TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 67, Issue Special I, February, 2024

PARAMETRIZED CAD MODELLING OF THE PATHOLOGICAL HUMAN LOWER LIMB AFFECTED BY AXIAL DEVIATION IN STATIONARY POSITION AND DURING GAIT CYCLE

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Abstract: *Within this paper we focused on modelling the complete human gait cycle, for pathological conditions as axial deviations, by using a fully parametric 3D assembly designed based on the Skeleton Systems method. Data acquisition could be provided from gait cycle laboratories or research centers and through the parametric assembly we can easily generate the associated virtual 3D model of the lower limb assembly within the three main phases of the gait: the initial heel contact (the heel strike), the mid-stance and the propulsion phase (the push off), as well as all the intermediary positions. Such an approach is of high interest due to the fact that the obtained model could further be used for finite element analysis or biomechanical studies.*

Key words: *Axial deviations of the lower limb, biomechanics, Skeleton Systems, CAD modelling, Parametrized 3D modelling.*

1. INTRODUCTION

Biomechanical studies tend to be used more often nowadays aiming to increase the precision of the corrective strategies or the surgical act, in this regard, reliable 3D models with user-friendly interfaces must be developed, which are mandatory for specific simulations or finite element analyses.

Based on the high complexity of the anatomical system within the lower limb, consisting of numerous bones, tendons, ligaments and muscles, the kinematics of it is accordingly, therefore, it is mandatory that the approach of the subject has to be interdisciplinary, combining the medicine with the engineering.

Within the specialty literature, it is noted a recent high interest in this thematic, researching both the biomechanics of the healthy human gait and the pathological ones, as the axial deviations, disease-specific diabetes, osteoarthritis etc [1], [2] or post-operative conditions [3-5].

Taking into consideration the notable interest revolving this thematic, the current paper aims modelling the pathological human lower limb, mid-stance and during the gait cycle, by developing a parametrized 3D assembly using the Skeleton Systems method.

2. LOWER LIMB ANATOMY, BIOMECHANICS AND GAIT CYCLE

2.1 The anatomy of the lower limb

The skeleton system of the lower limb assembly includes 30 bones, divided into three areas, the upper leg, consisting of the Femur and Patella, the lower leg, the main bone being the Tibia alongside with the Fibula and the bones of the foot, which are further sub-divided into other three groups: Tarsals, Metatarsals and Phalanges.

These three main areas are connected through numerous joints and tendons, the most important being the hip, the knee, ankle and the joints of the foot.

Within figure 1 the lower limb skeleton system is presented, divided into the previously mentioned areas.

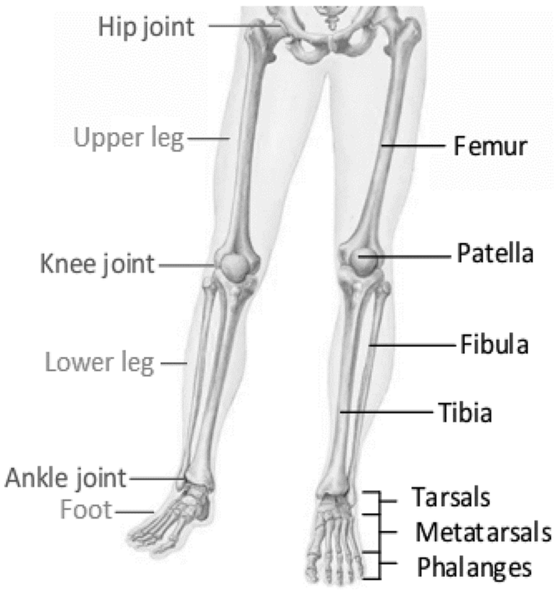

Fig. 1. The lower limb anatomy [6]

2.2. The biomechanics of the lower limb

The lower limb biomechanics are complex due to the high number of elements within it and based on the functionality that the locomotor system must provide, therefore, the biomechanics can be further synthesized into the hip, knee, ankle and foot joints, based on the joint types as following:

- The hip joint, between the femur and the pelvis is considered a ball-and-socket joint allowing a wide range of motions;
- The knee is a hinge-type joint, allowing only flexion and extension motions;
- Ankle joint is a hinge-type joint, allowing mainly flexion-extension motions, but also adduction-abduction and inversion-eversion motions, in smaller ranges;
- The metatarsophalangeal joints are condyloid joints, allowing both flexion-extension and adduction-abduction motions [7].

Although the wide range of motion possibilities, during gait, at all joint levels, the movements can be simplified to flexions-extensions [8].

