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Influence of the model's degree of freedom on human body dynamics identification

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Abstract— **In fields of sports and rehabilitation, opportunities of using motion analysis of the human body have dramatically increased. To analyze the motion dynamics, a number of subject specific parameters and measurements are required. For example the contact forces measurement and the inertial parameters of each segment of the human body are necessary to compute the joint torques. In this study, in order to perform accurate dynamic analysis we propose to identify the inertial parameters of the human body and to evaluate the influence of the model's number of degrees of freedom (DoF) on the results. We use a method to estimate the inertial parameters without torque sensor, using generalized coordinates of the base link, joint angles and external forces information. We consider a 34DoF model, a 58DoF model, as well as the case when the human is manipulating a tool (here a tennis racket). We compare the obtained in results in terms of contact force estimation.**

I. INTRODUCTION

Dynamics motion analysis of human behavior has been an active field of research and application in the past few years [1]. Simulating accurately human behavior has become an important asset in ergonomics, crash dynamics, sports, rehabilitation and even in the field human machine interface. The joint torque is often used as a computational index as it is directly related to muscle force and thus can provide information on motor control, energy consumption, fatigue and difficulty in achieving a task. To compute the joint torque, the motion information and the contact force with the environment must be measured; and an adequate model of the human body kinematics is required, as well as accurate inertial parameters information, which is subject specific. Joint angle can easily be obtained by using motion capture system. And contact forces can be measured using force sensors, and force-plates [2][3]. The kinematics of the human body model is often chosen as a compromise between the computational burden and the precision required by the analysis. Simple models may have only a few degrees of freedom, and their complexity can reach 150DoF [4][5]. However when the complexity increases the choice of the inertial parameters is also more delicate, as no prior information can be found in the literature.

To overcome this problem we proposed a method to identify the inertial parameters using motion and contact force information [6]. In our previous study we limited our model to 34DoF and validated the identifiability of the totality of the inertial parameters [7]. In the present paper using the same method we show that our method is also valid for more complex models of the human body. We present results for a 34DoF model, a 58DoF model, and a 34DoF model including tools (here a tennis racket), thus identifying also the dynamics of the tool that is manipulated. We therefore extend our results and generalized them for a broad use of individual inertial parameters, as well as tool inertial parameters' identification, that can be used for accurate human body modeling and simulations.

II. IDENTIFYING DYNAMICS WITH JOINT ANGLES AND CONTACT FORCE INFORMATION

A. Identification model of humanoid robots

The inverse dynamics (equation of motion) of any multibody system can be written in a linear form with respect to the inertial parameters. Thus the equations of motion of a legged system, composed of *n* rigid bodies and that has N_j degrees of freedom (DOF), is given by Eq. (1) [8][9][10].

$$\boldsymbol{Y}_A\boldsymbol{\Phi} = \begin{bmatrix}\boldsymbol{Y}_O\\ \boldsymbol{Y}_C\end{bmatrix}\boldsymbol{\Phi} = \begin{bmatrix}\boldsymbol{0}\\ \boldsymbol{\tau}\end{bmatrix} + \sum_{k=1}^{N_C}\begin{bmatrix}\boldsymbol{K}_{Ok}^T\\ \boldsymbol{K}_{Ck}^T\end{bmatrix}\boldsymbol{F}_k^{ext} \qquad (1)$$

where $\boldsymbol{\Phi} \in \boldsymbol{R}^{10n}$ is the vector of constant inertial parameters. $\boldsymbol{Y}_A \triangleq [\boldsymbol{Y}_O^T\ \boldsymbol{Y}_C^T]^T \in \boldsymbol{R}^{N_J\times 10n}$ is called regressor, and is a function matrix of generalized coordinates and derivatives of the base-link and joints. $\boldsymbol{Y_O} \in \boldsymbol{R}^{6\times 10n}$ is the regressor matrix corresponding in the six equations of motion of the base-link (or reference link that moves freely in the 3D space). $\boldsymbol{\tau} \in \boldsymbol{R}^{N_J-6}$ is the vector of joint torques. N_C is the number of contact points with the environment. $\boldsymbol{F}_k^{ext} \in \boldsymbol{R}^6$ is the vector of external forces exerted on the robot at the contact point *k*. $\boldsymbol{K}_k \triangleq [\boldsymbol{K}_{Ok}\ \ \boldsymbol{K}_{Ck}]^T \in \boldsymbol{R}^{6\times N_J}$ is the Jacobian matrix of the position at the contact point *k* and of the orientation of the contact link with respect to the generalized coordinates, which is used to map $\boldsymbol{F}_k^{ext}$ to the vector of generalized force.

