Computational and Experimental Study of the Interaction Between a Crutch and a Biomechanical Human Model

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1 Introduction

The 2022 global report on assistive technology of the World Health Organization and the United Nations Children's Fund (UNICEF) estimates that more than 2.5 billion people globally use one or more assistive devices, and this number is expected to rise to 3.5 billion in 2050 [1]. Crutches are assistive devices utilized by disabled patients to restore the mobility lost due to the disability and regain some degree of independence [2]. A biomechanical model of the human movement within the framework of multibody system methodologies is utilized in this work to study crutch-assisted gait with focus on the interaction that occurs between the model and the device.

2 Biomechanical Multibody Model

A three-dimensional biomechanical multibody model of the human body (see Figure 1) was developed in MATLAB. The model is composed of 18 rigid bodies kinematically connected to each other using 17 geometrically ideal joints. Table 1 presents a complete description of the all bodies and joints. The model has 39 degrees-of-freedom (DoF), which are guided using experimental data acquired at the Lisbon Biomechanics Laboratory of Instituto Superior Técnico.

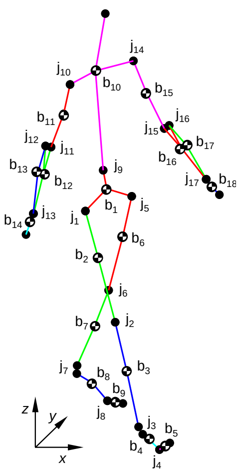


Figure 1 – Multibody model

Table 1 – Bodies and joints of the considered biomechanical multibody model

Body (nr.)	Joint (nr.)	Joint type (DoF)	Connected bodies
Lower Trunk (1)	Hip (1, 5)	Spherical (3)	Lower Trunk – Thigh
Thigh (2, 6)	Knee (2, 6)	Revolute (2)	Thigh – Leg
Leg (3, 7)	Ankle joint complex (3, 7)	Modified universal (2)[3]	Leg – Main Foot
Main Foot (4, 8)	Metatarsophalangeal (4, 8)	Revolute (1)	Main Foot – Toes
Toes (5, 9)	Back (9)	Spherical (3)	Lower Trunk – Upper Trunk
Upper Trunk (10)	Glenohumeral (10, 14)	Spherical (3)	Upper Trunk – Humerus
Humerus (11, 15)	Humeroulnar (11, 15)	Classical universal (2)	Humerus – Ulna
Ulna (12, 16)	Radioulnar (12, 16)	Body-follower (0)	Ulna – Radius
Radius (13, 17)	Radiocarpal (13, 17)	Spherical (3)	Radius – Hand
Hand (14, 18)			

3 INTERACTION BETWEEN THE CRUTCH AND THE HUMAN MODEL

The first approach utilized to introduce the crutches into the model was to use a fixed joint between the hand and the crutch to prevent the relative movement between these bodies, removing six degrees-of-freedom. The kinematic constraint equations, and the contribution of the fixed joint to the Jacobian matrix and to the right-hand side of the acceleration equations are defined as

