Computational and Experimental Analysis of Crutch-Assisted Gait: Findings from a Case Study

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ABSTRACT

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 require the use of one or more assistive devices, and this number is expected to rise to 3.5 billion in 2050 [1]. The use of assistive devices presents crucial functional benefits for subjects with permanent or temporary disability, as they not only improve independence, but also enable and enhance the participation in social activities and reduce the need for hospitalization [2].

An option for patients with mobility disabilities is to use crutches to restore the mobility lost due to the disability and regain some degree of independence [3]. Crutches are utilized as an aid to locomotion by patients with a variety of pathologies, providing them with a good level of mobility and flexibility. They are utilized to increase the patients' balance and base of support, and to partially or fully unload the lower limbs by transferring the body weight to the upper extremities [4].

Despite the existing investigation, the study of crutch-assisted locomotion has not become an established routine yet, and difficulties still exist in understanding how it may impact clinical interventions. Hence, this work aims to develop an advanced biomechanical model of the human movement within the framework of multibody system methodologies in order to study crutch-assisted locomotion with focus on the interaction that occurs between the model and the device. The knowledge on this topic may help provide promising options for the development of mobility assistive devices tailored to the needs of each subject.

2 Biomechanical multibody model

A three-dimensional biomechanical multibody model of the human body (see Figure 1) was developed in MATLAB using an in-house code named MUBODYNA. The model is composed of 18 rigid bodies, which are kinematically connected to each other using 17 geometrically ideal joints. Table 1 presents a complete description of the bodies and joints of the considered biomechanical model. As inferred from the observation of Table 1, the model has a total of 39 degrees of freedom (DoF), which are guided using experimental data of one adult female subject acquired at the Lisbon Biomechanics Laboratory of Instituto Superior Técnico. A kinematic consistency procedure is applied to obtain kinematically consistent positions and velocities, avoiding constraint violation.

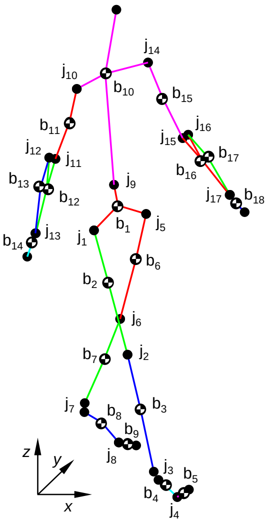

Figure 1: Multibody model

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	1	Thigh – Leg
Leg (3, 7)	Ankle joint complex (3, 7)	Modified universal [5]	2	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)				

DoF – degrees of freedom

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3 Crutch-model interaction

The crutches are introduced into the model using two approaches. First, a fixed joint is considered between the hand and the crutch to prevent the relative motion between these bodies, removing six DoF. The kinematic constraint equations are expressed as

$$\boldsymbol{\Phi}^{(\mathrm{f},6)} = \begin{cases} \mathbf{r}_j^P - \mathbf{r}_i^P = \mathbf{r}_j + \mathbf{s}_j^P - \mathbf{r}_i - \mathbf{s}_i^P = \mathbf{0} \\ \mathbf{a}_i^{\mathrm{T}}\mathbf{b}_j - \mathbf{a}_{i,0}^{\mathrm{T}}\mathbf{b}_{j,0} = 0 \\ \mathbf{c}_i^{\mathrm{T}}\mathbf{d}_j - \mathbf{c}_{i,0}^{\mathrm{T}}\mathbf{d}_{j,0} = 0 \\ \mathbf{e}_i^{\mathrm{T}}\mathbf{f}_j - \mathbf{e}_{i,0}^{\mathrm{T}}\mathbf{f}_{j,0} = 0 \end{cases} \tag{1}$$

where $\mathbf{r}_k^P$ is the global position vector of point P located on body k, $\mathbf{r}_k$ 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. The last three constraint equations of Eq. (1) are considered in order to establish a constant orientation between 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 $\mathbf{f}_{j,0}$). $\boldsymbol{\Phi}^{(\mathrm{f},6)}$ refers to a fixed (f) joint constraint with six (6) equations. The contribution of the joint to the Jacobian matrix and right-hand side of the acceleration equations is, respectively, as

$$\mathbf{D}^{(\mathrm{f},6)} = \begin{bmatrix} -\mathbf{I} & \tilde{\mathbf{s}}_i^P & \mathbf{I} & -\tilde{\mathbf{s}}_j^P \\ \mathbf{0} & -\mathbf{b}_j^{\mathrm{T}}\tilde{\mathbf{a}}_i & \mathbf{0} & -\mathbf{a}_i^{\mathrm{T}}\tilde{\mathbf{b}}_j \\ \mathbf{0} & -\mathbf{d}_j^{\mathrm{T}}\tilde{\mathbf{c}}_i & \mathbf{0} & -\mathbf{c}_i^{\mathrm{T}}\tilde{\mathbf{d}}_j \\ \mathbf{0} & -\mathbf{f}_j^{\mathrm{T}}\tilde{\mathbf{e}}_i & \mathbf{0} & -\mathbf{e}_i^{\mathrm{T}}\tilde{\mathbf{e}}_j \end{bmatrix} \tag{2}$$