2.3. The gait cycle

The gait cycle consists of successive motions performed during walking, involving the lower limbs, in the human case, there are three main phases, the heel strike (I), the mid-stance (II) and the lift-off (III), illustrated in Figure 2 [9].

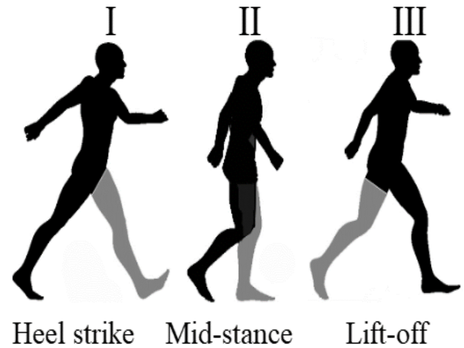

Fig. 2. Human gait cycle phases [9]

Closely related to these gait cycle phases are the Vertical Ground Reaction Forces (GRF) distribution. During a healthy gait cycle the applied forces fluctuate from 0% and up to 120% of the human body, as illustrated in Figure 3. [10]

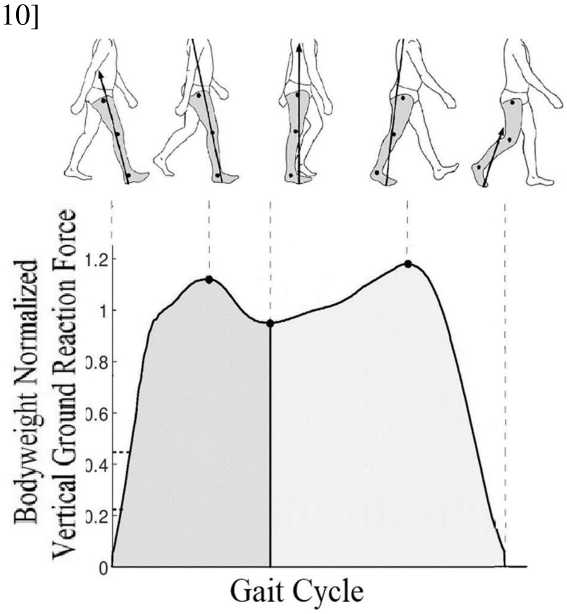

Fig. 3. GRF distribution diagram during gait cycle [10]

Although, in pathological cases, the diagram differs, reaching highs up to 180%-200% of the human bodyweight, especially on the heel strike phase.

3. PARAMETRIZED MODELLING OF THE LOWER LIMB DURING GAIT

Taking into consideration the necessity of a generalized model of the lower limb, we begun the development of the assembly by using existing 3D models of the necessary bones: the femur, the tibia, the fibula and the bones of the foot. Due to the aim of developing an easy-to-use assembly interface with high parametrization possibilities, we considered using the Skeleton Systems method. This specific approach provides the possibility of placing reference systems on each joint of interest which can further be associated with parameters for motion control within it. In the current case, the joints that require disposing reference systems are the knee joint, the ankle joint and the metatarsophalangeal joints.

The first step on modelling through the skeleton system method consists of determining the articular centers of the joints, as following:

- the knee joint – based on the geometry of the contact area between the femur and the tibia (concave-convex), this joint can be associated with a cylindrical joint mechanism, therefore, the articular center is placed on the rotation axis of the two component elements;
- the ankle joint – this joint is more complex and through the bibliographic research, its center is positioned on the midpoint of the tibia and fibula extremities (the transmalleolar axis);
- The metatarsophalangeal joints – due to the simultaneous motion of the five phalanges, the articular center can be considered on the median axis of the joints.

Based on the geometrical definition of the articular centers, the next step consists in placing the Skeleton Systems within them.

The assembly is divided into subassemblies to have the possibility of parametrizing it. Therefore, as illustrated in Figure 4, the lower limb product subassemblies are:

- Subassembly 1 – the femur,
- Subassembly 2 – the tibia and fibula,
- Subassembly 3 – the foot, consisting of:
  - Subassembly 3.1 – the tarsals and metatarsals,
  - Subassembly 3.2 – the phalanges.

Furthermore, since we aimed on modelling the pathological conditions during stationary and gait, we altered the healthy configuration of the foot into an axial deviation. This deviation is a moderate Hallux Valgus. We made this customization due to high frequency of this disease among patients. Figure 5 presents the lower limb assembly with the Hallux Valgus condition, in stationary position.

The assembly is now prepared for linking the subassemblies through the Skeleton reference systems.

