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Progressive Improvement of the Model of an Exoskeleton for the Lower Limb by Applying the Modular Modelling Methodology

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Abstract: Among the variety of applications of exoskeletons, it is possible to mention motor rehabilitation, enhancement of human capabilities and providing support to different types of tasks. Despite the remarkable achievements in this field, two major issues still need to be improved in the exoskeleton design methodology, the mechanical design and the controller. Considering that the dynamic modelling approach plays a key role in these issues, this article proposes the use of modular modelling methodology for the development of exoskeletons. Initially, the conceptual design of a lower limb exoskeleton is presented, then its kinematic and dynamic models are calculated. Finally, some performed simulations demonstrate the model consistency and the actuator torques estimation.

Keywords: exoskeletons; modular modelling methodology; dynamic modelling



Citation: Hess-Coelho, T.A.; Cortez, M.; Moura, R.T.; Forner-Cordero, A. Progressive Improvement of the Model of an Exoskeleton for the Lower Limb by Applying the Modular Modelling Methodology. *Machines* **2022**, *10*, 248. <https://doi.org/10.3390/machines10040248>

Academic Editors: Dar-Zen Chen and Kuan-Lun Hsu

Received: 18 February 2022

Accepted: 27 March 2022

Published: 30 March 2022

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1. Introduction

In mechatronics engineering, an exoskeleton can be defined as a wearable robot that acts as a robotic orthosis on the user [1]. Exoskeletons have different applications, namely, motor rehabilitation, enhancement of human capabilities and providing support to different types of tasks, ranging from work to daily life activities. They can be designed to be used by healthy subjects in order to augment their capabilities, e.g., carry large weights, or for people with disabilities that may rely on the exoskeleton to be able to perform simple tasks such as taking a glass of water.

These variety of applications have something in common: the exoskeleton is acting in parallel with the human body, hence, it should reproduce human movements at a functional level [2]. This requires the design of robotic systems with a large number of degrees of freedom (dof), for instance, up to seven dofs for the upper limb without considering the hand [3] and up to twelve dofs for the lower limb [4]. Therefore, this imposes some requirements on the mechanical design. Moreover, the exoskeleton must be designed to intervene in a certain way and interact with the movement of the user [5]. In order to do so, it is important to control the interaction force between the user and robot using, for instance, impedance control [6].

In the nineteen-sixties, the first powered exoskeleton, Hardiman, was developed. Later, in the nineteen-nineties, the military prototype from the University of Berkeley, called BLEEX, was presented [7]. The assistive robots must be able to amplify the residual movements of a patient suffering from muscle weakness or neurological diseases. In such case, next to the mechanical design challenges, as the exoskeleton has to adapt to the deformities of the patients, it needs to identify their intentions in order to provide the correct assistance. In this respect, the HAL-5 from Cyberdyne Inc., (Japan) was designed to help the elderly and handicapped people to walk. The intention of the user is measured by EMG, which is then used to control electrical motors [8].

Kazerooni and Steger [9] continued the development of BLEEX. They modelled it attached to human legs, only in the sagittal plane, and derived the inverse dynamics model for predicting the driving torques during the walking cycle phases. Additionally, they focused on the 1-dof feedback controller and its implementation. Acosta-Marquez and Bradley [10] presented a simple and lightweight exoskeleton for mobility in constrained environments, which employed crutches. They also developed a controller in order to satisfy some energy requirements.

Regarding the dynamic modelling, the Newton–Euler approach and the principle of virtual work are classical formalisms for generating the equations in implicit form [11]. Moreover, the computational efficiency can be greatly enhanced by the use of recursive algorithms [12]. On the other hand, the Lagrangian formulation is more suitable for obtaining those equations in explicit form. However, such an approach becomes prohibitive when dealing with closed-loop mechanisms [13]. In particular, with respect to the development of exoskeletons, there is an additional demand related to the easiness in building the dynamic model and modifying it as well.

Anam and Al-Jumaily [14] classified the control approaches for powered exoskeletons into four categories, namely, model-based, hierarchy-based, physical-parameter-based and usage-based controls. With respect to the model-based control, there are the mathematical model, the identification model, the AI model and the muscle model. Regarding the hierarchy-based control, there are three levels: the task, the high and the low levels. For the physical-parameter-based control, at the low level, there are the PID, the sliding mode, the LQ and H_∞ , while at the high level (interaction between the exoskeleton with the human being), impedance and admittance control are employed. With respect to the usage-based control, one can mention the virtual reality, teleoperation and gait pattern. Regarding this trend, one can mention the importance of developing exoskeletons that combine the three levels, detect user intention, have intrinsic modularity and use the distributed but not centralised control approach.

Concerning the unpowered exoskeletons, Agrawal et al. [15] developed a gravity-balanced mechanism by using tension springs. They developed the inverse dynamics model by applying the Newton–Euler approach. After performing several experimental tests, they noticed an increase of the range of motion for both the hip and knee. Collins et al. [16] developed an exoskeleton for the ankle that consisted of a mechanical clutch and a spring. From the analysis of the obtained results, they concluded that it was more energy-effective at walking.

Therefore, those considerations raise two major problems in the exoskeleton design, the mechanical design and the controller. The mechanical design also needs to have some flexibility in order to allow the adaptation of actions to different groups of people. Moreover, the model of the controller needs an accurate representation of the mechanical system. Therefore, the mechanical modelling technique should be capable of changing the parameters to adjust to users with different sizes and requirements. This is particularly important for a lower limb exoskeleton during its adaptation to the legs of the user. In order to do so, there is room for improvement in the mechanical modelling procedures currently available.

This article proposes a dynamic modelling approach based on the modular modelling methodology (MMM) for the progressive improvement of exoskeletons. The conceptual design of a lower limb exoskeleton is described in Section 2. In Section 3, the theoretical background related to the Gibbs–Appell and modular dynamic modelling methods is presented. In Section 4, its kinematic and dynamic models are carried out. Then, Section 5 shows the performed simulations and obtained results. Finally, in Section 6, the conclusions are drawn.

2. The Modular Modelling Methodology

Among the possible forms of deriving the equations of motion, one is that expressed by Equation (1) [17,18] which is known as either Gibbs–Appell’s or Kane’s approach. Hence,

the dynamic model of a N -body mechanical system can be obtained from the sum of dot products between the partial velocities and active/inertial efforts.

