Study of dynamic forces in human upper limb in forward fall

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Abstract: Knowledge of dynamic forces acting on the upper limb is useful, and sometimes even necessary, in its treatment and rehabilitation after injuries, during prostheses designing, as well as in optimization of the sports training process. In this work an attempt to determine the quantity of the inertia forces generated in forward fall has been undertaken. For this purpose a simplified mechanical model of the human body biokinematic chain has been prepared. Geometric data and mass of each element have been taken from anthropometric atlas for the Polish population. Kinematic data necessary to perform the analysis was calculated using fundamental laws of Mechanics. In this way accelerations of the selected points necessary for the determination of inertia forces acting on the individual links of the model were yielded. For validation of the obtained results a numerical model was constructed using SimMechanic module of the Matlab Simulink software. It made possible to compare the results obtained in both simulation methods. To make joints model more realistic a values of the viscous friction were assumed.

1. Introduction

Approximately 90% of all fractures of the distal radius, humeral neck and supracondylar region of the elbow are caused by the forward fall onto the outstretched hand [1]. The mechanism of joint interaction, the forces distribution within the joint and the contributory effects of elbow joint disorders must be fully understood in order to prevent and minimalize those injuries.

Chiu and Robinovitch [2] applied a two–degrees-of–freedom (2-DOF) lumped-parameter mathematical model for simulations of a fall on the outstretched hand with full elbow extension. Their model analysis suggested that fall from a height greater than 0.6 m carry significant risks of wrist fractures. The effect of elbow flexion at the moment of impact was investigated by Chou et al [3]. were considered elbow loads for models between elbows full flexion and full extension during a forward fall. The results of valgus-varus elbow analysis showed that shear force for the elbow full flexion model is 68% lower than in the case of the elbow full extension. Investigations of the ground reaction forces during forward fall showed that the first peak force value is reduced during an elbow flexion movement, while the impact peak force is postponed to the second peak force. From this follows conclusion that the elbow flexion movement may reduce the risk of injury during a forward fall. An experimental model for elbow load during a simulated one-armed fall arrest for three different forearm axially rotated postures and the relationship between the elbow flexion angle and different axially rotated postures were investigated in [4]. The results indicated that a fall on the outstretched hand with externally rotated forearm should be avoided in order to reduce excessive valgus-varus shear force on the elbow joint.

A 2-DOF impact model of bimanual forward fall arrests, basing on *in vivo* data of experimental falls, was constructed [5]. Its validation was confirmed by response simulation with separate experimental data. Results of its analysis indicated that the rapid arm movement towards the ground alone could be a major risk factor for fall-related injuries and that prolongation of the impact time through decreasing relative velocity between hand and ground allows to decrease the ground reaction force. In the study [6] authors investigated a stress contribution in the human upper limb during forward fall on the outreached hands. The results indicated that less risk of the fracture is supination position of the forearm.

Dynamic models of human movement help researchers identify key forces, movements, and movement patterns that should be measured. It was found that the muscle function depends strongly on both shoulder and elbow joints position. Using Lagrange' a method an at-home resistance training upper limb exoskeleton was designed with a 3DOF shoulder joint and a 1DOF elbow joint to allow both single and multiple joints upper limb movements in different planes [7]. The contribution of individual muscles motion of the glenohumeral joint during abduction and the examination of the effect of elbow flexion on shoulder muscle function was investigated by Ackland and Pandy [8].

The fall simulation studies have investigated the biomechanical analysis on elbow extension and elbow flexion models. However, there is very little information about dynamical forces acting on the upper limb. Thus, the present study performs an numerical investigations to evaluate the torque in each joint during forward fall. The numerical results may provide useful insights into potential reduced risk of injuries during forward fall.

2. Methods

Computer modeling is an effective tool to accelerate and improve the design of new mechanical system. Matlab and Simulink module are appropriate tools for creating computer model. To investigate the velocities and accelerations of the mass center of gravity (CG_i) of each parts of the proposed simplified model of the human body developed was the mathematical model by.

