

# Contributions regarding 3D modelling of biomechanics of the foot

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**Abstract.** Within this paper, a detailed study is elaborated regarding the human foot during both orthostatic and gait, the main goal being to develop 3D models which are very useful in the foot motion and loading state research. In order to elaborate the accurate 3D modelling of the human foot assembly, a thorough biomechanical study is done. Such a study was required due to the fact of the high anatomical complexity of the motions within the foot, taking into consideration the 26 bones and 33 joints consisting it. The research aims the CAD modelling of the biomechanics of the healthy subjects alongside with predisposed pathological conditions. The resulting models will have important utility in both educational field and for further CAE approaches and studies.

## 1 Introduction

The use of the engineering approach, as in the current paper, in terms of 3D modelling of solids using professional CAD system, proved its usefulness regarding the human bone system research [1-3]. The CAD modelling of the lower limb bone structure in general and the foot in special, is given by the geometric and dimensional complexity of the joints found within this area, the kinematics and dynamics of the body motion and the static or dynamic loading states during stance, gait and particular physical activities [4-8]. By using the 3D models, it is assured the possibility of elaborating the simulation of specific pathologies, predictions regarding the evolution of specific diseases, developing the simulations of virtual surgical interventions, including the usage of medical device such as implants or prosthesis. Another advantage can be achieved by using Finite Element Analysis methods, which can lead to pre-operative, intra-operative and post-operative simulation of diverse pathologies surgeries.

The previously mentioned methods shall be applied for the inferior part of the human leg, which consists of the tibia and fibula bones, alongside with the bones, joints, ligaments and tendons complex, compiling the foot [9-11].

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The main purpose of such a generalized assembly is to ensure the environment for the further elaboration of an assisted biomechanical system, through which a vast area of pathological conditions, displacements and other relevant medical cases can be studied.

Main objectives of the current paper are:

- Foot biomechanics comprehension and linking the anatomical conditions to engineering models;
- Developing coordinate reference systems and connecting the main geometrical and dimensional elements of the bones to them;
- Elaboration of the generalized model and developing the Skeleton systems within;
- 3D model particularization; defining and controlling the pathological conditions.

## 2 Anatomy and biomechanics of the foot

### 2.1 Anatomy of the foot

The human foot has the main purpose of supporting the body weight, being comprised by the following elements:

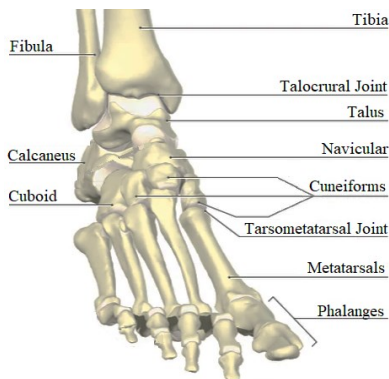
- Bones
- Joints
- Tendons, ligaments and muscles.

Regarding the bones of the foot, they are in a number of 26, and are divided into three main regions, from posterior to anterior: hindfoot, midfoot and forefoot.

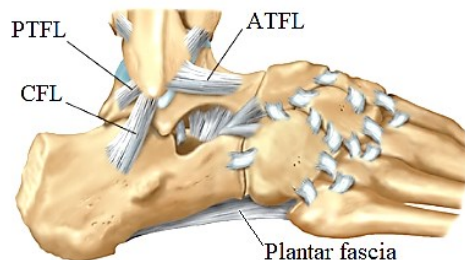
The lower limb bone system articulates to the foot through the talocrural joint, by the contact of the tibia and fibula with only the talus. Furthermore, the body weight is transmitted to the ground through the calcaneus, on which the talus is sitting. The two previously mentioned bones compile the hindfoot.

The midfoot consist in the assembly of the navicular, cuboid and the cuneiform bones, through which, the body weight is furtherly distributed towards the forefoot.

The third and final part of the foot, the forefoot has the most elements, a total of 21 bones. There are two sesamoids and five metatarsals, each one associated with a set of three phalanges, but the Hallux (first toe), which is the single one having a set of two phalanges, the talocrural joint (ankle joint) alongside with the bones composing the whole foot are illustrated in Fig. 1. The metatarsal heads touch the ground and act as a final support of the weight of the body. [12], [13].