$$\sum_{k=1}^N \frac{\partial \mathbf{v}_{G_k}^T}{\partial \dot{q}_i} (\mathbf{F}_{a_k} - m_k \dot{\mathbf{v}}_{G_k}) + \frac{\partial \boldsymbol{\omega}_k^T}{\partial \dot{q}_i} (\mathbf{M}_{a_k} - ([I]_k \dot{\boldsymbol{\omega}}_k + \boldsymbol{\omega}_k \times [I]_k \boldsymbol{\omega}_k)) = \mathbf{0} \quad (1)$$

$$i = 1, \dots, \mu$$

Alternatively, in order to systematise the derivation of the dynamic equations, Orsino and Hess-Coelho [19–21] proposed another representation for Gibbs–Appell’s or Kane’s method. Basically, it comprises the utilisation of redundant variables and coupling matrices for defining the variable dependency with the generalised velocities. Hence, the inclusion of bodies, subsystems and dynamic effects becomes relatively easier. It is called the modular modelling methodology [22]. For a system S with μ degrees of freedom, $\dot{q}_1, \dot{q}_2, \dots, \dot{q}_\mu$ are the generalized velocities and the kinematic variables of the k th body can be defined as

$$\begin{bmatrix} {}^0\mathbf{v}_G \\ {}^k\boldsymbol{\omega} \end{bmatrix}_k = \begin{bmatrix} u_1 \\ \vdots \\ u_{\lambda_k} \end{bmatrix} = C_k \begin{bmatrix} \dot{q}_1 \\ \vdots \\ \dot{q}_\mu \end{bmatrix} \quad (2)$$

where λ_k is the dimension of vector $[{}^0\mathbf{v}_G \ {}^k\boldsymbol{\omega}]^T$ (3 for planar and 6 for spatial motions) and the coupling matrix C_k is

$$C_k = \begin{bmatrix} \frac{\partial u_1}{\partial \dot{q}_1} & \cdots & \frac{\partial u_1}{\partial \dot{q}_\mu} \\ \vdots & \vdots & \vdots \\ \frac{\partial u_{\lambda_k}}{\partial \dot{q}_1} & \cdots & \frac{\partial u_{\lambda_k}}{\partial \dot{q}_\mu} \end{bmatrix}_k \quad (3)$$

Consequently, the matrix D_k , whose elements are the partial derivatives of linear and angular velocities with respect to $u_1, u_2, \dots, u_{\lambda_k}$, becomes the identity,

$$D_k = \begin{bmatrix} \frac{\partial \mathbf{v}_G^T}{\partial u_1} & \frac{\partial \boldsymbol{\omega}^T}{\partial u_1} \\ \vdots & \vdots \\ \frac{\partial \mathbf{v}_G^T}{\partial u_{\lambda_k}} & \frac{\partial \boldsymbol{\omega}^T}{\partial u_{\lambda_k}} \end{bmatrix}_k = \mathbf{1}_{\lambda_k \times \lambda_k} \quad (4)$$

In addition, the vector $\mathbf{f}_k$ takes into account the active/inertial efforts for the k th body,

$$\mathbf{f}_k = \begin{bmatrix} {}^0\mathbf{F}_a - m {}^0\dot{\mathbf{v}}_G \\ {}^k\mathbf{M}_a - ([I] {}^k\dot{\boldsymbol{\omega}} + {}^k\boldsymbol{\omega} \times [I] {}^k\boldsymbol{\omega}) \end{bmatrix}_k \quad (5)$$

Moreover, Equation (6) shows how to compute n , the total number of redundant kinematic variables, while the dynamic equations for the whole system S , composed of N moving bodies, are expressed by Equation (7).

$$n = \sum_{k=1}^N \lambda_k \quad (6)$$

$$C^T D \mathbf{f} = \begin{bmatrix} C_1^T & \cdots & C_N^T \end{bmatrix}_{\mu \times n} \begin{bmatrix} \mathbf{f}_1 \\ \vdots \\ \mathbf{f}_N \end{bmatrix}_{n \times 1} = \mathbf{0}_{\mu \times 1} \quad (7)$$

where the matrix D is

$$D = \begin{bmatrix} D_1 & \mathbf{0} & \dots & \mathbf{0} \\ \mathbf{0} & D_2 & \dots & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \dots & \mathbf{0} & D_N \end{bmatrix} = \mathbf{1}_{n \times n} \quad (8)$$

and the vectors of redundant velocities $\mathbf{u}$ and accelerations $\dot{\mathbf{u}}$ are, respectively,

$$\mathbf{u}_{nx1} = C_{nx\mu} \dot{\mathbf{q}}_{\mu x1} \quad (9)$$

$$\dot{\mathbf{u}}_{nx1} = C_{nx\mu} \ddot{\mathbf{q}}_{\mu x1} + \dot{C}_{nx\mu} \dot{\mathbf{q}}_{\mu x1} \quad (10)$$

3. The Lower Limb Exoskeleton

3.1. Conceptual Design

Since exoskeletons are worn by the user, they have an inherent requirement of compatibility with the anatomy and movement of the human body. Otherwise, they would disturb the activities they try to aid or improve. Furthermore, it is highly desirable that an exoskeleton not only be as thin and light as possible, but also comfortable and easy to wear. To illustrate the application of the method proposed in this work we will use the exoskeleton developed in the Laboratory of Biomechatronics of the Universidade de Sao Paulo, called ETMICA (Exoesqueleto de Tronco e Membros Inferiores para Caminhada Autônoma Estável, in Portuguese), which means exoskeleton of the trunk and lower limbs for an autonomous stable gait. The ETMICA was designed for applications in the areas of physiotherapy and research, for the purpose of rehabilitation and motor assistance of paraplegic people. Differently to most of the state of art exoskeletons, the attachments between the equipment and user at the limbs are frontal. In this way, it is possible to reduce the torsion caused by lateral exoskeleton attachments in order to improve the user comfort and to make it easier to wear, even with the concomitant use of a wheelchair. To reduce the swinging masses, the actuation is performed by cables, allowing to place the motors in the back of the body. An overview of the exoskeleton configuration is depicted in Figure 1.

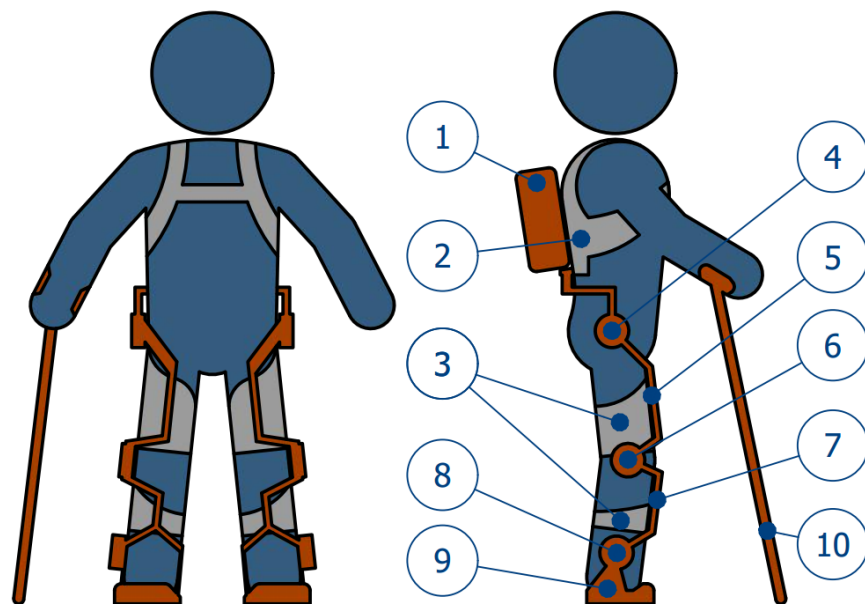


Figure 1. exoskeleton components: (1) power pack; (2) trunk attachments; (3) limbs attachments; (4) hip joint; (5) upper leg frame; (6) knee joint; (7) lower leg frame; (8) ankle joint; (9) foot frame; (10) instrumented crutch.

There are several configurations of exoskeletons for rehabilitation varying the number of degrees of freedom according to their purpose [23]. However, in general, the actuated ones are in the sagittal plane of motion, preponderant in the walk. The ETMICA-E has 7 degrees of freedom on each leg, distributed according to Table 1. As it is intended to use just one crutch, the adduction–abduction dof is actuated to position the centre of mass on the support foot. Additionally, it has a passive degree of freedom at the foot, at the metatarsophalangeal joint, to improve the ground contact during the terminal stance phase.