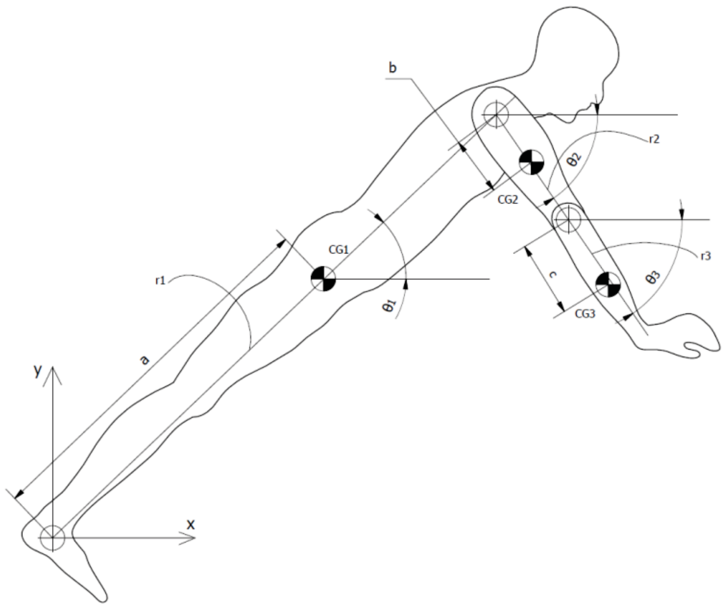


Figure 1. Mathematical model of human body

Human body was modeled as a three parts system including: torso with legs (link1 - dimension r_1), arm (link2 - dimension r_2) and forearm with hand (link3 - dimension r_3). Each part is represented as a rigid link with length proportions and mass distribution corresponding to the Polish population. The dynamic equations of such a mechanical system were derived using energy method. Lagrangian L of this system is defined as:

$$L(q,\dot{q}) = T(q,\dot{q}) - V(q) \tag{1}$$

where T is the total kinetic energy and V is the total potential energy of the system, q and $\dot{q}$ are the generalized coordinates and generalized velocities of the system, respectively. The equation of motion is given by:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}\right) - \frac{\partial L}{\partial q} = -\frac{\partial \Delta}{\partial \dot{q}} \tag{2}$$

where $\Delta(q,\dot{q})$ is the dissipation function.

A three links system has three degrees of freedom (3-DOF), and hence three generalized coordinates are needed to describe it in arbitrary configuration. The generalized coordinates are θ_n, where n=1,2,3.

In formulation of the dynamic equations the following designations were used:

r_i - length of i^{th} body part, where i = 1,2,3,
CGi – locations of the center of gravity of i^{th} link, where i = 1,2,3,
a – distance from joint 1 to $CG2$,
b - distance from joint 2 to $CG2$,
c - distance from joint 3 to $CG3$,
m_i – mass of i^{th} body part, where i = 1,2,3,
I_i – moment of inertia of i^{th} link about CG_i, where i = 1,2,3,
k_i - friction factor of i^{th} link, where i = 1,2,3.

The position vectors for the center of mass for parts 1, 2 and 3 with respect to the fixed coordinate system are as follows:

- torso with legs

$$\vec{r}_{CG1} = a\cos\theta_1 i + a\sin\theta_1 j \;, \tag{3}$$

- arm

$$\vec{r}_{CG2} = (r_1\cos\theta_1 + b\cos\theta_2)i + (r_2\sin\theta_1 + b\sin\theta_2)j \;, \tag{4}$$

- forearm with hand

$$\begin{aligned}\vec{r}_{CG3} &= (r_1\cos\theta_1 + r_2\cos\theta_2 + c\cos\theta_3)i + \\ &+(r_2\sin\theta_1 + r_2\sin\theta_2 + c\sin\theta_3)j\end{aligned} \;. \tag{5}$$

Differentiation of the equations (3), (4), (5) gives the velocities of the CGi:

- torso with legs

$$\dot{\vec{r}}_{CG1} = -a(\sin\theta_1\dot{\theta}_1)i + a(\cos\theta_1\dot{\theta}_1)j \;, \tag{6}$$

- arm

$$\dot{\vec{r}}_{CG2} = (-r_2\sin\theta_1\dot{\theta}_2 - b\sin\theta_2\dot{\theta}_2)i + (r_1\cos\theta_1\dot{\theta}_2 + b\cos\theta_2\dot{\theta}_2)j \;, \tag{7}$$