Only the minimal-set of inertial parameters, which describes the dynamics of the system, can be identified straightforwardly without a-priori knowledge. This minimal-set is called base parameters $\boldsymbol{\Phi}_B \in \boldsymbol{R}^{N_B}$. It is obtained symbolically from $\boldsymbol{\Phi}$ by eliminating those that have no influence on the dynamics and regrouping them according to the kinematics of the system. The minimal identification model given by Eq. (2) is thus obtained. $\boldsymbol{Y}_{AB} \in \boldsymbol{R}^{N_J\times N_B}$ is the regressor for the base parameters.

$$\boldsymbol{Y}_{AB}\boldsymbol{\Phi}_B = \begin{bmatrix}\boldsymbol{Y}_{OB}\\ \boldsymbol{Y}_{CB}\end{bmatrix}\boldsymbol{\Phi}_B = \begin{bmatrix}\boldsymbol{0}\\ \boldsymbol{\tau}\end{bmatrix} + \sum_{k=1}^{N_C}\begin{bmatrix}\boldsymbol{K}_{Ok}^T\\ \boldsymbol{K}_{Ck}^T\end{bmatrix}\boldsymbol{F}_k^{ext} \qquad (2)$$

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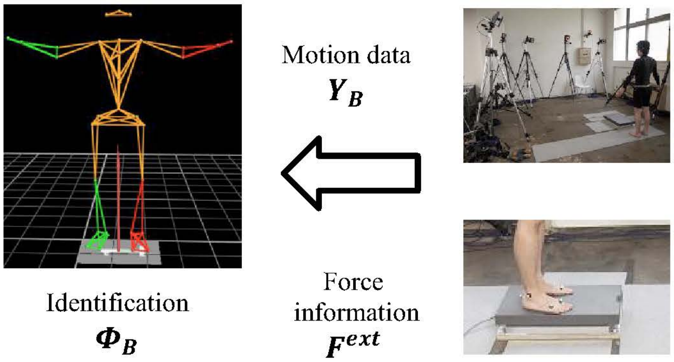


Fig.1 Conceptual diagram of the inertial parameters identification method using the motion data and the contact force information.

B. Contact Force Sensor Base Identification

The most common identification methods use Eq.(2), and thus require the measurement of the base-link information $\boldsymbol{q}_O \in \boldsymbol{R}^6$, the chains information $\boldsymbol{q}_C \in \boldsymbol{R}^{N_J-6}$, the joint torque $\boldsymbol{\tau}$, and the external forces $\boldsymbol{F}_k^{ext}$ at the N_C contact points. However measuring the joint torque at each DoF in the human body is not possible simultaneously. We thus propose to perform the identification of $\boldsymbol{\Phi}_B$ using only the upper-part of the identification model Eq.(2), the equations of motion of the base-link.

$$\boldsymbol{Y}_{OB}\boldsymbol{\Phi}_B = \boldsymbol{F} = \sum_{k=1}^{N_C} \boldsymbol{K}_{Ok}^T \boldsymbol{F}_k^{ext} = [\, F_x\, F_y\, F_z\, M_x\, M_y\, M_z \,]^T \quad (3)$$

We obtain the system given by Eq.(3) that is not a function of the joint torque $\boldsymbol{\tau}$. Consequently to estimate the set of base parameters $\boldsymbol{\Phi}_B$, the measurement of τ is not required. Only the measurement of the contact forces $\boldsymbol{F}_k^{ext}$ at the contact point *k*, the joint angles $\boldsymbol{q}_C$ and the generalized coordinates $\boldsymbol{q}_O$ are necessary. This information can be measured by 6-axis forcesensors, acceleration sensors, and gyro sensors, or computed from motion capture data. The conceptual diagram of the identification method is presented in Fig.1.