Table 1. Number of dofs on each leg.

Joint	Dof	Actuated	Passive
Hip	3	Flex–extension Adduction–abduction	Rotation Internal–external
Knee	1	Flex–extension	–
Ankle	2	Flex–extension	Inversion–eversion
Metatarsophalangeal	1	–	Flex–extension

The exoskeleton must be able to accommodate users from 1.55 m to 1.80 m tall and with a body mass up to 80 kg, who have trunk control and enough arm strength to transfer from a bed to a chair. Therefore, to position the joints properly, some adjustments are required for each individual. Moreover, due to the offset between the human and exoskeleton joint rotation axes, there occur movement misalignments that could cause singularities or even locking in the movement. Thus, mechanisms are required to compensate those misalignments. The mechanism used in the hip joint of ETMICA-E for this purpose is shown in Figure 2. A four-bar linkage compensates the misalignment that would occur for the flexion–extension axis when the adduction–abduction is performed. Moreover, the exoskeleton joint for the adduction–abduction allows the user to sit comfortably.

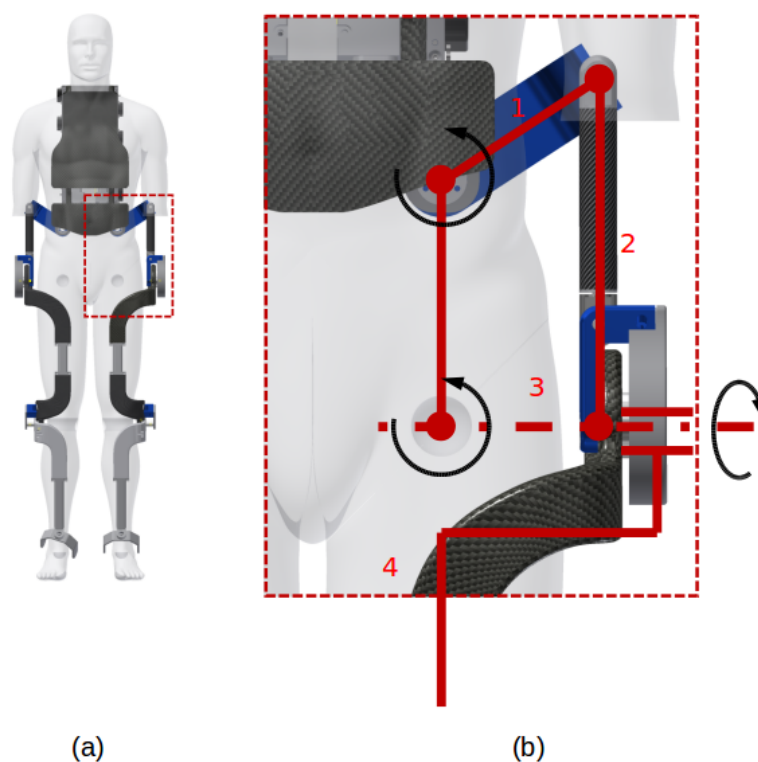


Figure 2. CAD model: (a) exoskeleton attached to the trunk and lower limbs; (b) detailed view of links and joints.

3.2. Mobility Analysis

In order to determine the mobility of a substructure of the proposed lower limb exoskeleton, the Lie's displacement group theory was employed [24,25]. Initially, the mechanical structure can be divided into two kinematic chains (Figure 3). The kinematic chain I, composed of links 0, 1, 2, 3 and 4, provides $\mathcal{L}_I(0,4)$ as the set of displacements

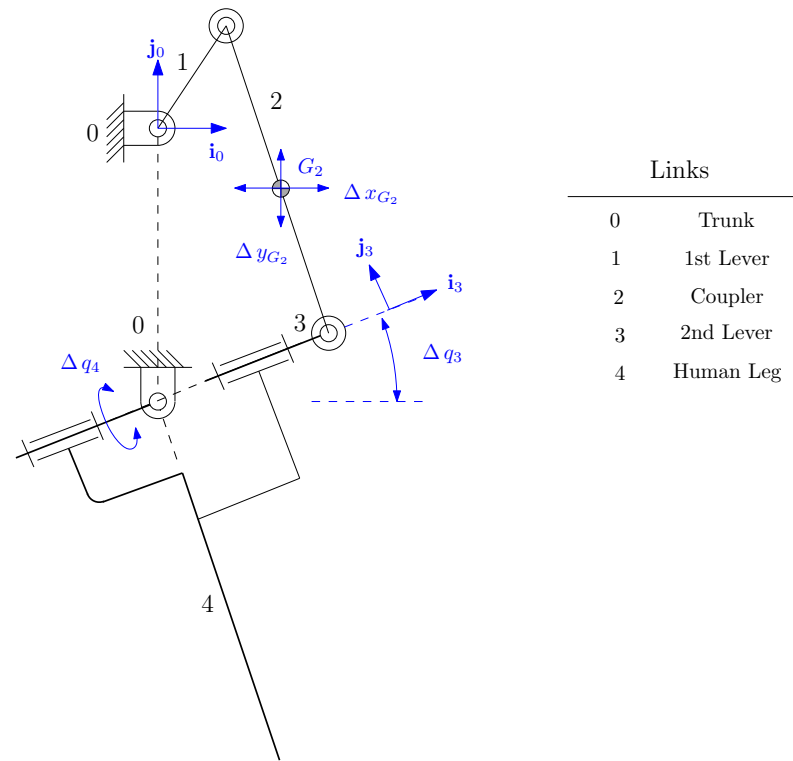


Figure 3. The kinematic diagram of a substructure of the exoskeleton for the lower limb.

$$\mathcal{L}_I(0,4) = \text{Trans}(\Delta x_{G_2} \mathbf{i}_0) \cup \text{Trans}(\Delta y_{G_2} \mathbf{j}_0) \cup \text{Rot}(\Delta q_3 \mathbf{k}_3) \cup \text{Rot}(\Delta q_4 \mathbf{i}_3) \quad (11)$$

On the other hand, the kinematic chain II, composed of links 0 and 4, is capable of performing the set of displacements $\mathcal{L}_{II}(0,4)$

$$\mathcal{L}_{II}(0,4) = \text{Rot}(\Delta q_3 \mathbf{k}_3) \cup \text{Rot}(\Delta q_4 \mathbf{i}_3) \quad (12)$$

Therefore, from the intersection between the sets of displacements of the two chains, one can conclude that the independent displacements are

$$\mathcal{L}(0,4) = \mathcal{L}_I(0,4) \cap \mathcal{L}_{II}(0,4) = \text{Rot}(\Delta q_3 \mathbf{k}_3) \cup \text{Rot}(\Delta q_4 \mathbf{i}_3) \quad (13)$$

which means that the whole system has 2 degrees of freedom.

4. The Exoskeleton Modelling

According to Figure 4, the substructure of the exoskeleton is assumed to have only three bodies, namely, links 1, 3 and 4. In Section 4.1, the kinematic variables are obtained, while in Section 4.2, the dynamic model is derived by applying the MMM method. Later, Section 4.3 explains how the dynamic model can be modified in order to consider the dynamic effects of link 2 and possible changes in the design parameters.