**Fig. 1.** Foot bones alongside with the talocrural joint. [13]



**Fig. 2.** The main ligaments within the foot. [13]

As mentioned, the bones are linked through ligaments, which also confer the stability of the established structure. Ligaments are made out of fibrous tissue and have low vascularity, which leads to a longer heal time due to low blood flow. Within the foot there are numerous ligaments, the main ones being the Plantar fascia, the longest ligament of the foot, aiding the balance of the body during walking, and the ankle ligaments: the anterior talofibular ligament (hereinafter ATFL), connecting the talus to the fibula frontally, the calcaneofibular ligament (hereinafter CFL), which links the calcaneus to the fibula and the posterior talofibular ligament (hereinafter PTFL), linking the rear of the talus to the fibula [14]; the positioning of the main ligaments are illustrated in Fig. 2.

## 2.2 Reference elements. Planes, axes and coordinate systems.

With the purpose of illustrating the accurate positioning and potential displacements of the segments within the human body structure, they must be related to certain reference coordinate systems, therefore, precise orientation elements must be referred to, such as planes and axes.

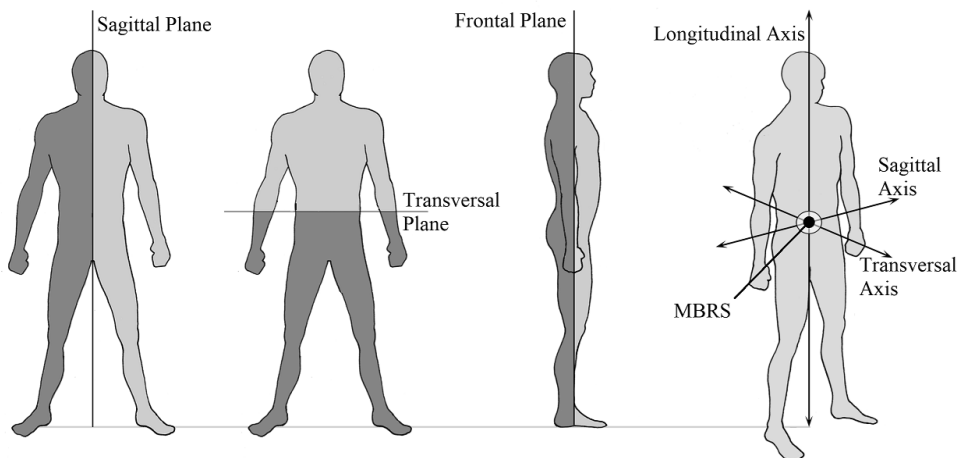
The human body, being a tri-dimensional complex, include three axis – longitudinal, transversal and sagittal, which further define three afferent planes, frontal, transversal and sagittal plane. The next paragraphs are dedicated to illustrate the three defining axes, which concur to each other at a 90° angle.

The longitudinal axis, or the body length axis, is vertically oriented, starting from the top of the head and continuing to the sole surface.

The sagittal axis is defined by the body thickness, having two poles, one anterior and one posterior.

The third axis is characterised by the width of the body, horizontally oriented, having two poles as well, left and right; this last axis is named transversal axis.

By intersecting each two of the presented axes, we obtain the three planes of the body, as following: composing the longitudinal and sagittal axis we obtain the sagittal plane, which splits the body into two symmetrically halves, the frontal plane consists in the longitudinal and transversal axes, being disposed parallel to the forehead and finally, by concurring the sagittal and transversal axes, the transversal plane is established. Once the three planes are set up, by intersecting them, the main body reference system (hereinafter MBRS) can be defined, as presented in Fig. 3.