- forearm with hand:

$$\begin{aligned}\dot{\vec{r}}_{CG3} &= (-r_2\sin\theta_1\dot{\theta}_1 - r_2\sin\theta_1\dot{\theta}_2 - c\sin\theta_3\dot{\theta}_3)i + \\ &+(r_1\cos\theta_1\dot{\theta}_1 + r_2\sin\theta_2\dot{\theta}_2 + c\sin\theta_3\dot{\theta}_3)j\end{aligned} \tag{8}$$

The total kinetic energy of the whole system is given by:

$$T(q,\dot{q}) = \frac{1}{2}(m_1v_1^2 + m_2v_2^2 + m_3v_3^2) + I_1\dot{\theta}_1 + I_2\dot{\theta}_2 + I_3\dot{\theta}_3) \tag{9}$$

Where v_1, v_2, v_3 are the absolute velocities of CG_1, CG_2 and CG_3, respectively. They was found by solving the equations (4), (5), (6). After simplification we have:

$$v_1 = \sqrt{a^2 \dot{\theta}_1^2} \tag{10}$$

$$v_2 = \sqrt{r_1^2 \dot{\theta}_1^2 + b^2 \dot{\theta}_2^2 + 2 r_1 b \dot{\theta}_1 \dot{\theta}_2 \cos(\theta_2 - \theta_1)} \tag{11}$$

$$\begin{aligned} v_3 = &\sqrt{r_1^2 \dot{\theta}_1^2 + r_2^2 \dot{\theta}_2^2 + c^2 \dot{\theta}_3^2 + 2 r_1 r_2 \dot{\theta}_1 \dot{\theta}_2 \cos(\theta_2 - \theta_1)} + \\ &+ \sqrt{2 r_1 c \dot{\theta}_1 \dot{\theta}_3 \cos(\theta_1 + \theta_3) + 2 r_2 c \dot{\theta}_2^2 \dot{\theta}_3 \cos(\theta_2 + \theta_3)} \end{aligned} \tag{12}$$

Substituting equations (10), (11), (12) into equation (9) we get following equation for the total kinetic energy of the system:

$$\begin{aligned} T(q,\dot{q}) = &\frac{1}{2}(m_1 a^2 + m_2 r_1^2 + m_3 r_1^2 + I_1)\dot{\theta}_1^2 + \frac{1}{2}(m_2 b^2 + m_3 r_2^2 + I_2)\dot{\theta}_2^2 + \frac{1}{2}(m_3 c^2 + I_3)\dot{\theta}_3^2 + \\ &+ r_1(m_2 b + m_3 r_2)\cos(\theta_2 - \theta_1)\dot{\theta}_2 \dot{\theta}_3 + \\ &+ m_3 r_1 c \cos(\theta_1 + \theta_3)\dot{\theta}_1 \dot{\theta}_3 + m_3 r_2 c \cos(\theta_2 + \theta_3)\dot{\theta}_2 \dot{\theta}_3 \end{aligned} \tag{13}$$

Potential energy of the system is expressed by the following formula:

$$V(q) = m_1 g h_{CG1} + m_2 g h_{CG2} + m_3 g h_{CG3}, \tag{14}$$

where $h_{CGi}, i = 1,2,3$ is the height of center of gravity of i^{th} link. The respective values are as follows:

$$h_{CG1} = a \sin\theta_1 \tag{15}$$

$$h_{CG2} = r_1 \sin\theta_1 + b \sin\theta_2 \tag{16}$$

$$h_{CG3} = r_1 \sin\theta_1 + r_2 \sin\theta_2 + c \sin\theta_3 \tag{17}$$

Substituting equations (15), (16), (17) into equation (14), we obtained the total potential energy of the system as:

$$V(q) = (m_1 a + m_2 r_1 + m_3 r_1) g \sin\theta_1 + (m_2 b + m_3 r_2) g \sin\theta_2 + m_3 g c \sin\theta_3) \tag{18}$$

