Joint torque estimation during a squat motion.

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Résumé :

Un mouvement répété sur une longue période, l'accoutumance à une mauvaise posture, la manipulation de charges lourdes peuvent entraîner des troubles musculo-squelettiques (TMS). Il est important de prévenir les TMS en automatisant les tâches répétitives. Mais il est également nécessaire d'aider un patient en phase de rééducation lorsqu'une TMS apparait. En ce qui concerne le système musculo-squelettique humain, les couples articulaires développés par les muscles sont utiles pour prévenir ou traiter les TMS. La connaissance de ces couples est importante pour évaluer les possibilités d'assister une articulation avec une orthèse par exemple. Dans cette étude, nous analysons un mouvement de demi-squat spécifique considéré comme un mouvement planaire. Les couples articulaires sont estimés à l'aide de deux modèles : un modèle 3D sur Opensim et un modèle 2D sur Matlab. Les variations de couple issues des deux modèles sont cohérentes même si les amplitudes diffèrent. Ce résultat s'explique par le fait que les modèles se basent sur des tables anthropométriques différentes. Une autre stratégie développée ici consiste à estimer les couples articulaires sans utiliser la mesure des forces de réaction du sol sur les pieds. Dans ce cas, la force de réaction verticale totale est bien estimée. L'utilisation du modèle 2D Matlab est un moyen simple et efficace d'analyser préalablement les trajectoires de squat.

Abstract :

A repetitive movement over a long period of time, habituation to poor posture, handling heavy load can lead to musculoskeletal disorders. The most important thing is to prevent MSDs by automating repetitive tasks. But it is also necessary to help a patient with rehabilitation when an MDS has appeared. Regarding the human musculoskeletal system of movement analyses, joint torques developed by muscles are useful to prevent or treat MSDs. The knowledge of these torques is important to evaluate the possibilities of assisting a joint with an orthosis for instance. In this study, we analyze a specific half squat motion considered as a planar movement. Joint torques are estimated with two models -a 3D Opensim and a 2D Matlab model. Torque variations from the two models are consistent even if the amplitudes differ. This result is attributable to the different anthropometric tables which the two models are based on. Another strategy developed here consists in estimating joint torques without the measured ground reaction forces. In that case, global vertical reaction force is well estimated. The use of the 2D Matlab model is a simple and efficient way to preliminarily analyze squat trajectories.

Keywords : squat/robotics/motion capture/force plate

Nomenclature

$\mathbf{\Gamma}$	Joint torques vector	$N.m$
$\mathbf{B}$	Constant matrix composed of 0, 1 and -1	
$\mathbf{B}^+$	Pseudo-inverse matrix of $\mathbf{B}$	
$\mathbf{C}$	Coriolis effect matrix	
$\mathbf{D}$	Symmetric positive inertia matrix	
$\mathbf{G}$	Gravity effect vector	
$\mathbf{J}_i$	Jacobian matrix expressed at A_i	
$\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}}$	Generalized parameters vector and its time derivatives	
A_i	Ground projection of foot i	
H	Height of the subject	m
$\mathrm{H_a}$	Length between the hip and the shoulders	m
$\mathrm{H_f}$	Height of the foot	m
I_j	Moment of inertia of the segment j in the sagittal plane	$kg.m^{-2}$
$\mathrm{L_d}$	Length between A_i and the heel of foot i	m
$\mathrm{L_f}$	Length of the foot i ($\mathrm{L_f} = \mathrm{L_d} + \mathrm{L_p}$)	m
$\mathrm{L_p}$	Length between A_i and the toe of foot i	m
L_j	Length of the segment j	m
M	Mass of the subject	kg
m_j	Mass of the segment j	kg
N	Total number of squat cycles during the experiment	
P_i	Center of pressure position of the foot i	
$\mathrm{sf}_x, \mathrm{sf}_y$	Center of mass position of the foot	
s_j	Center of mass position of the segment j	m
T	Duration of the squat cycle	s
$\widetilde{\mathbf{\Gamma}}$	Joint torques vector estimated	$N.m$
g	Standard gravity	$9.81\, m.s^{-2}$
$\mathbf{r}_i$	Ground reaction wrench expressed at A_i	
$\mathrm{R}_x, \mathrm{R}_y$	Global ground reaction forces	N

1 Introduction

A repetitive movement over a long period of time, habituation to poor posture, handling heavy load can lead to musculoskeletal disorders (*MSDs*). They are the leading cost drivers in the workers compensation system [1]. The most important thing is to prevent MSDs by automating repetitive tasks. Another solution is to assist the operator with a passive exoskeleton [2] to maintain posture or active [3], [4]. But it is also necessary to help a patient with rehabilitation when an MDS has appeared [5]. Regarding the human musculoskeletal system of movement analyses, joint torques developed by muscles are useful to prevent or treat MSDs. Often for these analyses the squat movement is routinely prescribed by physical therapists and sport medicine physicians [6]. In this paper authors demonstrate a technique to calculate the EMG instantaneous median frequency to assess muscle fatigue during a dynamic exercise commonly prescribed in patients with an anterior cruciate ligament deficiency. There are a lot of studies, which are based on the squat movement. Without being exhaustive we can mention the following interesting works. Hwang $et\ al$ [7] show that for two different symmetrical lifting techniques squat and stoop, there are no significant differences in maximum lumbar joint moments. Bonnet $et\ al$ [8] estimate in real-time the lower-limb joint and torso kinematics by using a single inertial measurement unit placed on the lower back. Wei $et\ al$ [9] compare the kinematics of young and elderly subjects during normal squatting activity. They observe that the elderly enjoys more hip flexion/extension angles than the young, with the squatting posture assumed. Their purpose is to establish a standard of designing lower extremity prosthesis.