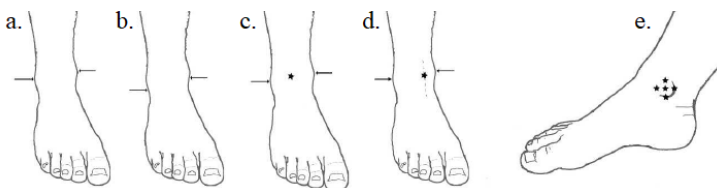


**Fig. 3.** The three planes of the body alongside with the main body reference system (MBRS). [12]

Subsequent, by translating and rotating the main system, several secondary coordinate systems can be defined; the purpose of this action is to have better control of the foot's motion. Such a system is considered on the ground surface (hereinafter Gcs), by projecting the MBRS to the sole. Furthermore, relating to this important point, other several coordinate systems can be defined in other major points of interest. Thus, relatively to the Gcs, the first secondary coordinate system is considered in the ankle joint (talocrural), due to the fact that all foot motions are related to this specific joint (hereinafter Tcs). The first step in defining this particular secondary coordinate system was to establish the exact location of the ankle joint centre. Based on the research [15], regarding the accuracy of the mechanical axis of the lower limb alignment, there are five main anatomic and two kinematic methods in defining the desired point:

Anatomic methods (Fig. 4):

- Extremes midpoint (a) – the ankle centre is considered to be located in the midpoint of the line which links the most lateral malleoli surfaces;
- Distal midpoint (b) – the centre of the ankle is determined by the midpoint of the line connecting the most distal peaks of the malleoli;
- Centre estimate (c) – by projecting the transmalleolar midpoint onto the frontal plane, is defined the ankle centre;
- TA Projection (d) – this method of defining the ankle centre consists in projecting the location of the main tibial muscle axis on the transmalleolar axis
- Sphere-fit (e) – the centre of ankle is considered to be determined by centre of the sphere defined by the five digitalized points of the lateral and medial malleoli.



**Fig. 4.** Anatomical methods of defining the ankle centre.

Kinematic methods (Fig. 5):

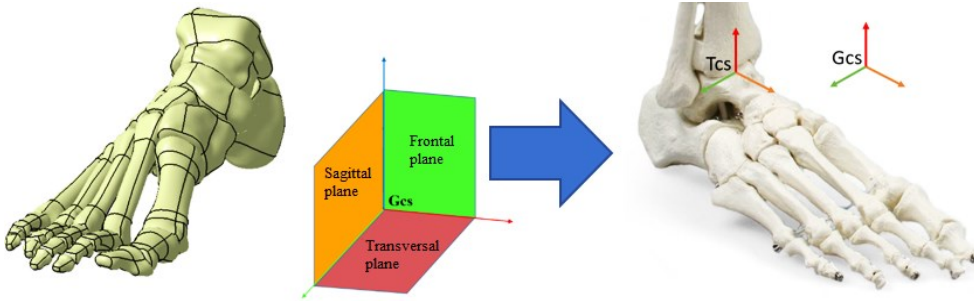
- Ball-and-Socket (a) – the centre of the joint is defined by the centre of the sphere fit to data resulted from the circumduction motion of the foot
- Biaxial model (b) – this method is requiring to intersect the talocrural and subtalar joints, on the transversal tibial plane in order to establish the ankle centre.



**Fig. 5.** Kinematic methods of defining the ankle centre.

Analysing the results presented in the research alongside with other specific papers, one of the most used methods for the ankle centre establishment is the “centre estimate” approach, therefore, for the further talocrural secondary reference system placement, this specific

method will be taken into consideration. The establishment of the Gcs and Tcs are illustrated in Fig. 6.



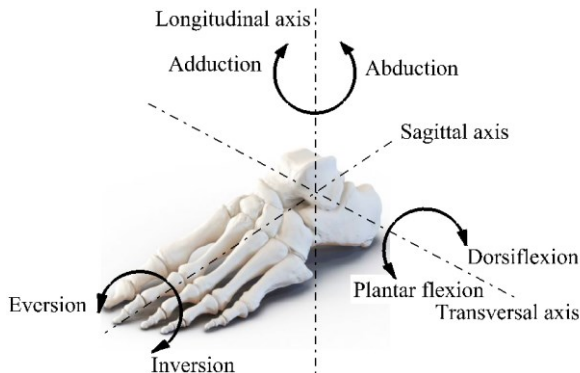
**Fig. 6.** Gcs and Tcs establishment

### 2.3 Basic foot biomechanics

From a functional point of view, the foot biomechanics has a high complexity several particular qualities, which offer the possibility to be rather stiff or flexible, whenever the case. For example, during gait the foot biomechanics are very interesting, regarding the fact that the first contact of the ground finds the foot eased, ready to mould on various types of terrain, with a high range of motion. Afterwards, during the next phases of the gait, when the foot departs the ground, it is acting similar to a rigid lever, being able to propel the limb forward [16].