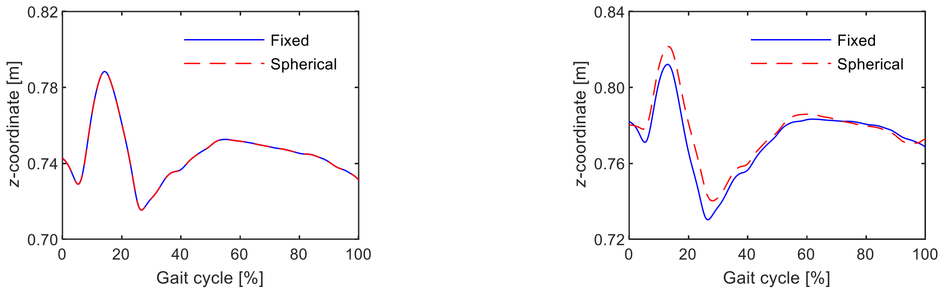
$$\boldsymbol{\Phi}^{(\mathrm{f},6)} = \begin{cases} \mathbf{r}_j + \mathbf{s}_j^P - \mathbf{r}_i - \mathbf{s}_i^P = \mathbf{0} \\ \mathbf{a}_i^{\mathrm{T}}\mathbf{b}_j - \mathbf{a}_{i,0}^{\mathrm{T}}\mathbf{b}_{j,0} = 0 \\ \mathbf{c}_i^{\mathrm{T}}\mathbf{d}_j - \mathbf{c}_{i,0}^{\mathrm{T}}\mathbf{d}_{j,0} = 0 \\ \mathbf{e}_i^{\mathrm{T}}\mathbf{f}_j - \mathbf{e}_{i,0}^{\mathrm{T}}\mathbf{f}_{j,0} = 0 \end{cases} \quad (1) \qquad \mathbf{D}^{(\mathrm{f},6)} = \begin{bmatrix} -\mathbf{I} & \tilde{\mathbf{s}}_i^P & \mathbf{I} & -\tilde{\mathbf{s}}_j^P \\ \mathbf{0} & -\mathbf{b}_j^{\mathrm{T}}\tilde{\mathbf{a}}_i & \mathbf{0} & -\mathbf{a}_i^{\mathrm{T}}\tilde{\mathbf{b}}_j \\ \mathbf{0} & -\mathbf{d}_j^{\mathrm{T}}\tilde{\mathbf{c}}_i & \mathbf{0} & -\mathbf{c}_i^{\mathrm{T}}\tilde{\mathbf{d}}_j \\ \mathbf{0} & -\mathbf{f}_j^{\mathrm{T}}\tilde{\mathbf{e}}_i & \mathbf{0} & -\mathbf{e}_i^{\mathrm{T}}\tilde{\mathbf{e}}_j \end{bmatrix} \quad (2) \qquad \boldsymbol{\gamma}^{(\mathrm{f},6)} = \begin{Bmatrix} -\tilde{\boldsymbol{\omega}}_j\dot{\mathbf{s}}_j^P + \tilde{\boldsymbol{\omega}}_i\dot{\mathbf{s}}_i^P \\ -\mathbf{b}_j^{\mathrm{T}}\tilde{\boldsymbol{\omega}}_i\dot{\mathbf{a}}_i - \mathbf{a}_i^{\mathrm{T}}\tilde{\boldsymbol{\omega}}_j\dot{\mathbf{b}}_j - 2\dot{\mathbf{a}}_i^{\mathrm{T}}\dot{\mathbf{b}}_j \\ -\mathbf{d}_j^{\mathrm{T}}\tilde{\boldsymbol{\omega}}_i\dot{\mathbf{c}}_i - \mathbf{c}_i^{\mathrm{T}}\tilde{\boldsymbol{\omega}}_j\dot{\mathbf{d}}_j - 2\dot{\mathbf{c}}_i^{\mathrm{T}}\dot{\mathbf{d}}_j \\ -\mathbf{f}_j^{\mathrm{T}}\tilde{\boldsymbol{\omega}}_i\dot{\mathbf{e}}_i - \mathbf{e}_i^{\mathrm{T}}\tilde{\boldsymbol{\omega}}_j\dot{\mathbf{f}}_j - 2\dot{\mathbf{e}}_i^{\mathrm{T}}\dot{\mathbf{f}}_j \end{Bmatrix} \quad (3)$$

where $\mathbf{r}_k$ is the global position vector of the center of mass of body k, $\mathbf{s}_k^P$ is the global position vector of point P located on body k with respect to the body's local coordinate system, $\mathbf{I}$ is the identity matrix, (~) denotes the skew symmetric matrix, the dot represents the derivative with respect to time, and $\boldsymbol{\omega}$ is the angular velocity vector. The last three constraint equations of Eq. (1) are considered in order to establish, in every time step, a constant orientation between the vectors $\mathbf{a}_i$, $\mathbf{b}_j$, $\mathbf{c}_i$, $\mathbf{d}_j$, $\mathbf{e}_i$ and $\mathbf{f}_j$ and their coordinates in the initial configuration ($\mathbf{a}_{i,0}$, $\mathbf{b}_{j,0}$, $\mathbf{c}_{i,0}$, $\mathbf{d}_{j,0}$, $\mathbf{e}_{i,0}$ and $\mathbf{f}_{j,0}$).

The second approach considers a spherical joint between the crutch and hand, which is formulated using the first equation of Eqs. (1)-(3). In this situation, since relative movement between the two bodies is allowed, the number of degrees-of-freedom of the model is adjusted to 45.

4 RESULTS AND DISCUSSION

Figure 2 depicts the *z*-coordinate of the right hand-crutch and radiocarpal joints. It can be concluded that there are no significant differences in the crutch-hand plot, but some differences are visible in the radiocarpal joint. The crutch can be considered an extension of the hand in the fixed approach because there is no relative movement between the two bodies. In turn, in the spherical case, three rotational degrees-of-freedom exist between the hand and the crutch and, thus, relative movement between these bodies is allowed. The results for the left side are identical.



(a) (b)

Figure 2 – Evolution of the *z*-coordinate of the right (a) hand-crutch and (b) radiocarpal joints throughout the gait cycle.

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