C. Validation of Inertial Parameters

As already mentioned, by Eq.(2), the calculation of the inertial parameters is possible without using torque. Deforming Eq.(2), the inertial parameters are given by Eq.(3) and Eq.(4). Where # denotes the Moore Penrose Pseudo inverse.

$$\boldsymbol{\Phi}_B = \begin{bmatrix} \phi_0^T & \phi_1^T & \cdots & \phi_j^T \end{bmatrix} = Y_{OB}^{\#} \sum_{k=1}^{N_C} \boldsymbol{K}_{Ok}^T \boldsymbol{F}_k^{ext} = Y_{OB}^{-1} F \quad (3)$$

$$\boldsymbol{\Phi}_{Bi} \triangleq \begin{cases} [M_i\ MS_{i,x}\ MS_{i,y}\ MS_{i,z}\ J_{i,xx}\ J_{i,yy}\ J_{i,zz}\ J_{i,yz}\ J_{i,zx}\ J_{i,xy}]^T \text{ baselink} \\ \left[MS_{i,x}\ MS_{i,y}\ J_{i,xx} - J_{i,yy}\ J_{i,zz}\ J_{i,yz}\ J_{i,zx}\ J_{i,xy}\right]^T \text{for } 1DoF \\ \left[MS_{i,x}\ MS_{i,y}\ MS_{i,z}\ J_{i,xx}\ J_{i,yy}\ J_{i,zz}\ J_{i,yz}\ J_{i,zx}\ J_{i,xy}\right]^T \text{ for 3DoF} \end{cases} \quad (4)$$

where M_i is the mass. $J_{i,xx}\ J_{i,yy}\ J_{i,zz}\ J_{i,yz}\ J_{i,zx}\ J_{i,xy}$ are the 6 independent components of the inertia matrix $\boldsymbol{J}_i$expressed in a frame attached to link *i* at joint *i*. $M_iS_{i,x}\ M_iS_{i,y}\ M_iS_{i,z}$ are the components of the vector $\boldsymbol{MS}_{i,}$, first moment of inertia of link *i* with respect to the origin of the frame attached to link *i* at joint *i*.

The upper part of Eq.(4) gives the inertial parameters in the base link; the middle of Eq.(4) gives the parameters for links with the 1DoF; the lower part of Eq.(4) gives the parameters for links with 3DoF. Once the inertial parameters identified, it is necessary to examine the validity of these inertial parameters. As there is no ground truth for human inertial parameters easily measurable, one method to validate the results is to use the contact forces as ground truth. Therefore, to calculate the estimated reaction force F_{ref} , using the Eq.(5) from motion data and inertial parameters .

$$F_{ref} = Y_{OB}\boldsymbol{\Phi}_B \quad (5)$$

Theoretically, estimated reaction force indicates the same value as measured ground reaction force. However, if the measurement noise is high, or there are errors in the model, the identification becomes insufficient, and deviation occurs in the result of F_{ref}. In particular, the identification results depend dramatically on the motion used to compute the inertial parameters. If generating motion for systems with few DoF is relatively simple, when the number of DoF is large it becomes non-trivial [2].

III. HUMAN MODELS

In this chapter, we present the structure of the human model used for identification. In the following notation we consider as DoF only the kinematics of the human body (actuated DoF), the base link used to describe the free motion of the whole system in the 3D space, which has 6 unactuated DoF is no included in number of DoF.

A. 15 Links and 34 DOF (1)

To calculate the inertial parameters of the human body, the most common model is a 15 links model with 34DoF. This model can simulate most of the daily life tasks and activities [6]. The configuration for this model is shown in Fig.2. Both knees and elbows are hinge joint with 1DoF, other joints are spherical joints with 3DoF.