The foot kinematics consist in six fundamental motions, also known as the gross movements of the foot, paired as following: inversion and eversion; abduction and adduction; dorsiflexion and plantar-flexion. Due to the high complexity of the foot structure, in order to be able to describe correctly its motions, the three planes of the human body must be referred to, alongside with the axes and coordinate systems previously mentioned.

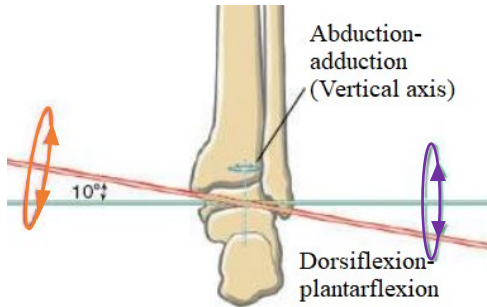
Within the sagittal plane through the transversal axis, dorsiflexion and plantarflexion occurs (the upward-downward motions), while the adduction and abduction rotate around the longitudinal axis and can be measured on the transversal plane. The third and final plane necessary for the motion description is the frontal plane – motions such as inversion and eversion being established around the sagittal axis. For a better comprehension, Fig. 7. illustrates the motions in the foot and ankle, seen from a 3D view.



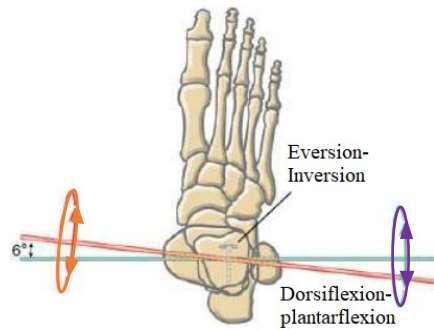
**Fig. 7.** The fundamental motions of the foot within the ankle joint

Owing to the fact that none of the mechanical axes of the lower limb are having perpendicular links to any axis of the MBRS, during gait of other physical activities, most of the motions are taking place triplanar, with few exceptions. The resulted 3D motions (by combining the plantar-dorsiflexion with inversion-eversion and abduction-adduction) are called applied movements defining specific plantar posture of the foot.

The combination of the adduction with inversion and plantarflexion has as result the supination, where the foot is leaning outward causing the sole to be medially-faced. The pronation is the opposite of the first one, consisting of dorsiflexion, eversion and abduction, leaning inward, facing the sole to be faced laterally. [17]



**Fig. 8.** Posterior view of the ankle joint, with the frontal plane angular constrain



**Fig. 9.** Superior view of the ankle joint, with the transversal plane angular constrain.

Due to the fact that supination and pronation are spatial motions, their rotation axis do not concur with any of the body's geometrical elements. [18] This axis is considered to be at a 10° rotation displacement away from the transversal axis within the frontal plane and a 6° displacement within the transversal plane. The posterior view of the axis positioning is presented in Fig. 8 and the superior view in Fig. 9. [19]

### 3 Generalized assembly. Skeleton systems. Developing parametrized structure

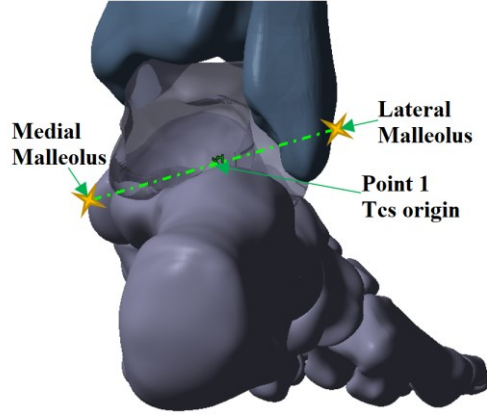
The main purpose of this paper was to create a parametric model of the lower leg, necessary for studying the behaviour of the foot and ankle joint within the consecrated fundamental motions and different pathologies, such as sprains or dislocations, which are among the first 10 orthopaedic injuries which require hospitalization; just in the UK, there are more than 300.000 new ankle sprains each year, and circa 15% of them are severe cases, accordingly to [20].

