exoskeleton New Ankle Joint Mechanism. *New Trends in Mechanism and Machine Science Mechanisms and Machine Science Springer International Publishing;* 24; 709-717.
17. Geonea I, Alexandru C, Margine A, Ungureanu A (2013). Design and Simulation of a Single DOF Human-Like Leg Mechanism. *Applied Mechanics and Materials*; 332: 491-496.
18. Geonea I, Ceccarelli M, Carbone G (2015). Design and Analysis of an Exoskeleton for People with Motor Disabilities. *14^{th} World Congress in Mechanism and Machine Science, Taipei, Taiwan*.
19. www.matlab.com
20. Tarnita D, Tarnita, DN, et.al. (2010). Numerical simulations of human tibia osteosynthesis using modular plates based on Nitinol staples. *Rom J Morphol & embryol*; 51(1): 145-150,
21. Tarnita D, Popa D, Tarnita DN, Grecu D (2006). CAD method for 3D model of the tibia bone and study of stresses using the finite element method. *Romanian Journal of Morphology and Embryology*; 47(2): 181-186.
22. Nagura T, Dyrby CO, Alexander EJ, Andriacchi TP (2002). Mechanical loads at the knee joint during deep flexion. *J. Orthop Res;* 20: 881–886.
23. Kubicek M, Zdenek F (2009). Stress strain analysis of knee joint. *Engineering Mechanics*; 16(5): 315–322.
24. Chantarapanich N, Nanakorn P, Chernchujit B (2009). A finite element study of stress distributions in normal and osteoarthritic knee joints. *J Med Assoc Thai*; 92, S97-103.
25. Tarnita D, Catana M, Tarnita DN (2014). Contributions on the modeling and simulation of the human knee joint with applications to the robotic structures. *New Trends on Medical and Service Robotics, Mechanisms and Machine Science 20, Springer*; 283-297.
26. Thambyah A, Goh JCH, De SD (2005). Contact stresses in the knee joint in deep flexion. *Medical Engineering & Physics*; 27(4): 329-335.
27. Tomaszewski PK, Verdonschot N, Bulstra SK, Verkerke GJ (2010). A Comparative Finite-Element Analysis of Bone Failure and Load Transfer of Osseointegrated Prostheses Fixations. *Annals of Biomedical Engineering*; 38(7): 2418–2427.
28. Tarnita D, Boborelu C, Popa D, Rusu L (2010). The three-dimensional modeling of the complex virtual human elbow joint. *Romanian Journal of Morphology and Embryology*; 51(3): 489-495.
29. Patrik C, Keita I, Ingrid K, Ralph M, Harry van Lenthe G, Bert van Rietbergen (2013). Subject-specific bone loading estimation in the human distal radius *Journal of Biomechanics;* 46 759–766.

30. Completo A, Pereira J, Fonseca F, Ramos A, Relvas C, Simões J (2011). Biomechanical analysis of total elbow replacement with unlinked iBP prosthesis: An in vitro and finite element analysis. *Clinical Biomechanics*; 26(10): 990–997.
31. Tarnita D, Tarnita DN, Hacman L, et al. (2010). In vitro experiment of the modular orthopedic plate based on Nitinol, used for human radius bone fractures. *Romanian Journal of Morphology and Embryology*; 51(2): 315-320.
32. Najmeh R, Jacob MR, Daniel GL, Ryan W, George SA, James AJ (2016). Comparison of proximal humeral bone stresses between stemless, short stem, and standard stem length: a finite element analysis. *Journal of Shoulder and Elbow Surgery*; 25(7): 1076–1083.

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