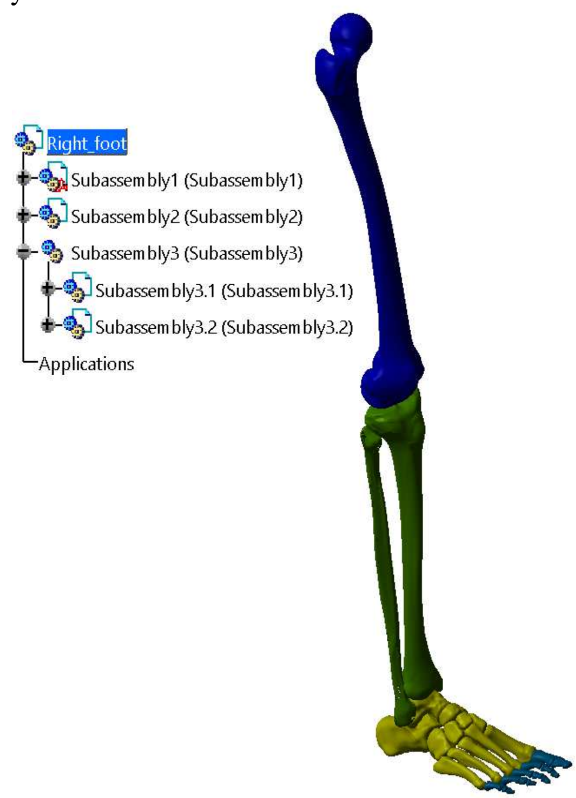

Fig. 4. Lower limb assembly

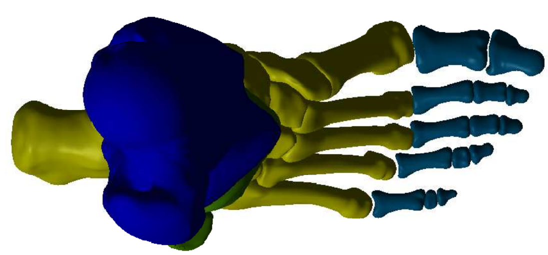

Fig. 5. Lower limb assembly with moderate Hallux Valgus condition

As mentioned, the first Skeleton system must link the femur to the tibia and fibula (subassemblies 1,2), being placed in the articular center of the joint. The overlapping and system constraining process is illustrated in Figure 6.

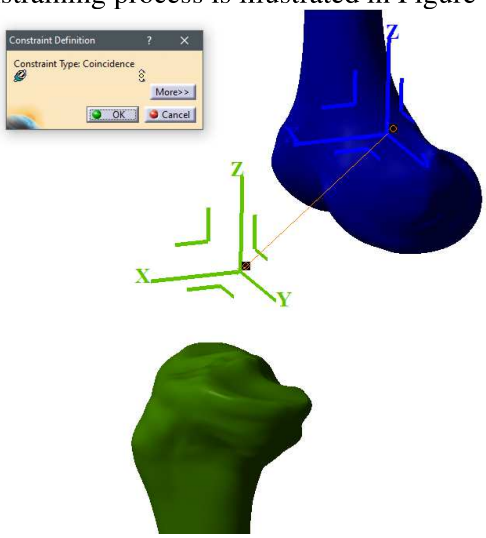

Fig. 6. Skeleton system overlapping

By using the same approach, subassemblies 2 and 3 are linked, as well as subassemblies 3.1 and 3.2. The final product in orthostatic position is presented in Fig. 7, with colors removed from the assembly elements for better understanding.

Fig. 7. Lower limb assembly linked through Skeleton Systems

The next step in the process consists of linking the angular constraints linking the Skeleton Systems to parameters for facile reconfiguration of the assembly. The angular constraints were disposed between the XoY planes within each Skeleton reference system. Therefore, three parameters were created and linked to the angular constraints, as shown in Figure 8.

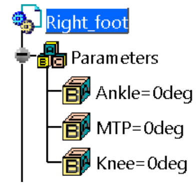

Fig. 8. Parameter definition

While all the parameters take the null value, the system is generated in orthostatic position, illustrated in Figure 9.