These studies focus mainly on the kinematics of movement. However, there is no investigation into the estimation of joint torques developed by muscles. The knowledge of these torques is important to evaluate the possibilities of assisting a joint with an orthosis for example. Our study is also based on a squat movement. Considering that this movement takes place in the sagittal plane our strategy is to evaluate the torques with a simplified 2D model as follows. During the squat experimental data are recorded with a motion capture device and two force plates. An *Opensim* Model allows us to estimate the position, velocity and acceleration of the ankle, knee an hip joints of the human subject. The main advantage of musculoskeletal models is to provide a non-invasive means to study human movement [10], [11]. Then a simplified inverse dynamic model of a biped, taking into account explicitly the contact with the ground, is designed. Several cases are considered to compare the articular torques calculated thanks to a 2D model with the torques estimated with *OpenSim*. Our objective is to define an efficient but simple tool, which is based on the dynamical effects of the lower-limbs to size an orthosis. This paper is outlined as follows. Section 2 presents the used material and the methods. Section 3 are devoted to the analyze of the experimental and numerical results. Section 4 offers our conclusion and perspectives.

2 Materials and Methods

2.1 Squat motion

The squat movement studied is defined as a four-step cycle so that it can be repeated in a continuous loop by the subject. The total duration of that cycle is $T = 4s$ and each step lasts one second. In its initial state, the subject stands upright with his knees slightly bent (Figure 1a). The arms are stretched horizontally. The trunk is also slightly inclined with respect to the longitudinal axis. From this posture, the cycle is defined as follows :

1. The subject goes down bending his knees while keeping his arms straight and his trunk slightly inclined forward. At the end of this step, the subject's thighs are parallel to the ground in order to perform a half squat (Figure 1b).
2. This pose is then maintained before starting the ascent step.
3. The subject returns to the initial pose (Figure 1c).
4. The initial pose is maintained.

(a) Initial pose. (b) Intermediate pose. (c) Final pose.

FIGURE 1 – Initial, intermediate and final position of the squat motion defined.

2.2 Data acquisition

The Motion Capture experiment was conducted with a 25-year-old woman, height H = 1.73 m and mass M = 62 kg. A set of 17 marker arrays were placed on the subject's head, trunk, arms, legs and feet. During the movement, the spatial coordinates of the marker arrays were estimated by the ART IR acquisition system using eight cameras with an acquisition frequency of 60 Hz. Two force plates were used to measure the center of pressure of each foot of the subject on the ground as well as the ground reaction forces and moments.
A total of $N = 20$ squats were performed by the subject according to the motion defined in 2.1. To eliminate the measurement noise, we applied a Butterworth low-pass filter to all signals with a cut-off frequency of 5 Hz. From the data of the force plates and more specifically the global vertical ground reaction, a rupture detection method -the CUSUM algorithm [12]- was employed to detect initial cycle times. All data presented in Section 3 were therefore averaged with respect to the N cycles.

2.3 *Opensim* Model

The model developed on the software *Opensim* is based on the Rajagopal model [10]. It is a complete musculoskeletal model designed to perform dynamic simulations of human movement. For the dynamic analysis of squat movement, this model has been adapted with unilateral constraints between the ground and both feet so that they are in full flat contact with the ground (Fig. 2). Virtual markers are defined in respect to the different bodies of the model.

The estimation of the articular torques with this model is done in three steps. First, a scaling step is required to adjust the size, mass distribution and position of the *Opensim* model's virtual markers. From

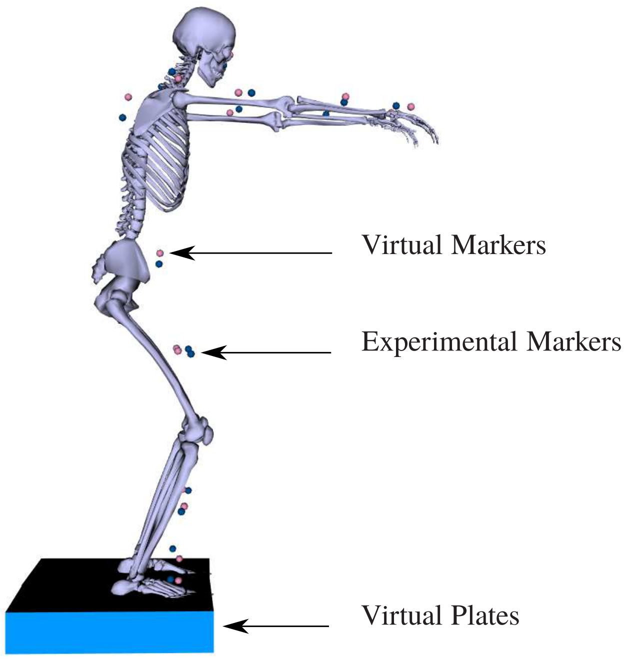


FIGURE 2 – Full-Body Musculoskeletal *Opensim* Model for the squat movement. Virtual markers are associated with bodies of the model and defined according to their anatomical landmarks. The platforms allow to model a flat contact between the ground and the feet of the model.

a static trial, the position data of the experimental markers are recorded via the motion capture system. Then, the position deviation between the experimental markers and their corresponding virtual marker is minimized in the sense of least squares. The optimization variables are the segment lengths.

Then, several squat trials are carried out by the subject. The position of the experimental markers are imported on *Opensim*. The inverse kinematic step consists in minimizing a least squares problem in order to model the motions performed. Finally, the inverse dynamic step enables the joint torques estimation from the forces measured by the force plates and the motions obtained by the inverse kinematic model.

2.4 *Matlab* Model

2.4.1 Anthropomorphic parameters

A 2D model of a nine-link planar biped is designed in order to evaluate the joint torques, which are developed during the squat motion. The physical parameters of this model are obtained from Winter's anthropometric table [13] by considering the height and weight of the subject. The planar biped has a trunk, two arms, two thighs, two shins and two feet, see Fig. 3. Table 1 lists the physical parameters used. For each segment $i = 1 \dots 9$, L_i corresponds to the segment length, m_i its mass, s_i defines its center of mass position and I_i its moment of inertia in respect of the sagittal plane.

To describe the biped configuration, we choose the following generalized vector $\mathbf{q}$:

$$\mathbf{q} = \left[q_1, q_2, q_3, q_4, q_5, q_6, q_7, q_{\mathrm{p}_1}, q_{\mathrm{p}_2}, x_{\mathrm{h}}, y_{\mathrm{h}}\right]$$

Its components are defined Fig. 3.