In this regard, we developed a flexible assembly of the lower leg, using the Skeleton system method. This specific method consists in the constraining assemblies using coordinate systems, which will further assure a facile remodelling of the whole framework.

In order to recreate the fundamental motions of the foot, the Skeleton system had to be inserted within the ankle joint, in the previously mentioned Tcs origin (the centre of the joint). The first step of the process was to insert all the lower limb bones in an assembly: tibia, fibula and the bones of the foot, as presented in Fig. 10; in their normal anatomical position, during stance. Furthermore, within the tibia and fibula bones, we created the transmalleolar axis (the axis which links the two malleoli, the two bony prominences on each side of the human ankle), in order to place the Tcs in the right position, as illustrated in Fig. 11.



**Fig. 10.** Lower limb bones, in stance position – isometric view



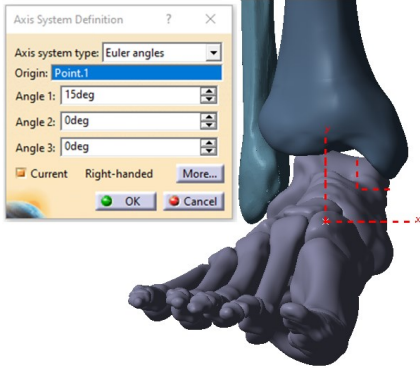
**Fig.11.** Transmalleolar axis midpoint (Point1 - origin of Tcs) – anterior-posterior view

Within this point, a new coordinate system will be inserted (S2), which will also be set-up as the “Current”, and the axis orientation will be considered related to the previously mentioned aspects, Fig.12. This specific coordinate system will also be copied and pasted within the tibia and fibula for further dimensional constrains. Regarding the foot motions (dorsiflexion, plantarflexion, adduction, abduction, inversion and eversion) the defining Euler angles will be linked to the assembly shifting, but for pathological modeling of the lower limb, in order to have better control of the system, instead of coincidence between the Skeleton systems, we constrained the elements with a 0 offset between respective planes. Once the elements are constrained, the tibia and fibula will be set as “Fixed” and all the motion will be relatively to them.

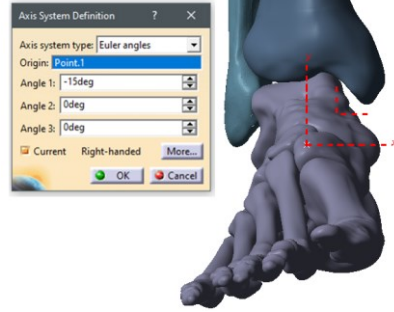


**Fig. 12.** Tcs definition

The generalized assembly has great flexibility, which allows us to generate all the motions through the Axis System Definition window, Angle 1 is controlling the inversion-eversion mobility, positive values for eversions and negative values for inversions (Fig. 13. – 15° eversion; Fig. 14. – 15° inversion).

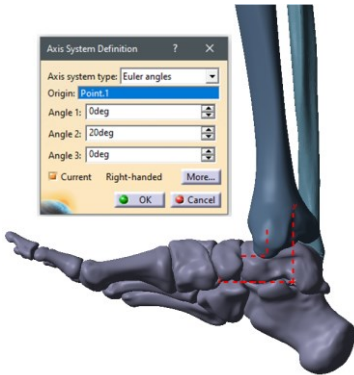


**Fig. 13.** Eversion motion

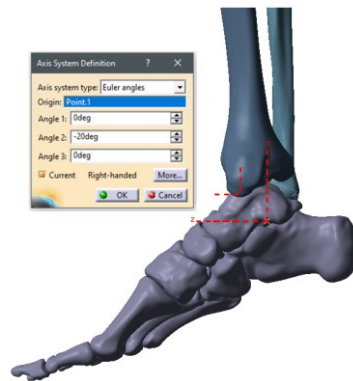


**Fig. 14.** Inversion motion

The second angle within the definition window is related to the plantar and dorsi-flexions. The positive values of Angle 2 are generating dorsiflexion movements and the negative values are generating plantar flexions (Fig. 15.  $-20^\circ$  dorsiflexion; Fig. 16.  $-20^\circ$  plantarflexion)