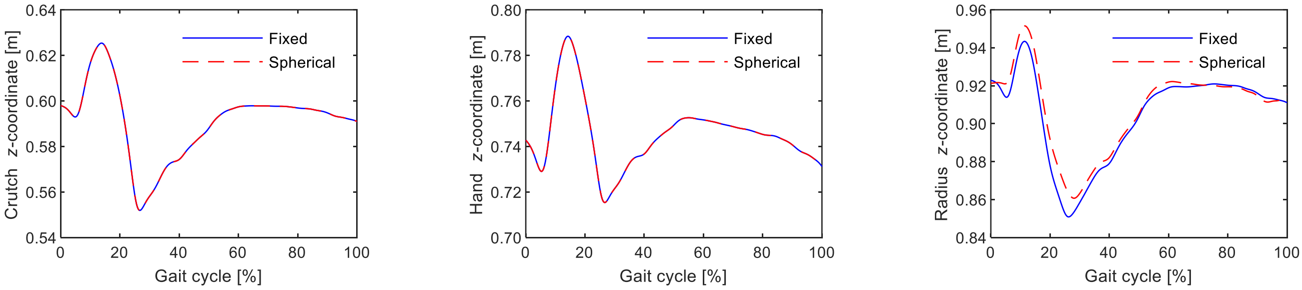
$$\boldsymbol{\gamma}^{(\mathrm{f},6)} = \begin{Bmatrix} -\tilde{\boldsymbol{\omega}}_j\dot{\mathbf{s}}_j^P + \tilde{\boldsymbol{\omega}}_i\dot{\mathbf{s}}_i^P \\ -\mathbf{b}_j^{\mathrm{T}}\tilde{\boldsymbol{\omega}}_i\dot{\mathbf{a}}_i - \mathbf{a}_i^{\mathrm{T}}\tilde{\boldsymbol{\omega}}_j\dot{\mathbf{b}}_j - 2\dot{\mathbf{a}}_i^{\mathrm{T}}\dot{\mathbf{b}}_j \\ -\mathbf{d}_j^{\mathrm{T}}\tilde{\boldsymbol{\omega}}_i\dot{\mathbf{c}}_i - \mathbf{c}_i^{\mathrm{T}}\tilde{\boldsymbol{\omega}}_j\dot{\mathbf{d}}_j - 2\dot{\mathbf{c}}_i^{\mathrm{T}}\dot{\mathbf{d}}_j \\ -\mathbf{f}_j^{\mathrm{T}}\tilde{\boldsymbol{\omega}}_i\dot{\mathbf{e}}_i - \mathbf{e}_i^{\mathrm{T}}\tilde{\boldsymbol{\omega}}_j\dot{\mathbf{f}}_j - 2\dot{\mathbf{e}}_i^{\mathrm{T}}\dot{\mathbf{f}}_j \end{Bmatrix} \tag{3}$$

where $\mathbf{I}$ is the identity matrix, (~) is the skew symmetric matrix, (.) is the derivative with respect to time, $\boldsymbol{\omega}$ is the angular velocity vector. It is assumed that (*i*) point P on the hand is located on its center of mass, (*ii*) point P on the crutch is located on its handle, and (*iii*) the orientation of the hand relative to the crutch is constant during the analysis and equal to the orientation in the first time instant.

The second approach utilized in this work to deal with the crutch-model interaction is to use a spherical joint between the crutch and the hand. To formulate this joint, the first row of Eqs. (1)-(3) is utilized. In this situation, since relative motion between the two bodies is allowed, the number of DoF is adjusted, yielding a biomechanical multibody model with a total of 45 DoF.

4 Results and discussion

Figure 2 depicts the *z*-coordinate of the center of mass of the right crutch, hand and radius. There are no significant differences in the crutch and hand plots, but some differences are visible in the radius. Since there is no relative motion between the hand and the crutch in the fixed approach, in reality, these two segments act as a unique body of the biomechanical model. In this situation, the crutch can be considered an extension of the hand. 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) (c)

Figure 2: Evolution of the *z*-coordinate of the right (a) crutch, (b) hand and (c) radius throughout the gait cycle.

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