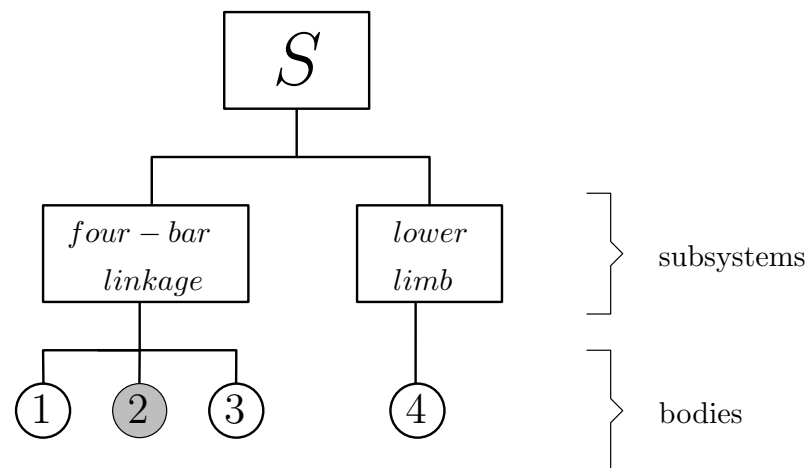


Figure 4. The system S: a four-bar linkage (bodies 1, 3) and the human lower limb (body 4).

4.1. Kinematic Model

Due to the fact that one actuator drives link 1, while the other drives link 4 (Figure 5), the chosen generalised velocities are $\dot{q}_1$ and $\dot{q}_4$. Then, the total number of redundant kinematic variables n can be computed as follows,

$$n = \sum_{k=1, \neq 2}^4 \lambda_k = 12$$

For link 1, the velocities $\mathbf{v}_{G_1}$ and ω_1 are

$$\mathbf{v}_{G_1} = L_1 \dot{q}_1 \mathbf{j}_1 = L_1 \dot{q}_1 \begin{bmatrix} -s_1 \\ c_1 \end{bmatrix} = \begin{bmatrix} {}^0v_{G_{1x}} \\ {}^0v_{G_{1y}} \end{bmatrix} = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$$

$$\omega_1 = \dot{q}_1 \mathbf{k}_1 = {}^1\omega_{1z} \mathbf{k}_1 = u_3 \mathbf{k}_1$$

For link 3, the velocities $\mathbf{v}_{G_3}$ and ω_3 are

$$\mathbf{v}_{G_3} = L_3 \dot{q}_3 \mathbf{j}_3 = L_3 \dot{q}_3 \begin{bmatrix} -s_3 \\ c_3 \end{bmatrix} = \begin{bmatrix} {}^0v_{G_{3x}} \\ {}^0v_{G_{3y}} \end{bmatrix} = \begin{bmatrix} u_4 \\ u_5 \end{bmatrix}$$

$$\omega_3 = \dot{q}_3 \mathbf{k}_3 = {}^3\omega_{3z} \mathbf{k}_3 = u_6 \mathbf{k}_3$$

For link 4, the velocities ω_4 and $\mathbf{v}_{G_4}$ are

$$\omega_4 = \dot{q}_3 \mathbf{k}_3 + \dot{q}_4 \mathbf{i}_4 = \dot{q}_3 {}^4R_3 {}^3\mathbf{k}_3 + \dot{q}_4 {}^4\mathbf{i}_4 = \dot{q}_3 \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_4 & s_4 \\ 0 & -s_4 & c_4 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} + \dot{q}_4 \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

$$= \begin{bmatrix} \dot{q}_4 \\ \dot{q}_3 s_4 \\ \dot{q}_3 c_4 \end{bmatrix} = \begin{bmatrix} {}^4\omega_{4x} \\ {}^4\omega_{4y} \\ {}^4\omega_{4z} \end{bmatrix} = \begin{bmatrix} u_{10} \\ u_{11} \\ u_{12} \end{bmatrix}$$

$${}^4\mathbf{v}_{G_4} = {}^4\omega_4 \times ({}^4\mathbf{r}_{G_4} - {}^4\mathbf{r}_{O_4}) = \begin{bmatrix} 0 & -{}^4\omega_{4z} & {}^4\omega_{4y} \\ {}^4\omega_{4z} & 0 & -{}^4\omega_{4x} \\ -{}^4\omega_{4y} & {}^4\omega_{4x} & 0 \end{bmatrix} \begin{bmatrix} 0 \\ -L_4 \\ 0 \end{bmatrix}$$

$$= L_4 \begin{bmatrix} {}^4\omega_{4z} \\ 0 \\ -{}^4\omega_{4x} \end{bmatrix} = L_4 \begin{bmatrix} \dot{q}_3 c_4 \\ 0 \\ -\dot{q}_4 \end{bmatrix}$$

$$\begin{aligned}
 {}^0\mathbf{v}_{G_4} &= {}^0R_3 {}^3R_4 {}^4\mathbf{v}_{G_4} = \begin{bmatrix} c_3 & -s_3 & 0 \\ s_3 & c_3 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_4 & -s_4 \\ 0 & s_4 & c_4 \end{bmatrix} \begin{bmatrix} \dot{q}_3 c_4 \\ 0 \\ -\dot{q}_4 \end{bmatrix} L_4 \\
 &= \begin{bmatrix} \dot{q}_3 c_4 c_3 - \dot{q}_4 s_4 s_3 \\ \dot{q}_3 c_4 s_3 + \dot{q}_4 s_4 c_3 \\ -\dot{q}_4 c_4 \end{bmatrix} L_4 = \begin{bmatrix} u_7 \\ u_8 \\ u_9 \end{bmatrix}
 \end{aligned}$$

By assuming $L_1 = L_3$, then $q_1 = q_3$ and the coupling matrix C becomes

$$C = \begin{bmatrix} C_1 \\ C_3 \\ C_4 \end{bmatrix} = \begin{bmatrix} -s_1 L_1 & 0 \\ c_1 L_1 & 0 \\ 1 & 0 \\ -s_1 L_1 & 0 \\ c_1 L_1 & 0 \\ 1 & 0 \\ c_1 c_4 L_4 & -s_1 s_4 L_4 \\ s_1 c_4 L_4 & c_1 s_4 L_4 \\ 0 & -c_4 L_4 \\ 0 & 1 \\ s_4 & 0 \\ c_4 & 0 \end{bmatrix}.$$