The Lagrangian of the system has the form:

$$L(q,\dot{q}) = T(q,\dot{q}) - V(q) \tag{19}$$

Substituting equations (13) and (18) into equation (19) we get

$$
\begin{aligned}
L(q,\dot{q}) = {} & \frac{1}{2}(m_1a^2 + m_2r_1^2 + m_3r_3^2 + I_1)\dot{\theta}_1^2 + \frac{1}{2}(m_2b^2 + m_3r_2^2 + I_2)\dot{\theta}_2^2 + \\
& + \frac{1}{2}(m_3c^2 + I_3)\dot{\theta}_3^2 + + r_1(m_2b + m_3r_2)\cos(\theta_2 - \theta_1)\dot{\theta}_2\dot{\theta}_3 + \\
& m_3r_1c\cos(\theta_1 + \theta_3)\dot{\theta}_1\dot{\theta}_3 + m_3r_2c\cos(\theta_2 + \theta_3)\dot{\theta}_2\dot{\theta}_3 - \\
& + (m_1a + m_2r_1 + m_3r_1)g\sin\theta_1 - (m_2b + m_3r_2)g\sin\theta_2 - m_3gc\sin\theta_3)
\end{aligned}
\tag{20}
$$

To find the dynamic equations of the system we have to compute partial derivatives of the Lagrangian (20):

$$
\begin{aligned}
\frac{\partial L}{\partial \theta_1} = {} & r_1(m_2b + m_3r_2)\sin(\theta_2 - \theta_1)\dot{\theta}_1\dot{\theta}_2 - \\
& + m_3r_1c\sin(\theta_1 + \theta_3)\dot{\theta}_1\dot{\theta}_3 - (m_1a + m_2r_1 + m_3r_1)g\cos\theta_1
\end{aligned}
\tag{21}
$$

$$
\begin{aligned}
\frac{\partial L}{\partial \theta_2} = {} & -r_1(m_2b + m_3r_2)\sin(\theta_2 - \theta_1)\dot{\theta}_1\dot{\theta}_2 - \\
& + m_3r_2c\sin(\theta_2 + \theta_3)\dot{\theta}_2\dot{\theta}_3 - (m_2b + m_3r_2)g\cos\theta_2
\end{aligned}
\tag{22}
$$

$$
\frac{\partial L}{\partial \theta_3} = -m_3r_1c\sin(\theta_1 + \theta_3)\dot{\theta}_1\dot{\theta}_3 - m_3r_2c\sin(\theta_2 + \theta_3)\dot{\theta}_2\dot{\theta}_3 - m_3gc\cos\theta_3 \tag{23}
$$

$$
\begin{aligned}
\frac{\partial L}{\partial \dot{\theta}_1} = {} & (m_1a^2 + m_2r_1^2 + m_3r_1^2 + I_1)\dot{\theta}_1 + \\
& + r_1\ (m_2b + m_3r_2)\cos(\theta_2 - \theta_1)\dot{\theta}_2 + m_3r_1c\cos(\theta_1 + \theta_2)\dot{\theta}_3
\end{aligned}
\tag{24}
$$

$$
\begin{aligned}
\frac{\partial L}{\partial \dot{\theta}_2} = {} & (m_2b^2 + m_3r_2^2 + I_2)\dot{\theta}_2 + r_1\ (m_2b + m_3r_2)\cos(\theta_2 - \theta_1)\dot{\theta}_2 + \\
& + m_3r_1c\cos(\theta_2 + \theta_3)\dot{\theta}_3
\end{aligned}
\tag{25}
$$

$$
\frac{\partial L}{\partial \dot{\theta}_3} = (m_3c^2 + I_3)\dot{\theta}_3 + m_3r_1\ c\cos(\theta_1 + \theta_3)\dot{\theta}_1 + m_3r_2c\cos(\theta_2 + \theta_3)\dot{\theta}_2 \tag{26}
$$

