11º CONGRESSO NACIONAL DE BIOMECÂNICA
A. P. G. Castro, C. Pina, P. R. Fernandes, C. Santos, J. Folgado & A. Amaro (Eds)
Sesimbra, Portugal, 21-22 de Fevereiro, 2025

MODELING AND ANALYSIS OF THE INTERACTION BETWEEN THE CRUTCH AND THE GROUND IN HUMAN LOCOMOTION

Mariana Rodrigues da Silva [1,2]***, Filipe Marques*** [1,2]***, Sérgio B. Gonçalves*** [3]***,***
Miguel Tavares da Silva [3]***, Paulo Flores*** [1,2]

[1] *CMEMS-UMinho, Departamento de Engenharia Mecânica, Universidade do Minho, Campus de Azurém, Guimarães 4804-533, Portugal*

[2] *LABBELS – Associate Laboratory, Braga/Guimarães, Portugal*

[3] *IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1, Lisboa 1049-001, Portugal*

m.silva@dem.uminho.pt; fmarques@dem.uminho.pt; sergio.goncalves@tecnico.ulisboa.pt; miguelsilva@tecnico.ulisboa.pt; pflores@dem.uminho.pt

KEYWORDS: Crutch-assisted gait, Crutch-ground interaction, Sphere-plane contact, Biomechanics of motion, Multibody dynamics

1 INTRODUCTION

Biomechanics of human motion is a multidisciplinary field that involves the study of the mechanical aspects of the human body and the impact that forces have on the movement of the anatomical segments [1]. The use of computational tools to understand the dynamic behavior of the human movement has been rising due to the wide range of applications related to improving performance or treating injury. The knowledge on this topic may provide promising options for the development of assistive devices tailored to the needs and disability of each patient [2].

Crutches are a type of assistive device utilized as an aid to locomotion by patients with a variety of pathologies, providing them with mobility and flexibility. The study of crutch-assisted locomotion is in early stages and the modeling of the interaction between the crutch and ground has not been approached in depth yet. Thus, this work uses a biomechanical multibody model incorporated with crutches to investigate the crutch-ground interaction. The knowledge on this topic may be a significant contribution to advance the development of this area of investigation.

2 BIOMECHANICAL MULTIBODY MODEL

A three-dimensional biomechanical multibody model of the human body (see Figure 1a) was developed in MATLAB using an in-house code named MUBODYNA. The model is composed of 20 rigid bodies and 19 geometrically ideal joints. The bodies include the lower trunk (1), right and left thighs (2, 6), legs (3, 7), main feet (4, 8) and toes (5, 9), upper trunk (10), and right and left humeri (11, 15), ulnae (12, 16), radii (13, 17), hands (14, 18) and crutches (19, 20). The lower trunk represents the pelvis, and the upper trunk is a unique segment combining the spine, thorax and head. The joints comprise the back joint (1), and the right and left hip (2, 6), knee (3, 7), ankle (4, 8), metatarsophalangeal (5, 9), glenohumeral (10, 14), humeroulnar (11, 15), radioulnar (12, 16), radiocarpal (13, 17) and crutch-hand (18, 19) joints. The connection between the crutch and hand is achieved by spherical joint located at the center of mass of the hand and crutch handle. Thus, the biomechanical multibody model has 45 degrees-of-freedom, which are guided using experimental data acquired at the Lisbon Biomechanics Laboratory of Instituto Superior Técnico.

3 Crutch-Ground Interaction

The sphere-plane contact detection algorithm is used, where the crutch tip is assumed as sphere *i* with center on point *C* and radius *R*, and the ground is considered a plane *j* defined by point *P* and normal unit vector $\mathbf{n}_j$ (see Figure 1b). The distance *d* from the sphere center to the plane is as [3]

$$d = \mathbf{n}_j^{\mathrm{T}}\left(\mathbf{r}_i^C - \mathbf{r}_j^P\right) \tag{1}$$

in which $\mathbf{r}_i^C$ and $\mathbf{r}_j^P$ are the global position vectors of points *C* and *P* on bodies *i* and *j*, respectively The coordinates of the potential contact point *Q* in the plane and sphere are, respectively,

$$\mathbf{r}_j^Q = \mathbf{r}_i^C - d\mathbf{n}_j = \mathbf{r}_i^C - \mathbf{d} \tag{2}$$

$$\mathbf{r}_i^Q = \mathbf{r}_i^C - R\mathbf{n}_j \tag{3}$$

Taking into consideration the previous formulation, the penetration is calculated as

$$\delta = R - d \tag{4}$$

Positive values of δ indicate the occurrence of contact between the sphere and the plane. Thus, the velocities of the contact points *Q* must be determined. In order to estimate the normal, $\mathbf{f}_{\mathrm{n}}$, and tangential, $\mathbf{f}_{\mathrm{t}}$, forces, the contact models utilized in [4] for crutch-ground interaction are utilized