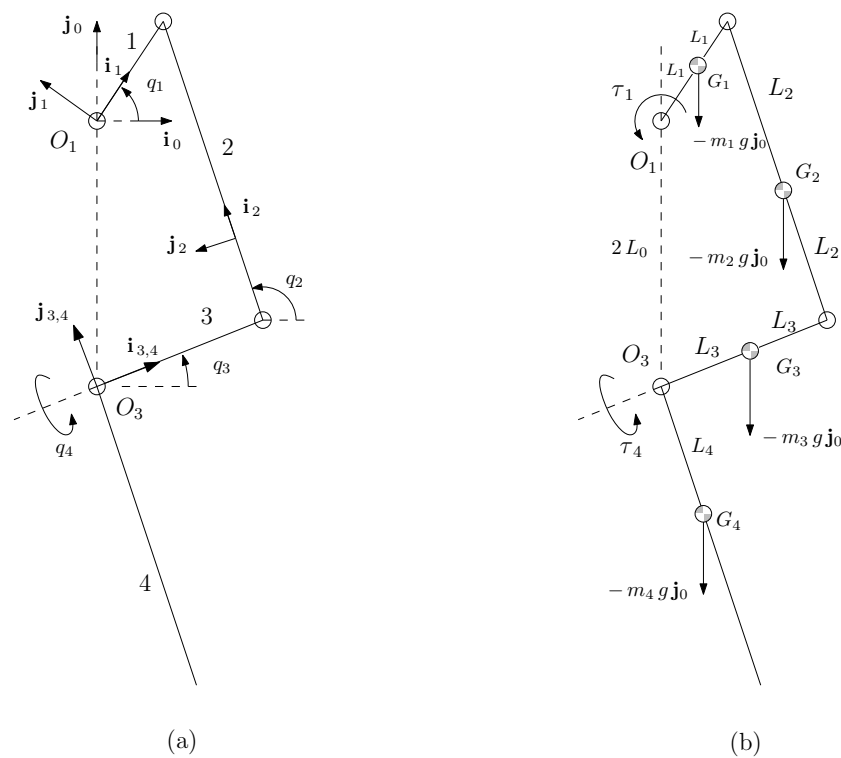


Figure 5. Model conventions: (a) frames and variables; (b) centres of mass, gravitational forces and torques.

4.2. Dynamic Model

The dynamic model of the exoskeleton considers the inertial and gravitational forces of links 1, 3 and 4. In addition, the driving torques of actuators 1 and 4 are taken into account, which are, respectively, τ_1 and τ_4 . Hence, the vector $\mathbf{f}$ can be calculated as follows,

$$\mathbf{f} = \begin{bmatrix} \mathbf{f}_1 \\ \mathbf{f}_3 \\ \mathbf{f}_4 \end{bmatrix} = \begin{bmatrix} -m_1 \dot{u}_1 \\ -m_1 (\dot{u}_2 + g) \\ \tau_1 - \dot{u}_3 I_1 \\ \\ -m_3 \dot{u}_4 \\ -m_3 (\dot{u}_5 + g) \\ -\dot{u}_6 I_3 \\ \\ -m_4 \dot{u}_7 \\ -m_4 (\dot{u}_8 + g) \\ -m_4 \dot{u}_9 \\ (I_{4y} - I_{4z}) u_{11} u_{12} - I_{4x} \dot{u}_{10} + \tau_4 \\ -(I_{4x} - I_{4z}) u_{10} u_{12} - I_{4y} \dot{u}_{11} \\ -I_{4z} \dot{u}_{12} - (I_{4y} - I_{4x}) u_{10} u_{11} \end{bmatrix}$$

From Equation (7), the dynamic equations are

$$\begin{bmatrix} C_1^T & C_3^T & C_4^T \end{bmatrix} \begin{bmatrix} \mathbf{f}_1 \\ \mathbf{f}_3 \\ \mathbf{f}_4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} -m_4 s_1 c_4 (\dot{u}_8 + g) L_4 - m_4 c_1 c_4 \dot{u}_7 L_4 - m_3 c_1 (\dot{u}_5 + g) L_1 + \\ m_3 s_1 \dot{u}_4 L_1 - m_1 c_1 (\dot{u}_2 + g) L_1 + m_1 s_1 \dot{u}_1 L_1 - \dot{u}_6 I_3 - \dot{u}_3 I_1 + \\ c_4 (-I_{4z} \dot{u}_{12} - (I_{4y} - I_{4x}) u_{10} u_{11}) + s_4 (- (I_{4x} - I_{4z}) u_{10} u_{12} - I_{4y} \dot{u}_{11}) + \tau_1 \\ m_4 c_4 \dot{u}_9 L_4 - m_4 c_1 s_4 (\dot{u}_8 + g) L_4 + m_4 s_1 s_4 \dot{u}_7 L_4 + (I_{4y} - I_{4z}) u_{11} u_{12} - I_{4x} \dot{u}_{10} + \tau_4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

By assuming that $m_1 = m_3$ and $I_1 = I_3$,

$$\begin{aligned} & \ddot{q}_1 (2m_1 L_1^2 + 2I_1 + m_4 L_4^2 c_4^2 + I_{4y} s_4^2 + I_{4z} c_4^2) + \\ & 2\dot{q}_1 \dot{q}_4 (-m_4 L_4^2 - I_{4z} + I_{4y}) c_4 s_4 + g (2m_1 L_1 c_1 + m_4 L_4 s_1 c_4) = \tau_1 \\ & \ddot{q}_4 (m_4 L_4^2 + I_{4x}) + \dot{q}_1^2 (m_4 L_4^2 + I_{4z} - I_{4y}) c_4 s_4 + g m_4 L_4 c_1 s_4 = \tau_4 \end{aligned}$$

4.3. Modifying the Dynamic Model

In order to take into account the effect of the gravitational force of link 2, the dynamic model needs to be modified. Then, the linear and angular velocities, $\mathbf{v}_{G_2}$ and ω_2 , can be calculated and three redundant variables, u_{13} , u_{14} and u_{15} are added,

$$\mathbf{v}_{G_2} = 2L_1 \dot{q}_1 \mathbf{j}_1 = 2L_1 \dot{q}_1 \begin{bmatrix} -s_1 \\ c_1 \end{bmatrix} = \begin{bmatrix} {}^0 v_{G_{2x}} \\ {}^0 v_{G_{2y}} \end{bmatrix} = \begin{bmatrix} u_{13} \\ u_{14} \end{bmatrix}$$

$$\omega_2 = 0 \mathbf{k}_2 = {}^2 \omega_{2z} \mathbf{k}_2 = u_{15} \mathbf{k}_2$$

Hence, the coupling matrix C_2 is

$$C_2 = 2 \begin{bmatrix} -s_1 L_1 & 0 \\ c_1 L_1 & 0 \\ 0 & 0 \end{bmatrix}$$

The vector $\mathbf{f}_2$ is

$$\mathbf{f}_2 = [0 \quad -m_2 g \quad 0]^T$$

Then, the dynamic equations become

$$\begin{bmatrix} C_1^T & C_2^T & C_3^T & C_4^T \end{bmatrix} \begin{bmatrix} \mathbf{f}_1 \\ \mathbf{f}_2 \\ \mathbf{f}_3 \\ \mathbf{f}_4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

$$\ddot{q}_1 (2m_1 L_1^2 + 2I_1 + m_4 L_4^2 c_4^2 + I_{4y} s_4^2 + I_{4z} c_4^2) + 2\dot{q}_1 \dot{q}_4 (-m_4 L_4^2 - I_{4z} + I_{4y}) c_4 s_4 + g(2m_1 L_1 c_1 + 2m_2 L_1 c_1 + m_4 L_4 s_1 c_4) = \tau_1$$

$$\ddot{q}_4 (m_4 L_4^2 + I_{4x}) + \dot{q}_1^2 (m_4 L_4^2 + I_{4z} - I_{4y}) c_4 s_4 + g m_4 L_4 c_1 s_4 = \tau_4$$