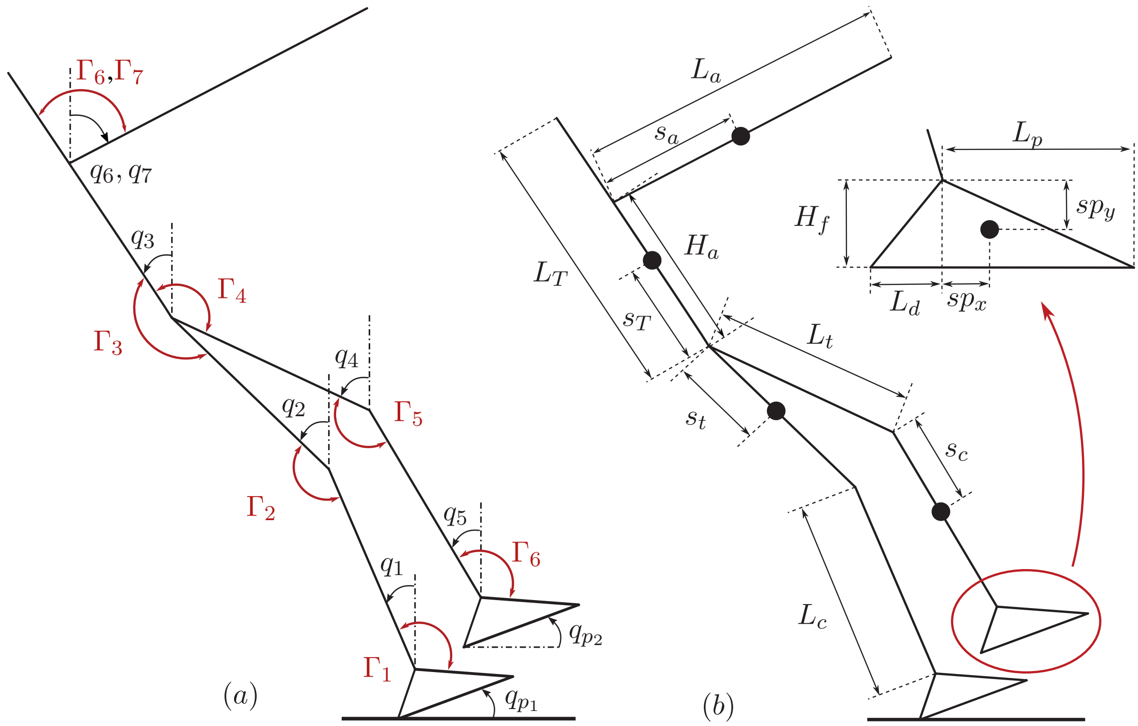


FIGURE 3 – Model of the planed biped. a) Parameterization of the biped. Note that angles are positive in counterclockwise. b) Length segments and position of centers of mass.

	Foot	Calf	Thigh	Trunk	Arm
Segment Weight (kg)	$m_f = 0.90$	$m_c = 2.88$	$m_t = 6.20$	$m_T = 35.8$	$m_a = 3.10$
Segment Length (m)	$L_f = 0.068$	$L_c = 0.426$	$L_t = 0.424$	$L_T = 0.813$	$L_a = 0.761$
	$L_d = 0.196$			$H_a = 0.498$	
	$H_f = 0.068$				
Inertia (kg.m^2)	$I_f = 0.0087$	$I_c = 0.0476$	$I_t = 0.1162$	$I_T = 2.2508$	$I_a = 0.1385$
Center of mass (m)	$sf_x = 0.098$	$s_c = 0.184$	$s_t = 0.184$	$s_T = 0.329$	$s_a = 0.304$
	$sf_y = 0.034$				

TABLE 1 – Anthropomorphic parameters of the human planar model.

2.4.2 Unilateral constraints between the ground and the stance foot

For the studied squat motion, both feet have a flat contact with the ground. In the sagittal plane, the action of the ground on each foot can be modeled as a wrench with three components, expressed at A_i, as illustrated in Figure 4 such as :

$$\mathbf{r}_i = \begin{bmatrix} r_{ix} \\ r_{iy} \\ M_{iz} \end{bmatrix}, \text{ for } i \in \{1, 2\}. \tag{1}$$

The contact is rigid, so that the conditions of feet flat contact on the ground can be written as in (2).

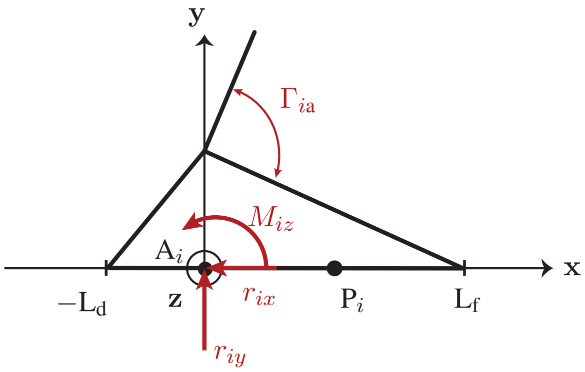


FIGURE 4 – Torques and forces acting on the foot.

$$\begin{bmatrix} x_{\mathrm{A}_i} \\ y_{\mathrm{A}_i} \\ q_{\mathrm{p}_i} \end{bmatrix} = \begin{bmatrix} 0 \\ -\mathrm{H_f} \\ 0 \end{bmatrix} \text{, for } i \in \{1,2\} \tag{2}$$

By deriving (2), we obtained the Jacobian matrices of contact between each foot and the ground, expressed in point A_i.

$$\mathbf{J}_i\dot{\mathbf{q}} = \mathbf{0}_{3\times1} \text{, for } i \in \{1,2\} \tag{3}$$

The non-rotation of the supporting feet reflects the dynamic equilibrium of the feet during the squat motion. This state can be described by the trajectory of the CoP of each foot. This particular point, let us call it P_i, represents the application point of the ground reaction forces such as $M_{iz} = 0$, for $i \in \{1,2\}$. That definition leads to :

$$x_{\mathrm{P}_i} = \frac{\Gamma_{ia} + \mathrm{m_f g s f}_x - \mathrm{H_f} r_{ix}}{r_{iy}} \text{, for } i \in \{1,2\} \tag{4}$$

$$-\mathrm{L_d} \leq x_{\mathrm{P}_i} \leq \mathrm{L_f} \text{, for } i \in \{1,2\} \tag{5}$$

The condition of dynamic equilibrium of the feet can be expressed by the inequalities of (5).