$$
\begin{aligned}
\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}_1}\right) = {} & (m_1a^2 + m_2r_1^2 + m_3r_1^2 + I_1)\ddot{\theta}_1 + r_1(m_2b + m_3r_2\ )\cos(\theta_2 - \theta_1)\ddot{\theta}_2 \\
& - r_1(m_2b + m_3r_2\ )\sin(\theta_2 - \theta_1)(\dot{\theta}_2 - \dot{\theta}_1)\dot{\theta}_2 + m_3r_1\cos(\theta_1 + \theta_3)\ddot{\theta}_3 \\
& - m_3r_1c\sin(\theta_1 + \theta_3)(\dot{\theta}_1 + \dot{\theta}_3)\dot{\theta}_3
\end{aligned}
\tag{27}
$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}_2}\right) = (m_2 b + m_3 r_2^2 + I_2)\ddot{\theta}_1 + r_1(m_2 b + m_3 r_2)\cos(\theta_2 - \theta_1)\ddot{\theta}_2$$
$$-r_1(m_2 b + m_3 r_2)\sin(\theta_2 - \theta_1)(\dot{\theta}_2 - \dot{\theta}_1)\dot{\theta}_1 + m_3 r_2 \cos(\theta_2 + \theta_3)\ddot{\theta}_3 \tag{28}$$
$$-m_3 r_2 c \sin(\theta_2 + \theta_3)(\dot{\theta}_2 + \dot{\theta}_3)\dot{\theta}_3$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}_3}\right) = (m_3 c^2 + I_3)\ddot{\theta}_3 + m_3 r_1 c \cos(\theta_1 + \theta_3)\ddot{\theta}_1$$
$$-m_3 r_1 c \sin(\theta_1 + \theta_3)(\dot{\theta}_1 + \dot{\theta}_3)\dot{\theta}_1 + m_3 r_2 c \cos(\theta_2 + \theta_3)\ddot{\theta}_3 \tag{29}$$
$$-m_3 r_2 c \sin(\theta_2 + \theta_3)(\dot{\theta}_2 + \dot{\theta}_3)\dot{\theta}_2$$

Assuming that the dissipation of the system comes from friction in the joints, we get the following relation:

$$\Delta(\dot{q}) = \frac{1}{2}[k_1\dot{\theta}_1^2 + k_2(\dot{\theta}_2^2 - \dot{\theta}_1^2) + k_3(\dot{\theta}_3^2 - \dot{\theta}_2^2)] \tag{30}$$

Partial differentiation of the equation (30) yields:

$$\frac{\partial \Delta}{\partial \dot{\theta}_1} = (k_1 + k_2)\dot{\theta}_1 - k_2\dot{\theta}_2 \tag{31}$$

$$\frac{\partial \Delta}{\partial \dot{\theta}_2} = (k_2 + k_3)\dot{\theta}_2 - k_2\dot{\theta}_1 - k_3\dot{\theta}_3 \tag{32}$$

$$\frac{\partial \Delta}{\partial \dot{\theta}_3} = k_3(\dot{\theta}_3 - \dot{\theta}_2) \tag{33}$$

Substituting equations (21)-(33) into equation (2), one gets the following dynamic equations of three parts human body model:

$$\begin{aligned}
&(m_1 a^2 + m_2 r_1^2 + m_3 r_1^2 + I_1)\ddot{\theta}_1 + r_1(m_2 b + m_3 r_2)\cos(\theta_2 - \theta_1)\ddot{\theta}_2 \\
&+ m_3 r_1 c \cos(\theta_1 + \theta_3)\ddot{\theta}_3 - r_1(m_2 b + m_3 r_2)\sin(\theta_2 - \theta_1)\ddot{\theta}_2 \\
&- m_3 r_1 c \sin(\theta_1 + \theta_3)\dot{\theta}_3^2 + (m_1 a + m_2 r_1 + m_3 r_1) g \cos\theta_1 = -(k_1 + k_2)\dot{\theta}_1 - k_2\dot{\theta}_2
\end{aligned} \tag{34}$$

$$\begin{aligned}
&(m_2 b^2 + m_3 r_2^2 + I_2)\ddot{\theta}_2 + r_1(m_2 b + m_3 r_2)\cos(\theta_2 - \theta_1)\ddot{\theta}_1 \\
&+ r_1(m_2 b + m_3 r_2)\sin(\theta_2 - \theta_1)\dot{\theta}_1 + \\
&m_3 r_2 c \cos(\theta_2 + \theta_3)\ddot{\theta}_3 - m_3 r_2 c \sin(\theta_2 + \theta_3)\dot{\theta}_3^2 + \\
&+ (m_2 b + m_3 r_2) g \cos\theta_2 = -(k_2 + k_3)\dot{\theta}_2 + k_2\dot{\theta}_1 + k_3\dot{\theta}_3
\end{aligned} \tag{35}$$