By assuming that the parameters L_3 and L_1 are distinct, the angular and linear velocities of links 2 and 3 must be recalculated,

$$\omega_2 = \dot{q}_2 \mathbf{k}_2 = {}^2\omega_{2z} \mathbf{k}_2$$

$$\dot{q}_2 = \dot{q}_1 \frac{2L_1}{2L_2} \frac{\mathbf{j}_1^T \mathbf{i}_3}{\mathbf{j}_2^T \mathbf{i}_3} = \dot{q}_1 \frac{L_1}{L_2} \left(\frac{-s_1 c_3 + c_1 s_3}{-s_2 c_3 + c_2 s_3} \right) = \dot{q}_1 \frac{L_1}{L_2} \frac{s_{1-3}}{s_{2-3}} = \dot{q}_1 \frac{L_1}{L_2} \Delta_2 = u_{15}$$

$$\omega_3 = \dot{q}_3 \mathbf{k}_3 = {}^3\omega_{3z} \mathbf{k}_3$$

$$\dot{q}_3 = \dot{q}_1 \frac{2L_1}{2L_3} \frac{\mathbf{j}_1^T \mathbf{i}_2}{\mathbf{j}_3^T \mathbf{i}_2} = \dot{q}_1 \frac{L_1}{L_3} \left(\frac{-s_1 c_2 + c_1 s_2}{-s_3 c_2 + c_3 s_2} \right) = \dot{q}_1 \frac{L_1}{L_3} \frac{s_{2-1}}{s_{2-3}} = \dot{q}_1 \frac{L_1}{L_3} \Delta_3 = u_6$$

$$\mathbf{v}_{G_3} = \dot{q}_3 L_3 \mathbf{j}_3 = \dot{q}_1 L_1 \Delta_3 \begin{bmatrix} -s_3 \\ c_3 \end{bmatrix} = \begin{bmatrix} u_4 \\ u_5 \end{bmatrix}$$

$$\mathbf{v}_{G_2} = \dot{q}_3 2L_3 \mathbf{j}_3 + \dot{q}_2 L_2 \mathbf{j}_2 = \dot{q}_1 L_1 (2\Delta_3 \mathbf{j}_3 + \Delta_2 \mathbf{j}_2) = \dot{q}_1 L_1 \begin{bmatrix} -2s_3 \Delta_3 - s_2 \Delta_2 \\ 2c_3 \Delta_3 + c_2 \Delta_2 \end{bmatrix} = \begin{bmatrix} {}^0v_{G_{2x}} \\ {}^0v_{G_{2y}} \end{bmatrix} = \begin{bmatrix} u_{13} \\ u_{14} \end{bmatrix}$$

Hence, the coupling matrices C_2 and C_3 are

$$C_2 = \begin{bmatrix} L_1 (-2s_3 \Delta_3 - s_2 \Delta_2) & 0 \\ L_1 (2c_3 \Delta_3 + c_2 \Delta_2) & 0 \\ \frac{L_1}{L_2} \Delta_2 & 0 \end{bmatrix}$$

$$C_3 = \begin{bmatrix} -s_3 L_1 \Delta_3 & 0 \\ c_3 L_1 \Delta_3 & 0 \\ \frac{L_1}{L_3} \Delta_3 & 0 \end{bmatrix}$$

As a consequence, the dynamic equations become

$$\begin{aligned}
& \ddot{q}_1 \left(m_1 L_1^2 + I_1 + \left(\frac{I_3}{L_3^2} + m_3 \right) L_1^2 \Delta_3^2 + m_4 L_4^2 c_4^2 + I_{4y} s_4^2 + I_{4z} c_4^2 \right) \\
& + \dot{q}_1^2 \left(\frac{I_3}{L_3^2} + m_3 \right) L_1^2 \Delta_3^2 \left(\frac{c_{2-1}}{s_{2-1}} \left(\frac{L_1}{L_2} \Delta_2 - 1 \right) + \frac{c_{2-3}}{s_{2-3}} \left(\frac{L_1}{L_3} \Delta_3 - \frac{L_1}{L_2} \Delta_2 \right) \right) \\
& + \dot{q}_1 \dot{q}_4 \left(1 + \frac{L_1}{L_3} \Delta_3 \right) \left(I_{4y} - I_{4z} - m_4 L_4^2 \right) c_4 s_4 \\
& + g m_1 L_1 c_1 + g m_2 L_1 (2 c_3 \Delta_3 + c_2 \Delta_2) + g m_3 L_1 \Delta_3 c_3 + g m_4 L_4 s_3 c_4 = \tau_1
\end{aligned}$$

$$\ddot{q}_4 \left(m_4 L_4^2 + I_{4x} \right) + \dot{q}_1^2 \left(m_4 L_4^2 + (I_{4z} - I_{4y}) \frac{L_1}{L_3} \Delta_3 \right) c_4 s_4 \frac{L_1}{L_3} \Delta_3 + g m_4 L_4 c_3 s_4 = \tau_4$$

5. Simulations and Results

From the dynamic equations deduced in previous sections, some simulations were performed in order to evaluate the model consistency and to estimate the actuator torques as well. Table 2 shows the selected parameters for the exoskeleton and a typical male adult (80 kg, 1.80 m) user [26]. In addition, we tested the application of this method to change the design parameters to adapt to other users with other heights and weights (60 kg, 1.70 m) and a shorter one (50 kg, 1.60 m) [27].

Table 2. Selected parameters for the analyses.

	Link 1		Link 2		Link 3
$m_1(kg)$	0.18	$m_2(kg)$	0.15	$m_3(kg)$	0.2
$L_1(m)$	0.09	$L_2(m)$	0.2	$L_3(m)$	0.1
$I_1(kg\ m^2)$	0.00068	$I_2(kg\ m^2)$	0.0014	$I_3(kg\ m^2)$	0.00072
Link 4	$m_4(kg)$	$L_4(m)$	$I_{4x}(kg\ m^2)$	$I_{4y}(kg\ m^2)$	$I_{4z}(kg\ m^2)$
1.8 m, 80 kg	13.3	0.36	0.819	0.0062	0.819
1.7 m, 60 kg	11.1	0.36	0.51	0.006	0.51
1.6 m, 50 kg	9.3	0.34	0.38	0.006	0.38

5.1. First Simulation: Inverse Dynamics

For the first simulation, the input motions for the exoskeleton were prescribed, namely, $q_1(t)$ and $q_4(t)$. Such functions were chosen as sinusoidal functions whose amplitudes were equal to 5 and 15 degrees, respectively, and both periods were equal to 2 s. Hence, the torques τ_1 and τ_4 for the motion cycle can be calculated. Figure 6 shows that the actuator torques were both periodic functions whose period was equal to 2 s. In addition, the maximum values of τ_1 and τ_4 were, respectively, for 1.8 m 80 kg: 2.3 and 5.8 Nm, for 1.7 m 60 kg: 2.2 and 5.3 Nm and for 1.6 m 50 kg: 1.9 and 4.4 Nm.