2.4.3 Dynamic model

The dynamic model of the nine-links planar model is defined as follows :

$$\mathbf{D}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{G}(\mathbf{q}) = \mathbf{B}\boldsymbol{\Gamma} + \mathbf{J}_1^\top\mathbf{r}_1 + \mathbf{J}_2^\top\mathbf{r}_2 \tag{6}$$

This model provides a link between the 8×1 joint torque vector $\boldsymbol{\Gamma}$, the 3×1 ground reaction wrenches $\mathbf{r}_1$ and $\mathbf{r}_2$ applied to respectively the feet 1 and 2, and the bodies motion defining the biped. $\mathbf{B}$ is a 11×8 matrix resulting from the writing of virtual works and is composed of 0, 1, and -1. MAtrices $\mathbf{J}_1^\top$ and $\mathbf{J}_2^\top$ are the 11×3 transposed jacobian matrices, which convert ground reaction wrenches at both feet 1 and 2 in torques applied to the different joints of the biped. $\mathbf{D}$ is the 11×11 symmetric positive inertia matrix, $\mathbf{C}$ is the 11×11 Coriolis effect matrix and $\mathbf{G}$ is the 11×1 gravity effect vector.

2.4.4 Calculation of the vector $\mathbf{\Gamma}$ of the joint torques and the ground reaction wrenches $\mathbf{r}_1$ and $\mathbf{r}_2$

By the means of the motion capture acquisition system, kinematic data related to the squat motion were recorded for each sampling time. Consequently, the left part of the dynamic equation (6) can be calculated. The unknown variables are the 8×1 joint torques vector $\mathbf{\Gamma}$ and the 3×1 ground reaction wrenches $\mathbf{r}_1$ and $\mathbf{r}_2$. Then, the global model can be considered as a system with 11 equations and 14 unknown variables.
By considering the sagittal plane as a symmetric plane for the motion and the distribution of masses, let us consider that $\mathbf{r}_1 = \mathbf{r}_2 = \mathbf{r}$. In this way, the inverse dynamic model can be totally resolved by using (7). Let us remark that the matrix $\begin{bmatrix}\mathbf{B} & \left(\mathbf{J}_1^\top + \mathbf{J}_2^\top\right)\end{bmatrix}$ has always been invertible in our numerical tests.

$$\begin{aligned}\begin{bmatrix}\mathbf{B} & \left(\mathbf{J}_1^\top + \mathbf{J}_2^\top\right)\end{bmatrix}\begin{bmatrix}\mathbf{\Gamma}\\ \mathbf{r}\end{bmatrix} &= \mathbf{D}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{G}(\mathbf{q})\\ \begin{bmatrix}\mathbf{\Gamma}\\ \mathbf{r}\end{bmatrix} &= \begin{bmatrix}\mathbf{B} & \left(\mathbf{J}_1^\top + \mathbf{J}_2^\top\right)\end{bmatrix}^{-1}\left(\mathbf{D}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{G}(\mathbf{q})\right)\end{aligned} \tag{7}$$

2.4.5 Calculation of the joint torque vector $\widetilde{\mathbf{\Gamma}}$ by the least mean squares estimation

During our trials, we were able to record the ground reaction forces applied to feet 1 and 2 by the means of two force plates. These data can be used to inverse the dynamic model (6). In that case, the global system has more equations than unknown variables. The least mean squares estimation allows us to estimate the joint torques $\widetilde{\mathbf{\Gamma}}$ with (8), where $\mathbf{B}^+$ is the 8×11 pseudo-inverse matrix of $\mathbf{B}$.

$$\widetilde{\mathbf{\Gamma}} = \mathbf{B}^+\left(\mathbf{D}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{G}(\mathbf{q}) - \mathbf{J}_1^\top\mathbf{r}_1 - \mathbf{J}_2^\top\mathbf{r}_2\right) \tag{8}$$

3 Results

3.1 Kinematic and force plates data of the squat motion

The data resulting from the motion capture session were imported into *Opensim*. The inverse kinematic model was solved according to Section 2.3 to obtain angular variable trajectories for each joint. For the use of the 2D *Matlab* planar model, motion trajectories have been projected in the sagittal plane. Figure 5 shows the angular positions and velocities of the projected motion according to parameters defined in Figure 3.
The analysis of the measured average trajectory of the pressure centre for the left and right foot is shown in Figure 6. For each of them, we can see the presence of a privileged direction. The trajectory of the global pressure centre -the average of the trajectories of the pressure centres for the left and right foot- evolves mainly along an axis parallel to the $\mathbf{x}$ axis. This result shows that the squat movement is a plane-type movement.