$$\begin{aligned}
&(m_3 c^2 + I_3)\ddot{\theta}_3 + m_3 r_1 c \cos(\theta_1 + \theta_3)\ddot{\theta}_1 \\
&- m_3 r_1 c \sin(\theta_1 + \theta_3)\dot{\theta}_1^2 + m_3 r_2 c \cos(\theta_2 + \theta_3)\ddot{\theta}_2 \\
&- m_3 r_2 c \sin(\theta_2 + \theta_3)\dot{\theta}_2^2 + m_3 g c \cos\theta_3 = -k_3(\dot{\theta}_3 - \dot{\theta}_2)
\end{aligned} \tag{36}$$

Figure 2 presents the Simulink diagram used to solve the equations (34), (35) and (36). The results obtained in this way was validated using Simmechanic module of Matlab (Figure 3).

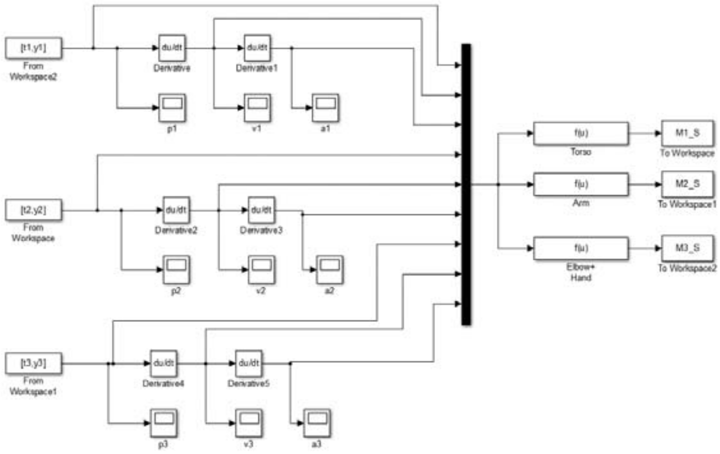


Figure 2. Simulink diagram used to simulate the dynamical system.

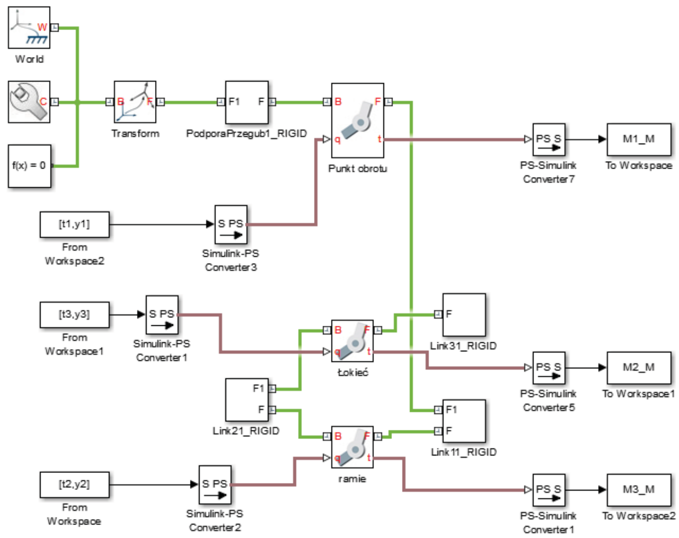


Figure 3. Simmechanic diagram used to simulate the dynamical system.

3. Results

A *sin*e function has been used as an input for calculation of the angular position of each link at the time. The sine input function is presented in Figure 4. Each joint is actuated individually with the sine function as an angular displacement about rotational axis z_i, where $i=1,2,3$. Continuous line (y1) represents angular position of link 1 (torso with legs), dotted-dashed line (y2) denotes angular position of link 2 (arm), and fine dashed line (y3) shows angular position of link 3 (forearm with hand).