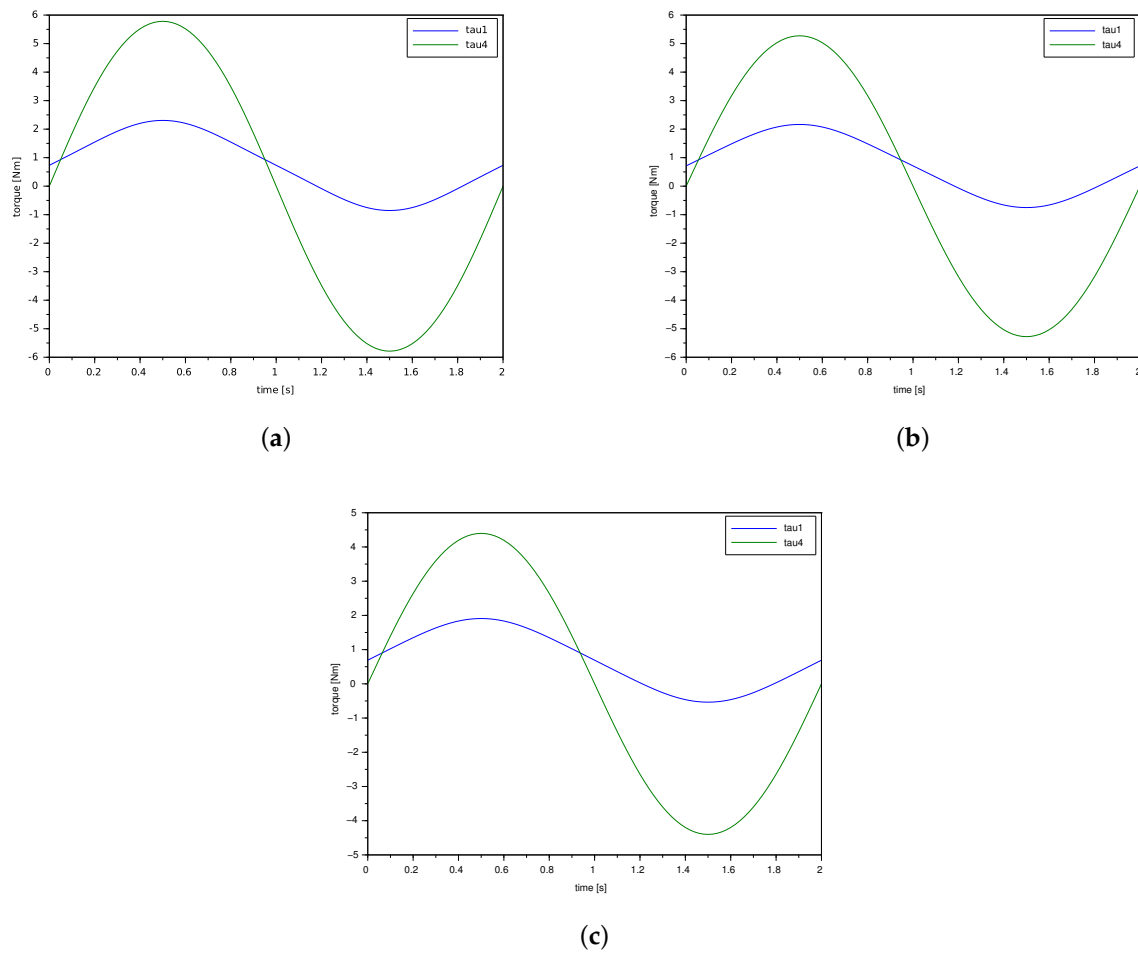


Figure 6. Inverse dynamics: torques of actuators 1 (τ_1 : tau1) and 4 (τ_4 : tau4) simulated for subjects of different heights and weights: (a) 1.8 m and 80 kg; (b) 1.7 m and 60 kg; (c) 1.6 m and 50 kg.

5.2. Second Simulation: Direct Dynamics

For the second simulation, the actuator torques were considered null while the initial conditions were $q_1(0) = 5$ deg, $q_4(0) = 15$ deg, $\dot{q}_1(0) = 0$ rad/s, $\dot{q}_4(0) = 0$ rad/s. Figure 7 shows the generalized coordinates and velocities during a 5 s simulation. One can notice that the simulated system has a conservative behaviour once there is no dissipative effects such as friction or damping. Regarding the oscillation around the k_0 -axis, the equilibrium position is approximately $q_1 = -1.03$ deg, which is expected since the exoskeleton behaves as an unbalanced pendulum. Moreover, there are two natural periods associated to this free vibration for the 1.8 m, 80 kg simulation, which correspond to 1.53 (q_1) and 1.46 s (q_4). Similarly, the natural periods for 1.7 m, 60 kg were: 1.47 and 1.40 s, while for 1.6 m, 50 kg they were 1.43 and 1.36 s, for q_1 and q_4 , respectively.

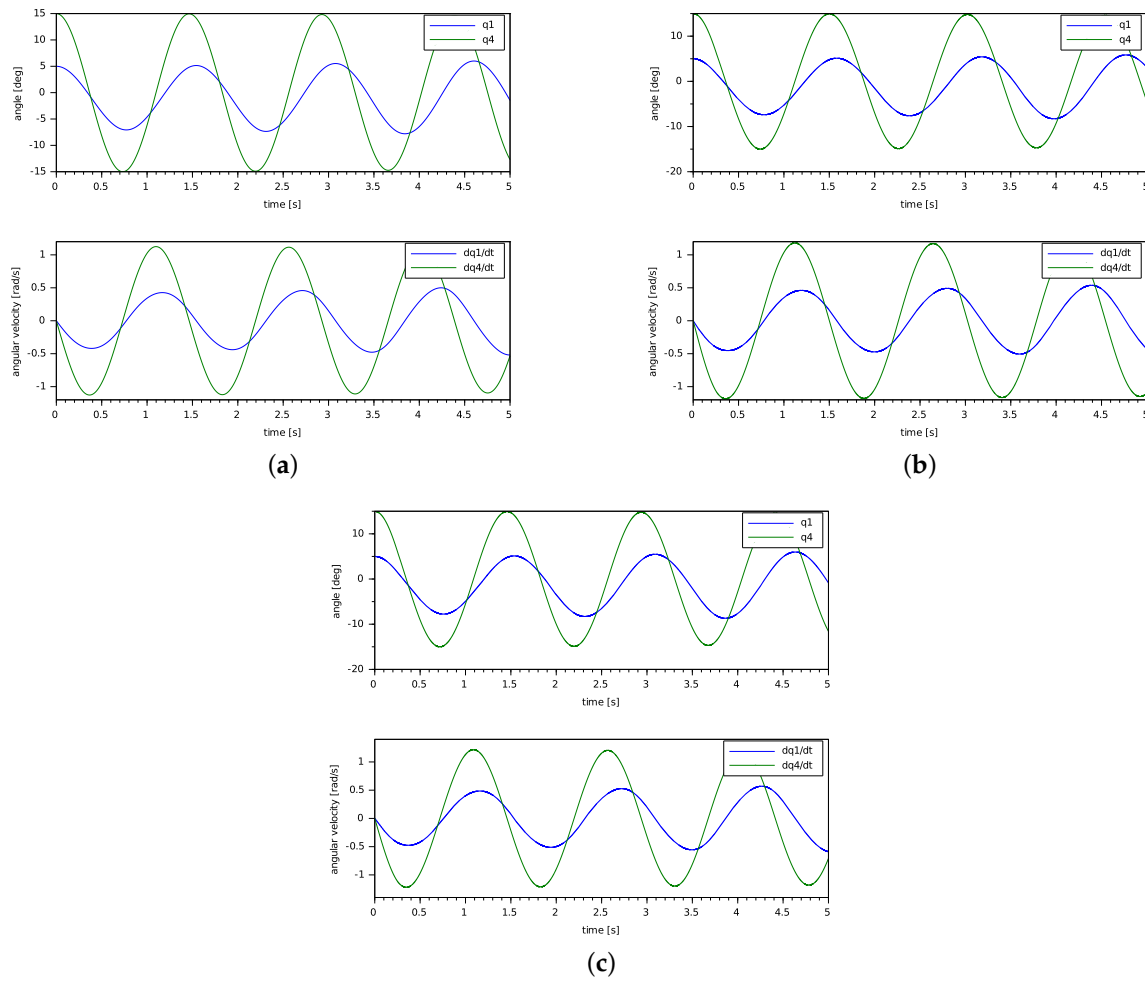


Figure 7. Direct dynamics: generalized coordinates and velocities of joints 1 (q_1 , dq_1/dt) and 4 (q_4 , dq_4/dt) simulated for subjects of different heights and weights: (a) 1.8 m and 80 kg; (b) 1.7 m and 60 kg; (c) 1.6 m and 50 kg.