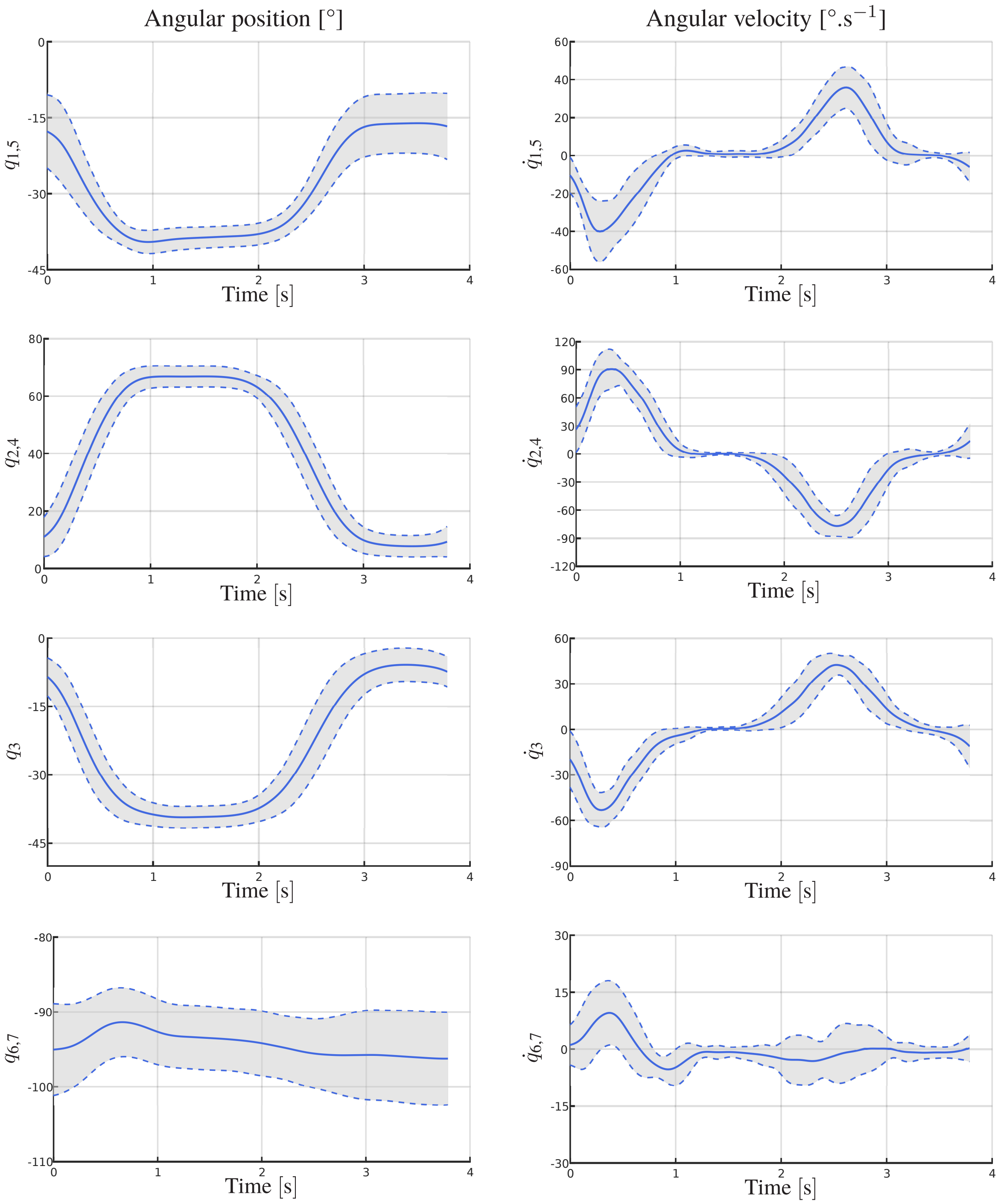


FIGURE 5 – Kinematic data of the squat motion realized. Angular positions and velocities are represented respectively on the left and right column. For each plot, the average trajectory is in solid line and the standard deviation envelope is delimited in dashed lines.

3.2 Comparison of the estimation of the joint torques between a 3D *Opensim* model and a 2D *Matlab* model.

From the motion obtained previously (see Section 3.1), inverse dynamic model has been first resolved with the 3D *Opensim* model. From the projected trajectories in the sagittal plane (see Figure 5), the resolution was carried out by using (8). Figures 7 and 8 illustrate the results obtained from both resolutions

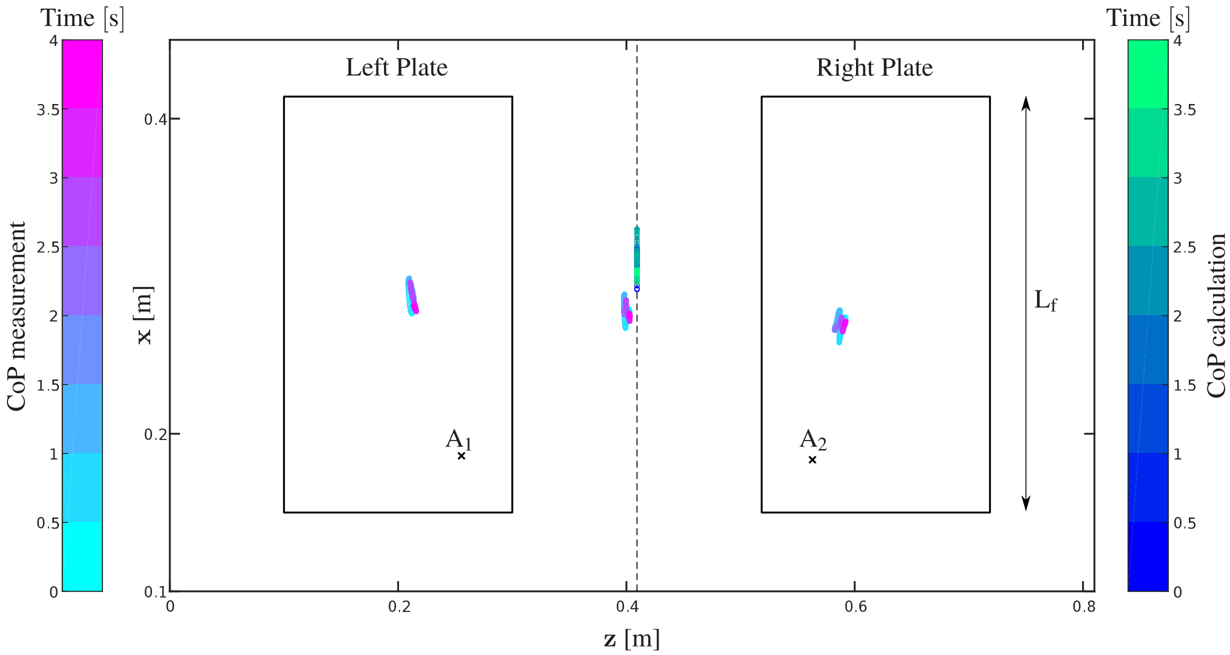


FIGURE 6 – Measured and calculated center of pressure trajectories. A_1 and A_2 corresponds to the left and right projected position of the ankle estimated with *Opensim*.

for the left and right sides of the human body respectively.

We can observe that the torque estimation made by the two models at the ankle and knee joints are almost the same for both left and right sides. Nevertheless, the hip torque estimation made by the *Matlab* model differs from the *Opensim* model. Variations in the anthropomorphic data used in both models can lead to these differences.

The few torques variations of both shoulders are due to the gravity effect in order to maintain a stable position.