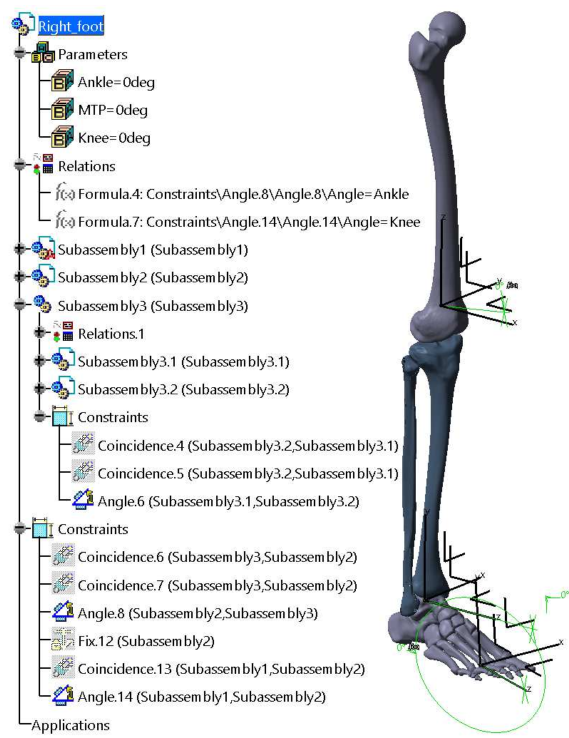

Fig. 9. Lower limb assembly in orthostatic position

Starting from this position, by changing the values of parameters “Knee”, “Ankle” and “MTP” we can easily generate the three main phases of the gait, but also all the intermediary positions within the gait cycle.

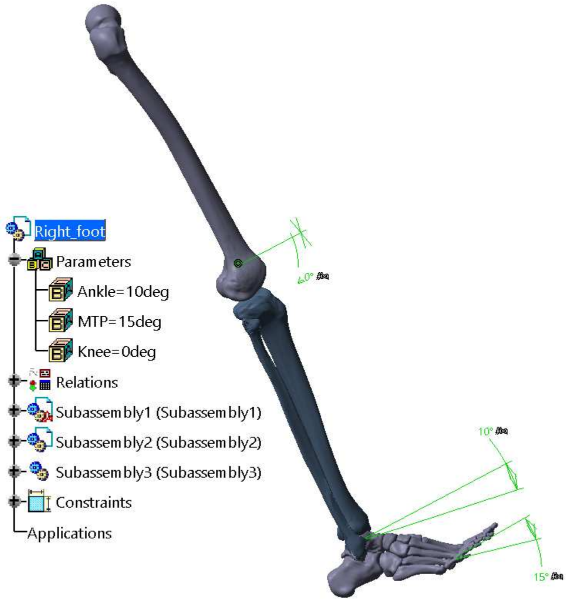

Fig. 10. Lower limb assembly in heel strike position

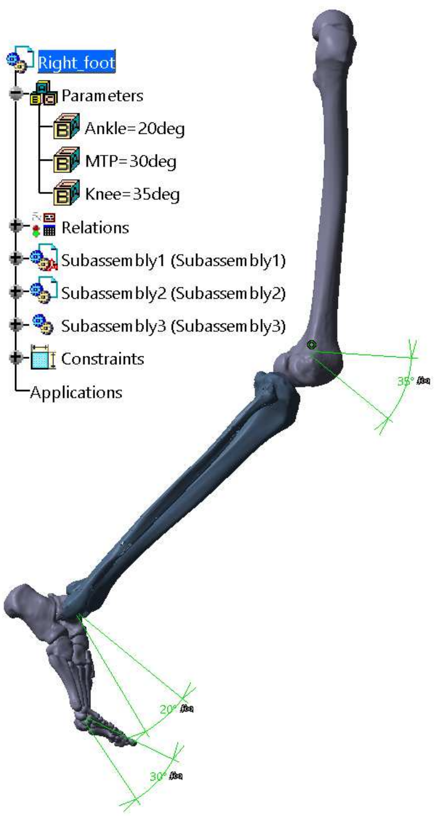

Fig. 11. Lower limb assembly in swing-off position

Since the second position of the lower limb is already generated, within Figure 10 and Figure 11 the heel strike and swing-off positions are illustrated. For the first phase, the set of parameters is: Knee=0°, Ankle=10° and MTP=15°, while for the last phase, the parameters are: Knee=35°, Ankle=20° and MTP=30°.

The obtained assembly could further be linked to a Microsoft Excel spreadsheet with different values for the defined parameters, by which the user could easily generate specific positions or configurations of the lower limb. Due to the fact that the Hallux Valgus axial deviation was also modeled through parametric values, found within the third Subassembly, a wide range of pathological conditions can be facile developed.

4. CONCLUSIONS AND FURTHER RESEARCH

Within this paper, we achieved a CAD Modelling and Assembly of the bones of the human lower limb and the axial deviations existing in the lower limb. The generalized 3D model proposed has a high level of generality due the fact that through Skeleton Systems created, we can to assemble the bones in various customization options. In this sense only through modify the geometrical parameters and Skeleton system's values we could make CAD 3D models for all possible axial deviations existing at the level of the knee, ankle or foot. In this way can be biomechanical modeled a large number of pathological situations that involve a multitude of medical strategies.