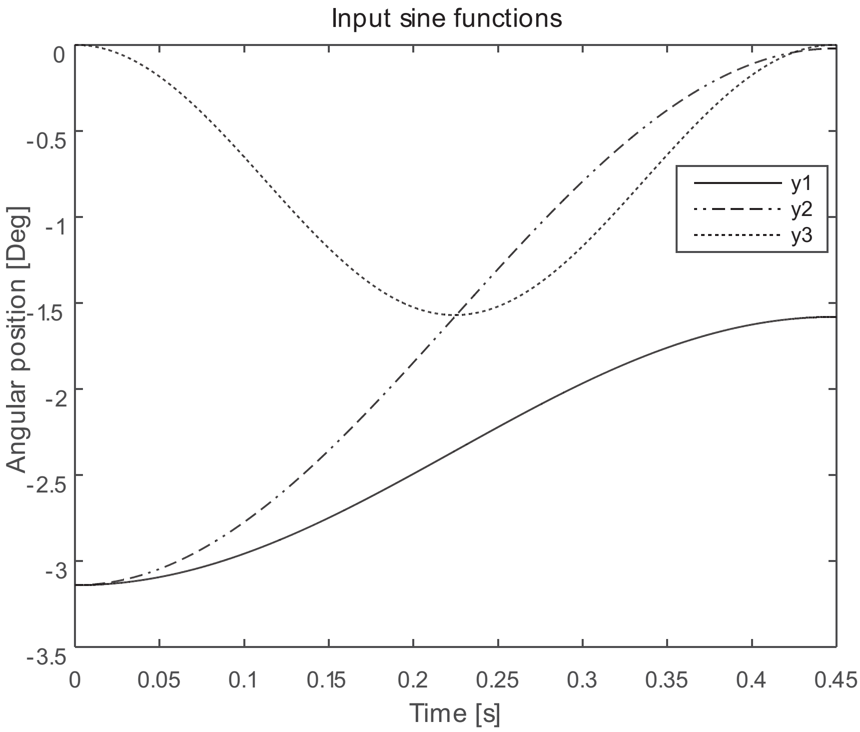
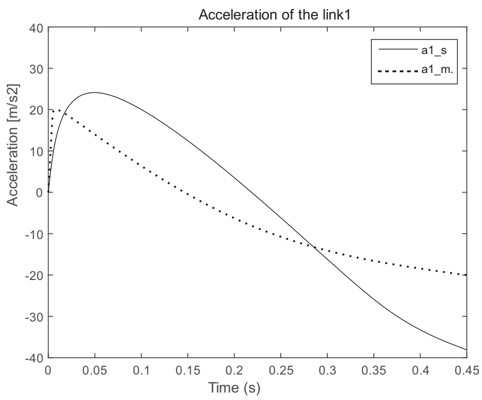


Figure 4. Angular input function.

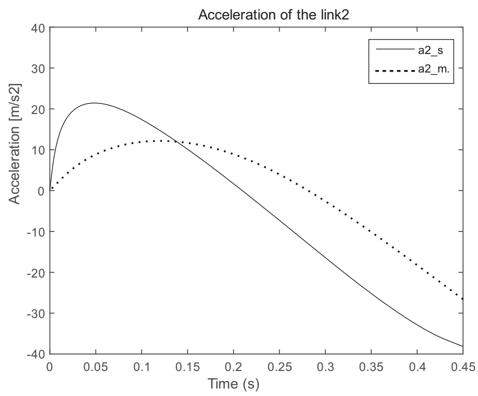
The figure above shows the simulated movement of the torso with legs, where ankle, shoulder and elbow joints are actuated. The functions were chosen in order to reflect the movement of the human body during the forward fall. The simulation time corresponds to the movement of the body without external forces, only under the action of the force of gravity.

Table 1. Model parameters of the simulated system.