3.3 2D *Matlab* solution

In a simulation approach, to study other squat trajectories, it may be interesting to solve the dynamic model by freeing us from the measured data. In this case, an assumption on the efforts distribution is necessary. As shown with (7), joint torques and reaction forces can be calculated by assuming that the subject distributes the forces equally over each of his feet. The global calculated reaction forces R_x and R_y are illustrated Figure 9 in green lines. Figure 10 shows the average measured distribution for each foot in blue lines.

From Figure 10, we can see that the magnitude of the vertical reaction is greater for the right foot than for the left one in average. This means that the subject uses the right foot to a higher extent during the experiment. Consequently, the assumption of equally distribution on both feet is not valid. Nevertheless, Figure 9 shows that the global vertical reaction is quite well estimated in average. The use of the 2D *Matlab* model combined with the extracted kinematic data is in accordance with the global external forces measured.

Under the assumption symmetric effort distribution, the calculated joint torques are the same at the left side of the human model than at the right one. By averaging the torques estimated by *Opensim* on the left side with those on the right side, we can compare the two models (Figures 7 and 8).

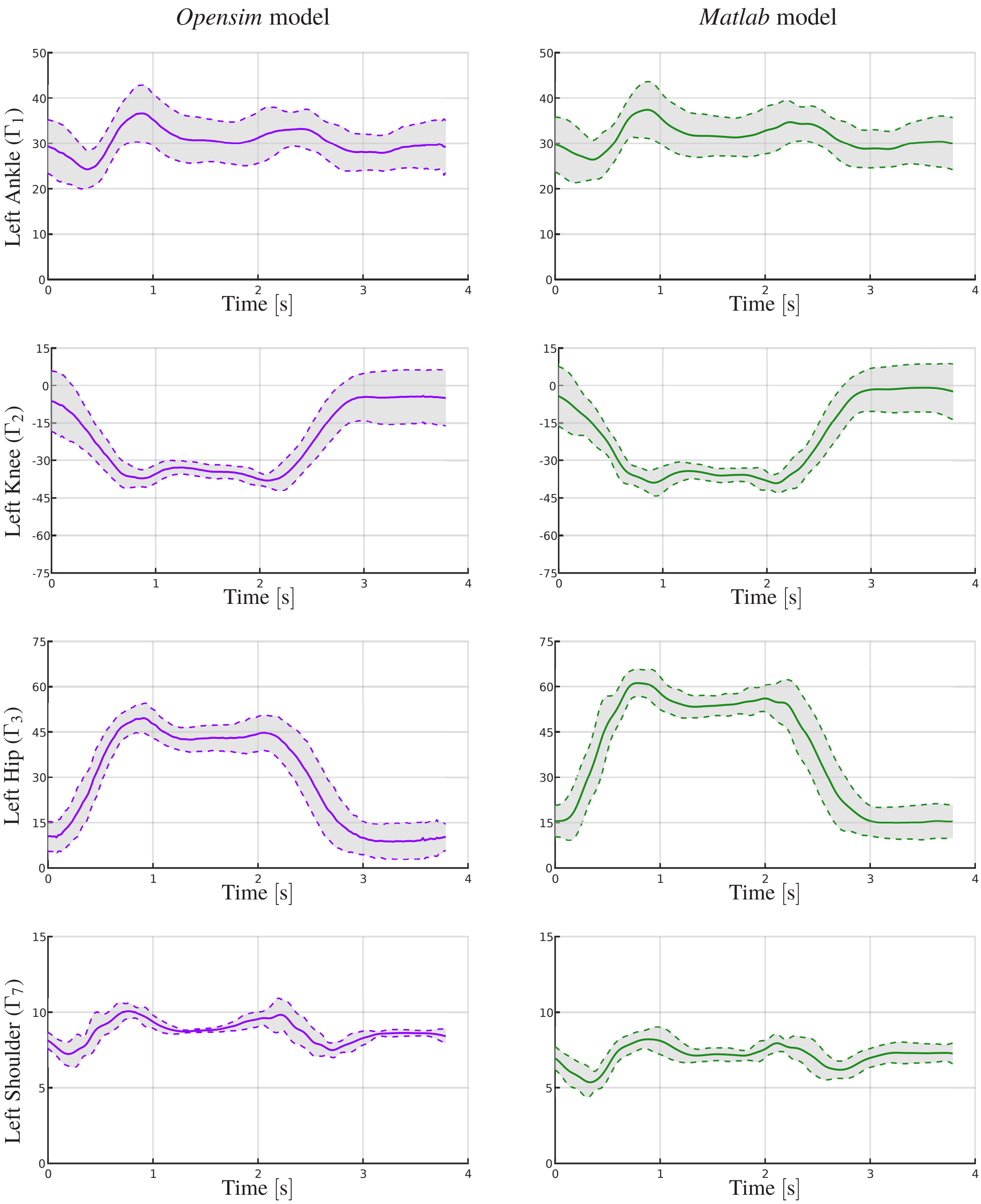


FIGURE 7 – Joint torques estimation of the squat motion realised (left side).