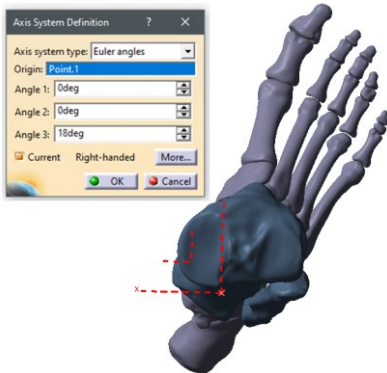


**Fig. 15.** Dorsiflexion motion

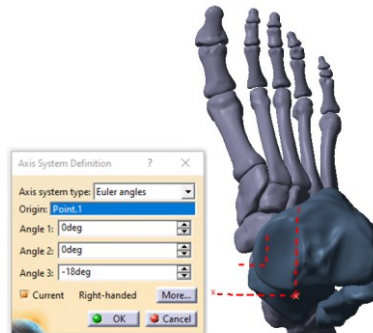


**Fig. 16.** Plantarflexion motion

Finally, by modifying the values of Angle 3, we obtain abduction and adduction motions, values above  $0^\circ$  for abduction and values under  $0^\circ$  for adduction (Fig. 17.  $-18^\circ$  abduction and Fig. 18.  $-18^\circ$  adduction).



**Fig. 17.** Abduction motion

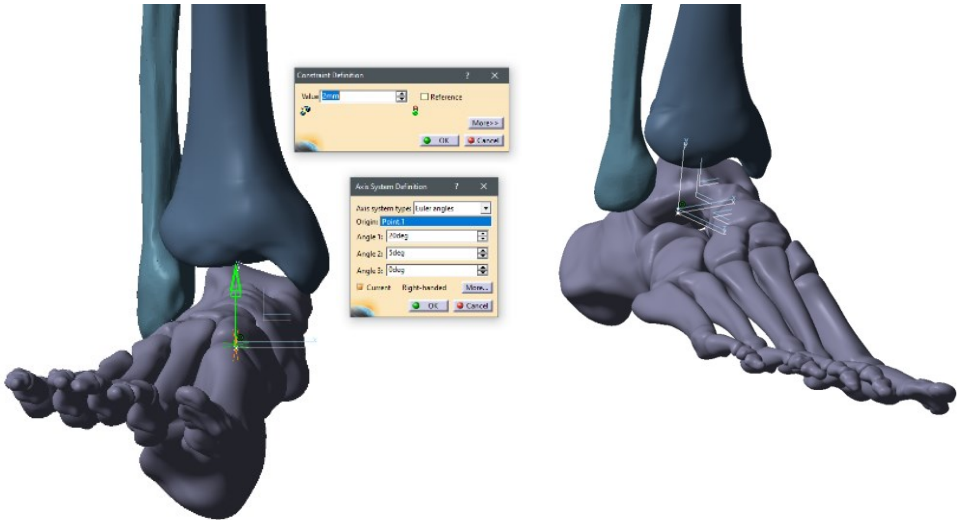


**Fig. 18.** Adduction motion

An important educational contribution brought by the present paper is the possibility of elaborating any type of anatomical position within the talocrural joint, by introducing single or multiple fundamental motions. Another application of the present structure is in simulating pathological conditions, such as dislocation or medial and lateral sprained ankles.



**Fig. 19.** Lateral and medial sprained ankle [20]



**Fig. 20.** Anterior view of medial sprained ankle alongside with the defining parameters

**Fig. 21.** Isometric view of medial sprained ankle

The sprained ankle occurs when the talocrural joint is stretched too far, fact that leads to PTFL or ATFL tearing up [19]; Fig. 19 illustrates the medial or lateral spraining of the ankle. In this regard, Fig. 20 and Fig. 21. are illustrating a medial sprained ankle condition by simultaneously modifying the assembly with a 20° eversion (Angle 1 – 20°), 5° dorsiflexion (Angle 2 – 5°) and a plane displacement of 2mm between the XoZ planes of the talus and tibia; data harvested from papers [21], [22].