This approach is an original contribution which is very useful for researcher who could to use 3D geometrical model for others applications (such as Finite Element Method) for medicine student who could to clear and well understand the axial deviations or for medical personnel who could to simulate and to train for the real surgery strategies.

5. REFERENCES

[1] D'Souza, N., Charlton, J., Kobayashi, S., Hutchison, L., Hunt, M., Simic, M. *Are biomechanics during gait associated with the structural disease onset and progression of lower limb osteoarthritis? A systematic review and meta-analysis*, Osteoarthritis and

Cartilage, Volume 30, Issue 3, Pages 381-394, ISSN 1063-4584, 2022.

[2] Singh, B., Takeda M.M., Niino, M.F., Goulart J.D., Hammons A.J., Roos, J.M., Yack, J.Y., *The effects of adiposity, muscular strength, cardiorespiratory fitness, and fatigue on gait biomechanics in overweight and obese children*, Clinical Biomechanics, Volume 84, ISSN 0268-0033, 2021.

[3] Deleu, P.A., Besse, J.L., Naaim A., Leemrijse T., Birch, I., Bevernage B.D., Cheze, L., *Change in gait biomechanics after total ankle replacement and ankle arthrodesis: a systematic review and meta-analysis*, Clinical Biomechanics, Volume 73, Pages 213-225, ISSN 0268-0033, 2020.

[4] Cofaru, N.F.; Oleksik, V.; Cofaru, I.I.; Simion, C.M.; Roman, M.D.; Lebada, I.C.; Fleaca, S.R. *Geometrical Planning of the Medial Opening Wedge High Tibial Osteotomy—An Experimental Approach.* Appl. Sci. 2022, 12, 2475. https://doi.org/10.3390/app12052475

[5] Cofaru, I.I.; Oleksik, M.; Cofaru, N.F.; Branescu, A.H.; Haşegan, A.; Roman, M.D.; Fleaca, S.R.; Dobrotă, R.D. *A Computer-Assisted Approach Regarding the Optimization of the Geometrical Planning of Medial Opening Wedge High Tibial Osteotomy.* Appl. Sci. 2022, 12, 6636. https://doi.org/10.3390/app12136636

[6] Marieb, E.N., Wilhelm, P.B., Mallatt, J.B., *Human Anatomy, Media Update, Books a la Carte Edition, (6th Edition)*, Benjamin-Cummings Publishing Company, 2011.

[7] Pop, S. P., Gergely, I., Russu, O. M., Roman, C. O., *Elemente de ortopedie ed. II*, ISBN 978-973-169-259-3, 2013.

[8] Sharma S., *Biomechanics of Ankle joint*, Kathmandu University School of Medical Sciences, Nepal, 2015.

[9] Cicirelli, G., Impedovo, D., Dentamaro, V., Marani, R., Pirlo, G., D'Orazio, T.R., *Human Gait Analysis in Neurodegenerative Diseases: A Review*, IEEE Journal of Biomedical and Health Informatics, Vol. 26, No. 1, pp. 229-242, 2022.

[8] Slijepcevic, D., Horst, F., Lapuschkin, S., Horsak, B., Raberger, A.M., Kranzl, A., Samek, W., Breiteneder, C., Schöllhorn W.I.,, Zeppelzauer, M.. *Explaining Machine Learning Models for Clinical Gait Analysis*, ACM Trans. Comput. Healthcare 3, 2, 2022.

MODELAREA ASISTATĂ DE CALCULATOR PARAMETRIZATĂ A MEMBRULUI INFERIOR UMAN PATOLOGIC AFECTAT DE DEVIAȚII AXIALE ÎN POZIȚIE STAȚIONARĂ ȘI ÎN TIMPUL CICLULUI DE MERS

Rezumat: În cadrul acestei lucrări ne-am focalizat pe modelarea ciclului de mers uman, pentru condiții patologice precum deviațiile axiale, utilizând un ansamblu 3D complet parametrizat realizat pe baza metodei sistemelor Skeleton. Achiziția de date s-ar putea face de la laboratoare de studiu de mers sau de la centre de cercetare, iar prin intermediul ansamblului parametrizat putem genera cu ușurință modelul virtual 3D asociat membrului inferior în cadrul celor trei faze principale ale mersului: contactul inițial cu călcâiul, poziția ortostatică și faza de propulsie, precum și toate pozițiile intermediare. O astfel de abordare este de mare interes datorită faptului că modelul obținut ar putea fi utilizat ulterior pentru analiza cu elemente finite sau pentru studii biomecanice.

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