B. 23 Links and 58 DOF

The 34DoF model may fail in simulating or representing detailed motion of the torso, the shoulder and the forearm. Thus, a more complex model taking into account additional DoF of the torso, the shoulder complex and the pronation/supination movement is proposed. The configuration for this model is shown in Fig.3. The added DoF are the following:

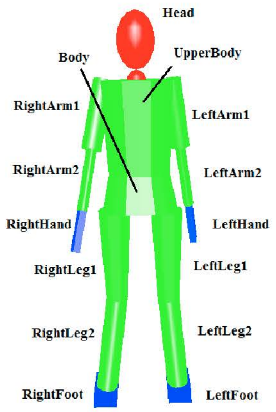
- Scapula, Clavicle, Cervical Spine, Lumbar Spine, which have each 3DoF
- Radius ,Ulna, which have each 1DoF

This model is particularly useful when analyzing skilled motion such as movements in sports, driving movements…

C. 15 Links and 34 DOF (2)

Finally, as humans often interact with their environment using tools, we propose a model that includes a tool hold in the hand, and we identify the dynamics properties of the tool simultaneously to the human body inertial parameters. The configuration for this model shown in Fig.4 . This model has

34DoF and it has a tennis racket in the left-hand of the model (left-handed player). The motion for the identification is thus performed while the subject is holding the tennis racket.



name of joint	type of joint	number of DOF
neck	spherical	3
waist	spherical	3
right shoulder	spherical	3
right elbow	revolute	1
right wrist	spherical	3
left shoulder	spherical	3
left elbow	revolute	1
left wrist	spherical	3
right hip	spherical	3
right knee	revolute	1
right ankle	spherical	3
left hip	spherical	3
left knee	revolute	1
left ankle	spherical	3

Fig.2. Configuration information for the model with 15 links and 34 DoF

name of joint	type of joint	number of DOF
neck	spherical	3
cervical spine	spherical	3
waist	spherical	3
lumbar spine	spherical	3
right hip	spherical	3
right knee	revolute	1
right ankle	spherical	3
left hip	spherical	3
left knee	revolute	1
left ankle	spherical	3
right scapula	spherical	3
right clavicle	spherical	3
right humerus	spherical	3
right ulna	revolute	1
right radius	revolute	1
right wrist	spherical	3
left scapula	spherical	3
left clavicle	spherical	3
left humerus	spherical	3
left ulna	revolute	1
left radius	revolute	1
left wrist	spherical	3

Fig.3. Configuration information for the model with 23 links and 58 degrees of freedom

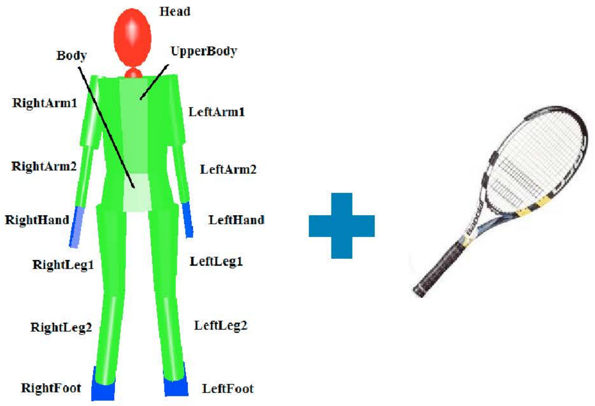


Fig.4. Configuration information for the model with 15 links and 34DoF and with a tennis racket

IV. RESULT

In this section we report on the experimental results obtained for each of the kinematics model presented in the previous section. The results are evaluated in terms of ability to reconstruct the contact forces, as this is the only ground truth parameter that can be measured. The graphs shows the measured contact force compared to the reconstructed force as given by (5). For a concern of space we present only the graphs of the Z-axis (perpendicular to the ground upward positive) reaction force and the moment around the Z-axis. The origin of the coordinate system is located at the base of the model link, model described below is a link of the lower abdomen to the base link.