		Body parts		
		Torso with legs	Arm	Forearm with hands
Parameters	r_i [m]	1.80	0.3	0.4
	a [m]	0.861	-	-
	b [m]	-	0.15	-
	c [m]	-	-	0.2
	m_i [kg]	66	2.4	1.9
	I_i [kg m^2]	21.564	0.015	0.017
	k_i	0.01	0.01	0.01



a)



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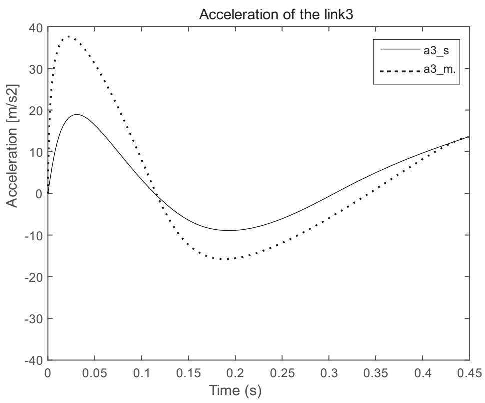
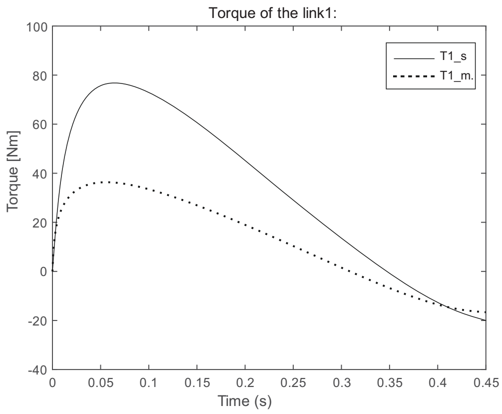
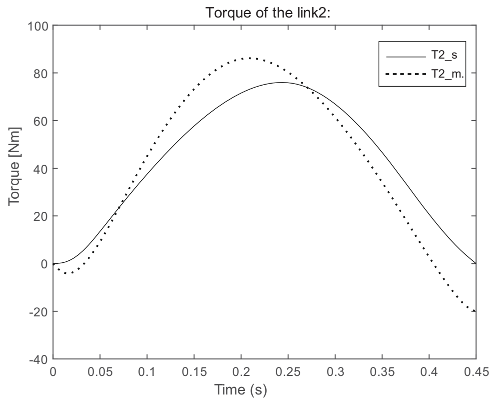


c)

Figure 5. Accelerations of the links' centers of gravity: a) torso with legs, b) shoulder, c) forearm with hands.



a)



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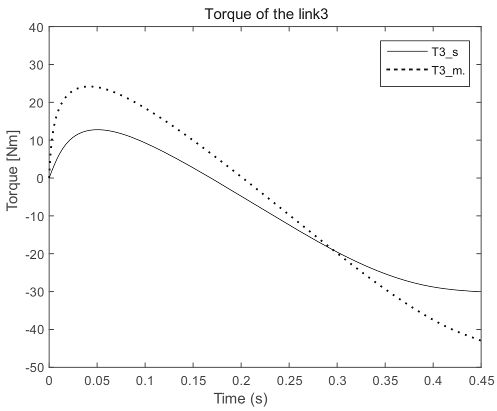

c)

Figure 6. Torques applied to the links: a) torso with legs, b) shoulder, c) forearm with hands.

The diagrams on the figures 5 and 6 present accelerations and torques, respectively. Figures 5a and 6a refer to CG_1 of torso with legs body part, figures 5b and 6b to CG_2 of arm, figures 5c and 6c to CG_3 of forearm. The subscripts *m* and *s* occurring in diagrams' description denote values obtained using Simulink and Simmechanic programs, respectively.

4. Conclusions

Modelling of the upper limb is important for better understanding of the relationship between different kinds of motion parameters and generated internal forces. The proposed model, although very simplified, gives some insight on the possible human dynamic behavior under the influence of various forces acting on a man, during his locomotion, for example. The model discussed in this study was built to identify the problems arising from modelling in general and the issues concerning the forward dynamics simulation. In the results of the forward model, it could be seen that the initial conditions are of extreme importance. The aim of this research was to develop a dynamic model of the human upper limb and to evaluate this model by adopting an appropriate motion analysis system to verify hypotheses of the established motion during forward fall and to determine the torque in each joint of the upper limb for further verification studies.

Comparison of the results of the motion simulation during forward fall, obtained using both Simulink and Simmechanic methods, showed good consistency. The little discrepancies in the results may be due to minor differences in the geometric model built in Simmechanic and its mathematical description.

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