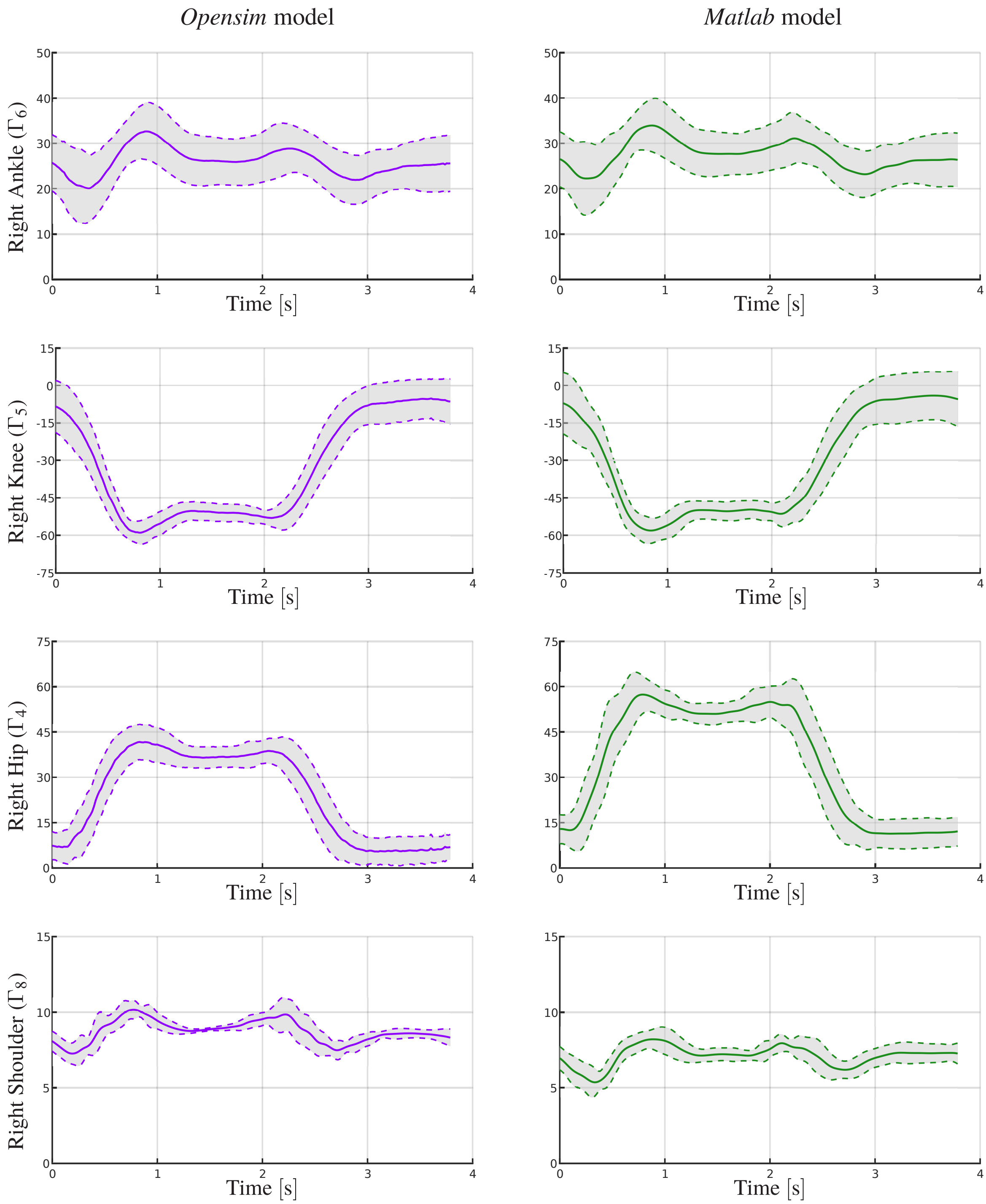


FIGURE 8 – Joint torque estimation of the squat motion realised (right side).

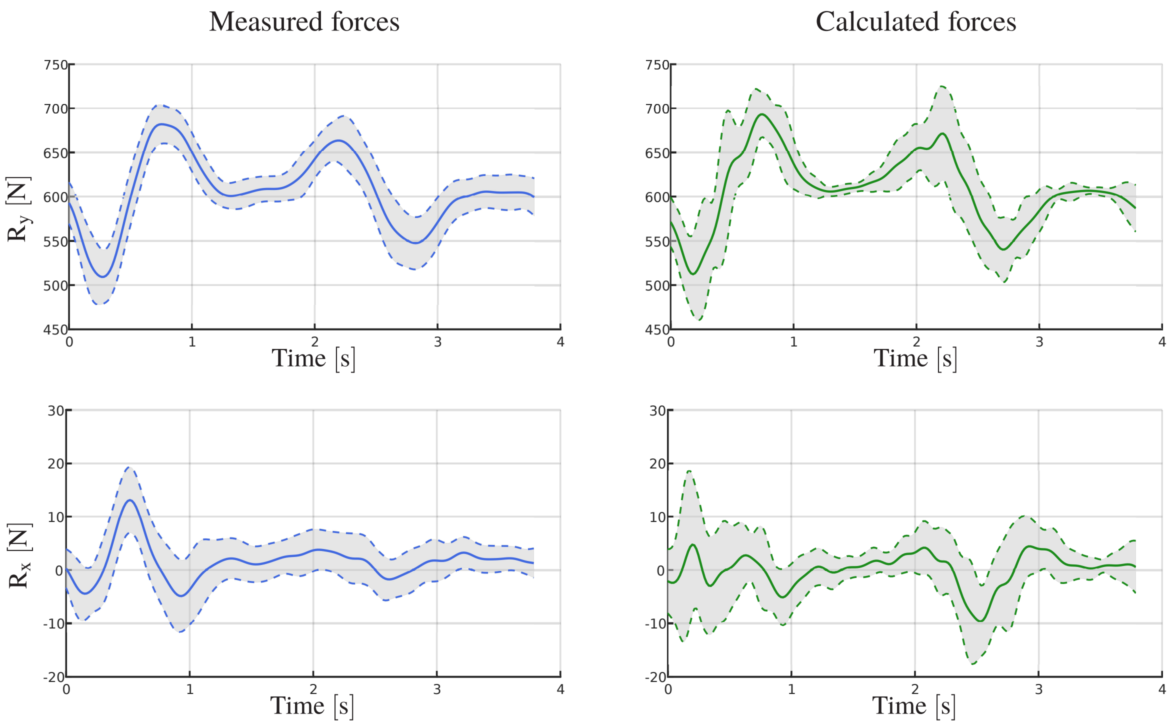
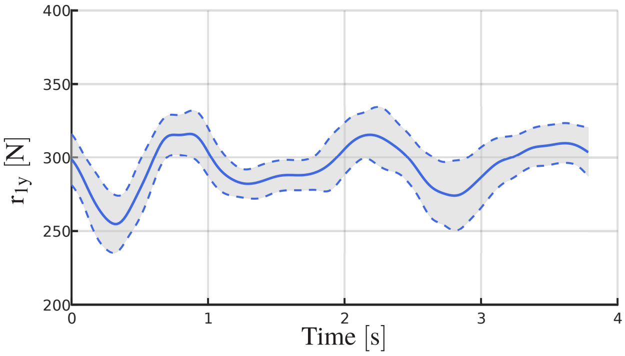


FIGURE 9 – Comparison between total measured forces and total calculated forces.