5.3. Third Simulation: Inverse Dynamics

For the third simulation, the input motions for the exoskeleton were prescribed, namely, $q_1(t)$ and $q_4(t)$. Such functions were also chosen to be sinusoidal with amplitudes equal to 6 and 15 degrees, and periods equal to 1.53 and 1.46 s, respectively. Hence, the actuator torques τ_1 and τ_4 for the motion cycle can be recalculated. Figure 8 shows that the maximum absolute values for τ_1 and τ_4 reached 0.27 Nm and 0.15 Nm, respectively. Finally, the maximum torques τ_1 and τ_4 for 1.7 m, 60 kg were, respectively, 0.28 and 0.09 Nm, while for 1.6 m, 50 kg they were 0.34 and 0.11 Nm.

Consequently, it can be noted that if the input motions take into account the natural frequencies of the system, the actuator torques can be significantly reduced.

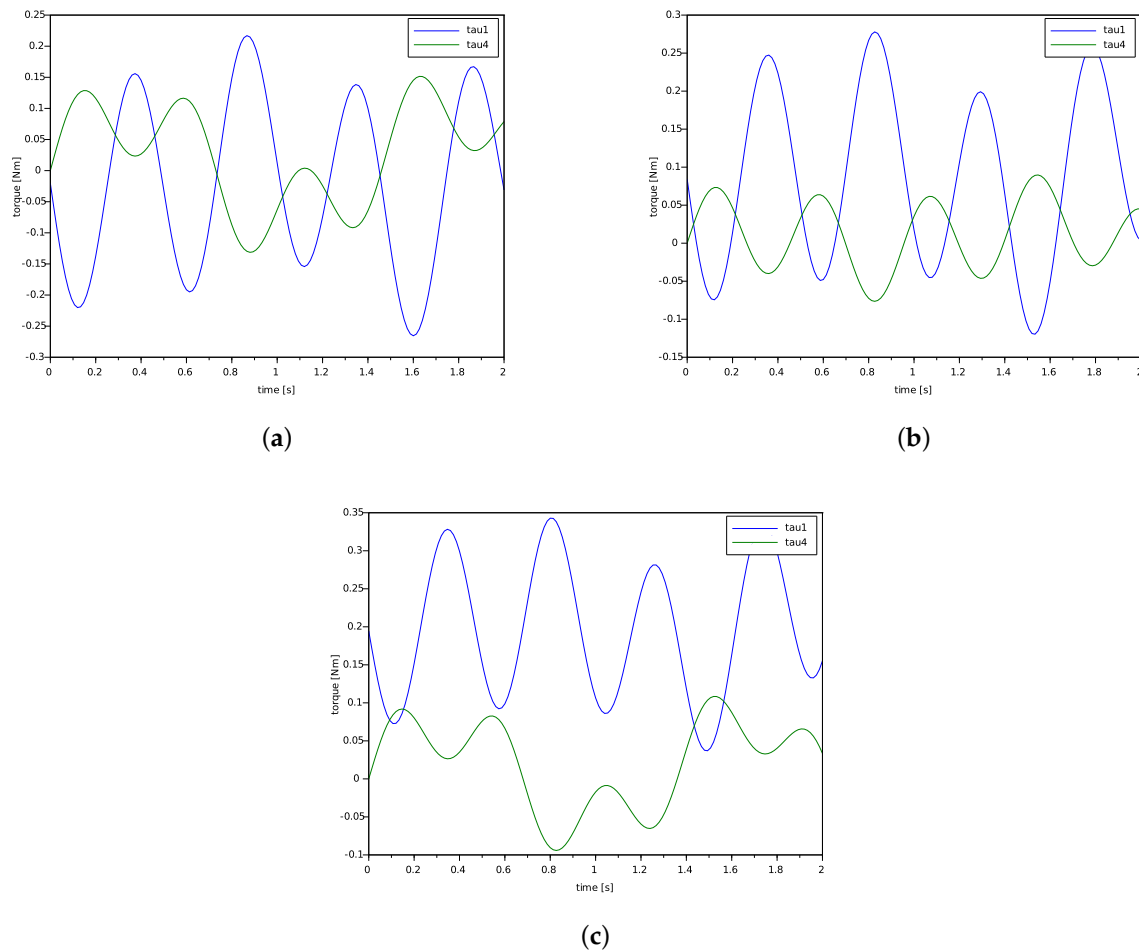


Figure 8. Inverse dynamics: torques of actuators 1 (τ_1 : tau1) and 4 (τ_4 : tau4) simulated for subjects of different heights and weights: (a) 1.8 m and 80 kg; (b) 1.7 m and 60 kg; (c) 1.6 m and 50 kg.

6. Conclusions

In this article we presented a dynamic modelling approach based on the Modular modelling methodology (MMM) for the development of exoskeletons. Initially, the conceptual design of a lower limb exoskeleton was presented. Then, the kinematic and dynamic models of a substructure of the exoskeleton were calculated. In addition, performed simulations demonstrated the model consistency and the actuator torques estimation.

The MMM provides an easy procedure to obtain the dynamic model as a first step to address some challenges in exoskeleton design, such as real time control, sensor signal fusion or user intent detection. In this respect, we note that the MMM method has several contributions: it is not only suitable for modelling exoskeletons but also has advantages over other previous approaches in terms of ease of building the dynamic model and modifying it as well.

In order to illustrate an application of this method, we performed three simulations for different types of users to show that it is possible to easily adjust the exoskeleton parameters to different users. Therefore, this method can help the exoskeleton designer during the synthesis process, facilitating the definition of the parameters, the actuator selection and the model-based control simulations.

Author Contributions: Conceptualization, T.A.H.-C., M.C. and A.F.-C.; methodology, T.A.H.-C. and M.C.; software, T.A.H.-C.; validation, T.A.H.-C., M.C., R.T.M. and A.F.-C.; resources, R.T.M. and A.F.-C.; writing—original draft preparation, T.A.H.-C., M.C. and A.F.-C.; writing—review and editing, T.A.H.-C., R.T.M. and A.F.-C.; visualization, T.A.H.-C. and M.C.; supervision, T.A.H.-C., R.T.M. and A.F.-C.; project administration, A.F.-C.; funding acquisition, A.F.-C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Brazilian National Council of Scientific Development—CNPq, for the financial support during the development of this research, grant No. 442216/2016-5, named *Validação clínica do exoesqueleto de tronco e membros inferiores (ETMICAE II)*.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: A.F.C. acknowledges CAPES-PRINT, Brazil for Visiting Professorship at Scuola Superiore Sant’Anna (num. 88887.573215/2020-00) and the CNPq for research grant 312236/2019-0.

Conflicts of Interest: The authors declare no conflict of interest.

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