$$\mathbf{f}_{\mathrm{n}} = \left(\frac{4}{3}\sqrt{R}\left(\frac{1-\upsilon_i^2}{E_i} + \frac{1-\upsilon_j^2}{E_j}\right)^{-1}\delta^{\frac{3}{2}} + \chi\delta^{\frac{3}{2}}\dot{\delta}\right)\mathbf{n}_j \tag{5}$$

$$\mathbf{f}_{\mathrm{t}} = \mu_{\mathrm{k}} f_{\mathrm{n}} \tanh\left(\frac{v_{\mathrm{t}}}{v_1}\right)\frac{\mathbf{v}_{\mathrm{t}}}{v_{\mathrm{t}}} \tag{6}$$

where υ and E are Poisson's ratio and Young's modulus, $\dot{\delta}$ is penetration rate, χ is damping factor μ_k is kinetic coefficient of friction, v_1 is threshold for velocity and v_{t} is relative tangential velocity. The results obtained in this work are compared with experimental data and with the literature.

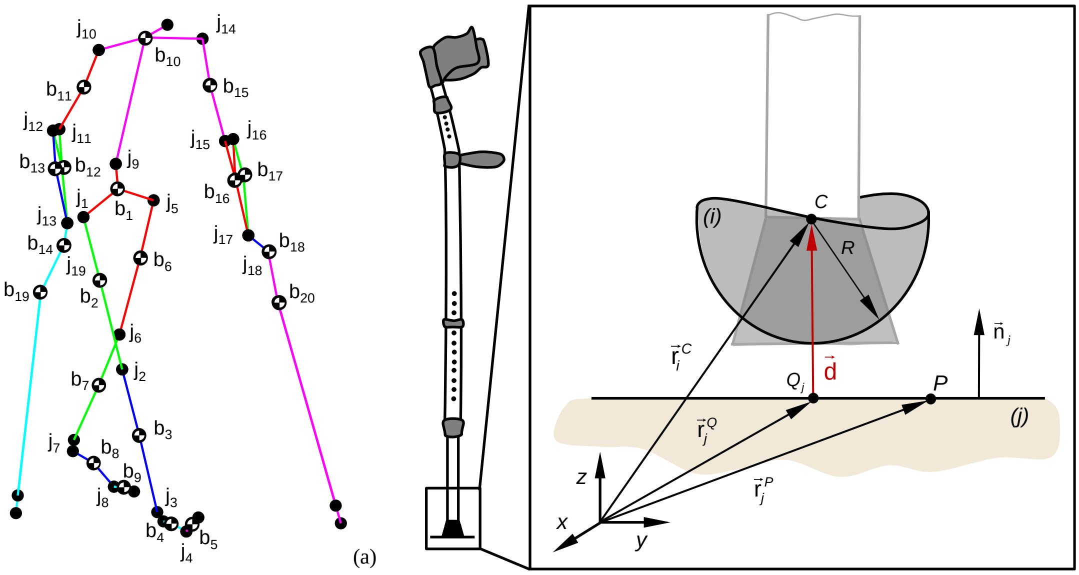

Figure 1 – Schematic representation of the (a) biomechanical multibody model and (b) crutch-ground interface.

Acknowledgements

This work has been supported by Portuguese Foundation for Science and Technology (FCT), under the national support to R&D units grants (reference project UIDB/04436/2020; UIDP/04436/2020), and IDMEC-LAETA (Base Funding: 10.54499/UIDB/50022/2020; Programmatic Funding: 10.54499/UIDP/50022/2020). The first author expresses her gratitude to FCT (10.54499/2021.04840.BD).

References

[1] D. A. Winter, *Biomechanics and Motor Control of Human Movement*, 4th ed. Ontario, Canada: John Wiley & Sons, Inc, 2009.

[2] M. R. Silva, F. Marques, M. T. Silva, and P. Flores, "A Comprehensive Review on Biomechanical Modeling Applied to Device-Assisted Locomotion," *Arch Comput Methods Eng*, vol. 30, pp. 1897–1960, Nov. 2023.

[3] R. G. Moreno, F. Marques, E. Corral Abad, J. Meneses Alonso, P. Flores, and C. Castejon, "Enhanced modelling of planar radial-loaded deep groove ball bearings with smooth-contact formulation," *Multibody Syst Dyn*, vol. 60, no. 1, pp. 121–159, Jan. 2024.

[4] J. M. Font-Llagunes, A. Barjau, R. Pàmies-Vilà, and J. Kövecses, "Dynamic analysis of impact in swing-through crutch gait using impulsive and continuous contact models," *Multibody Syst Dyn*, vol. 28, no. 3, pp. 257–282, Sep. 2012.