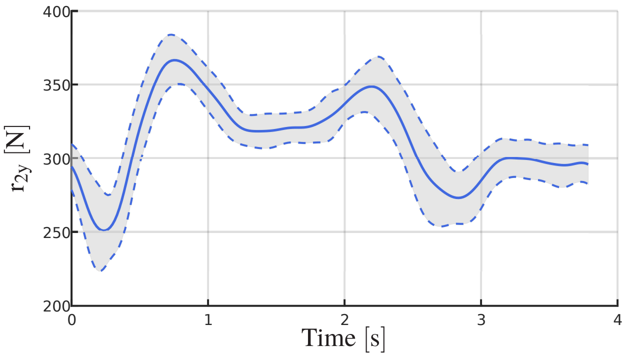
4 Conclusion

In this paper, a half squat movement has been studied. Joint trajectories and external forces have been reported for a complete squat cycle. These data were integrated into two distinct models : a 3D *Opensim* model and a *Matlab* planar model. An estimation of the joint torques was made in both cases. The analysis of this latter shows a coherence between the two models. It also highlights a variability according to the anthropometric data used.

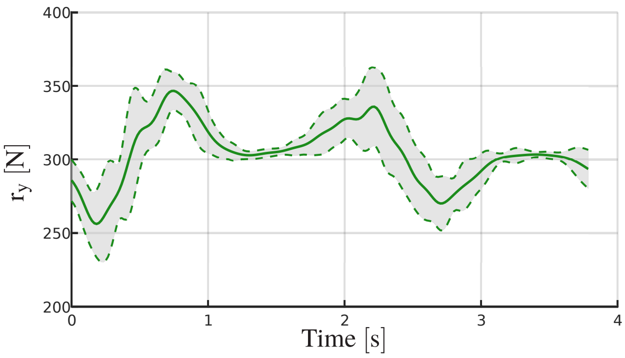
On the other hand, from the planar model, we have shown that it is possible to completely solve the inverse dynamic model by making an assumption on the distribution of forces. In this case, we saw that the total vertical reaction was well estimated. These results underline the interest of using a planar model for a squat movement.



(a) Left foot 1.



(b) Right foot 2.



(c) For each foot.

FIGURE 10 – Comparison between left and right foot vertical forces.

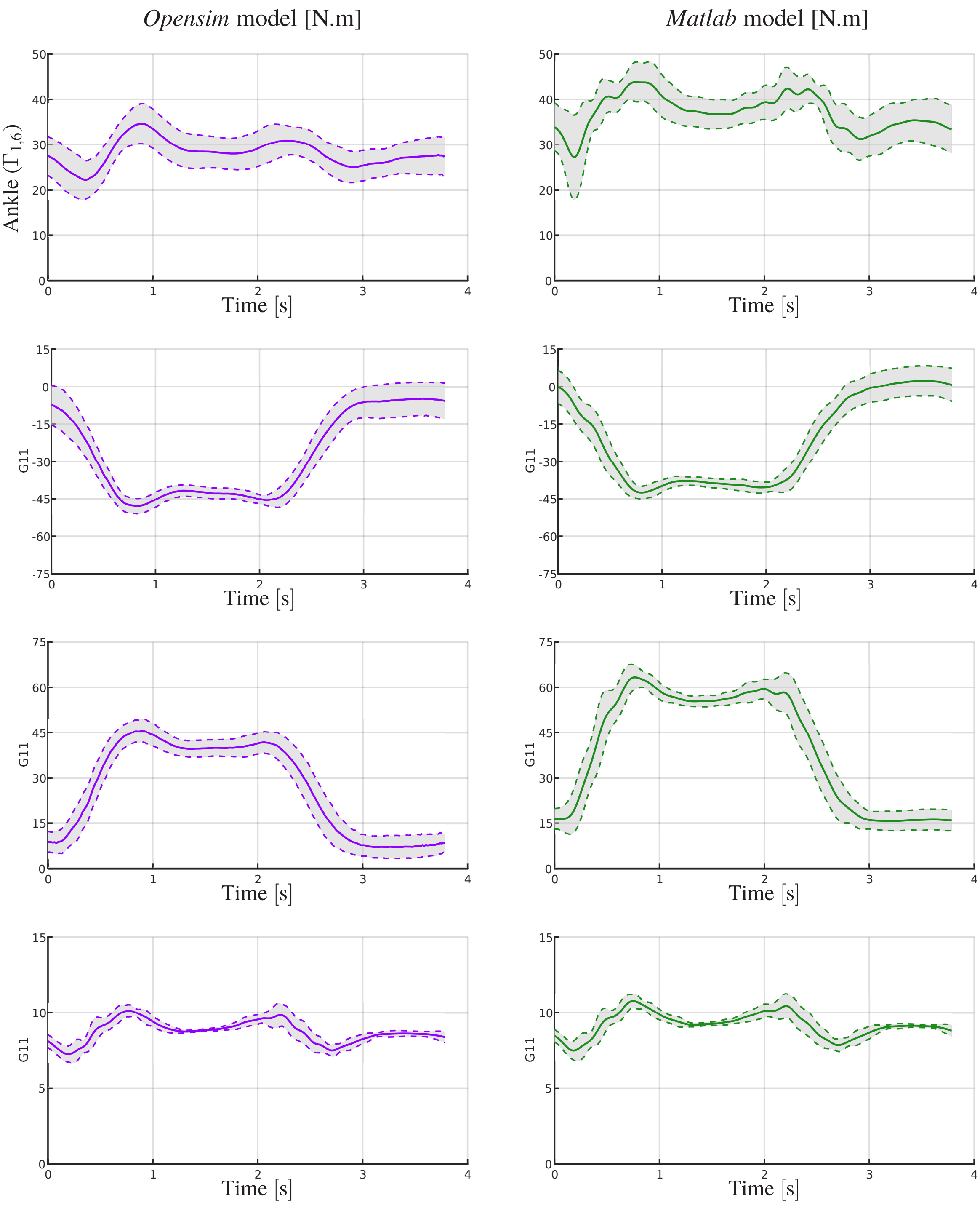


FIGURE 11 – Joint torques calculated by the *Matlab* model (green lines) and estimated by the *Opensim* model where left and right sides have been averaged (violet lines).

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