## 4 Conclusions

The 3D assembly modelled within this paper is, through the generalized and parametrized manner in which has been developed, a very good tool for studying and research the biomechanics of the inferior side of the human lower limb. The reference elements and coordinate systems which manage this model are related to the established human body planes and axes, fact which confers to the elaborated model a high applicability grade, due

to its allowance of the lower limb biomechanics study relatively other elements within the bone system.

The development of a Skeleton type 3D framework, in a specific point of the foot, has allowed creating a biomechanical assisted system, which assured good premises regarding the biomechanics of a vast variety of medical conditions within the foot, alongside with their related treatment strategies. The generalized model can be particularized just by modifying the Euler angles within the Skeleton system, thus resulting controlled rotations around the three reciprocally perpendicular axes and translations along them as well. All these mentioned motions can be used singularly, or in a composed manner, in any desired configuration, from which it's resulted the complexity of the model, assuring analysis or simulation possibilities, using CAE methods, for diverse existing real-life cases, such as: stationary position, gait, running, jumping or other various sport-specific physical exercising.

## References

1. A. C. Cilingira, V. Ucara, R. Kazana, Trends Biomater. Artif. Organs, **21**, pp. 63-72, (2007);
2. P. Hartley, I. Pillinger, *Numerical Modelling of Material Deformation Processes*. R. D & Applications, Springer Verlag, (1992);
3. M. A. New, Proceedings of the 2003 Summer Bioengineering Conference, pp 27-28, (2003);
4. I. I. Cofaru, MATEC Web Conf, **121**, No. 4004, (2017);
5. I. I. Cofaru, E. I. Huzu, The 1st International Conference for Doctoral Students, (2013);
6. I. I. Cofaru, *The CAD modelling of the human tibia affected by form deviations*, Fascicle of Management and Technological Engineering, Issue 1, (2014);
7. I. I. Cofaru, *Biomechanic of the opening tibial osteotomy*, Fascicle of Management and Technological Engineering, Issue 1, (2014);
8. Z. Milojević, S. Navalušić, R. Obradović, M. Milankov, M. V. Drăgoi, L. Beju, Academic Journal of Manufacturing Engineering 8 (1), pp. 73-78, (2010);
9. D. Wu, P. Isaksson, S. J. Ferguson, C. Persson, Acta Biomaterialia, pp. 1-12, (2018);
10. C. C-De la Portilla, R. L. Garijo, J. Bayod, Clin Biomech., **61**, pp 163-171, (2019);
11. Z. Yosibash, Comput. Methods Appl. Mech. Engrg, pp. 169-184, (2012);
12. K. Chan, Handbook of Footwear Design and Manufacture, pp. 3-26, (2013);
13. K. Wesker, Thieme Atlas of Anatomy: *General Anatomy and Musculoskeletal System*. (2007);
14. S. Standring, *Gray's Anatomy, thirty-ninth ed. Elsevier Churchill Livingstone*, Edinburgh. J. Orthop. Res. 13 (4), pp. 609–614, (2005);
15. R. A. Siston, A. C. Daub, N. J. Giori, S. B. Goodman, S. L. Delp, Clinical orthopaedics and related research, **439**, pp. 129–135, (2005);
16. C. L. Brockett, G. Chapman, Basic Science, **30**, Issue 3, pp. 232-238, (2016);
17. F. A. Magalhães, T. Rezende, L. Araújo, O. Marques, L. de Paula Silveira, J. de Melo Ocarino, S. Fonseca, Journal of Biomechanics, (2019);
18. S. Angin, I. Demirbuken, Ankle and foot complex, pp. 411-439, (2020);
19. A. Bähler, Clinical Prosthetics & Orthotics, **10**, pp. 8-14, (1986);
20. N. A. Ferran, O. Francesco, N. Maffulli, Sports Med Arthrosc, **17**, pp. 139–145 (2009);
21. A. H. Crawford, C. T. Mehlman, S. N. Parikh, Parkland Trauma Handbook, **3**, Chapter 17, (2015);
22. M. W. Wolfe, C. G. Mattacola, L. C. McCluskey, American family physician, **63**, pp. 93-104, (2001).