The 34DoF and the 58DoF models are tested with the same dataset. In the dataset to be used is subject performs motion to move the joints of the whole body. The model when holding the tennis racket has obviously a different dynamics due to the tennis racket and is thus tested with a different motion, which is recorded when holding the tennis racket.

A. 15 Links and 34 DOF (1)

Fig.5 shows the results of identification of the model 15 links and 34DoF. From comparison diagram of reaction force and moment, we can confirm that the identified parameters are well identified and can reconstruct accurately the contact forces. The error is about ±2%, and reached a maximum of ±8%.The spike that are observed are not due to the identification but rather to error in the inverse kinematics computation.

B. 23 Links and 58 DOF

Fig.6 shows the results of identification of the model 23 links and 58DoF. We can see similar results as that shown in Fig.5. From this result, even if the model has a complex structure, it is still identifiable. The system is well identified, however the increase in link, accompanies an increase in the number of parameter to identify, as well as a reduction of the value of these parameters (due to the decomposition is small links, with little mass). The motion used to identify the 34DoF model may prove to be insufficient to identify the 58DoF model. A longer sequence of motion with specific movement of the added DoF is desirable. There is always a threshold between the precision of the model desired in term of kinematics and the precision that can be reached in terms of dynamics.

C. 15 Links and 34 DOF (2)

Fig.7 shows the results of identification of the model with 15 links and 34DOF and with a tennis racket. Since the motion requires the racket, the motion used for the identifications and the validation identification of this model are different than those for the 2 other models (Fig.5 and Fig.6). From the comparison results, we see that even when carrying and manipulating a tool, identification is successful and allows reconstructing the contact force with a high accuracy. With respect to the reaction force, the error is about ±1%, and for the moment, the error of about ±1% , which confirms. The large spikes do not occur in this trial, which confirms that the spikes are due to the inverse kinematics or measurement error.

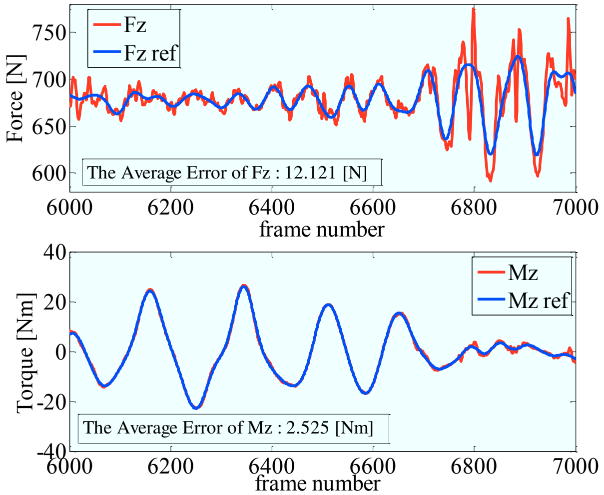


Fig.5. Comparison of reaction force and moment in model 15 links and 34 degrees of freedom

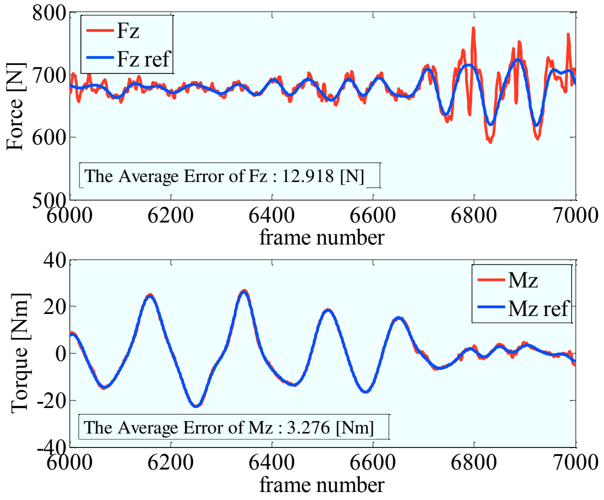


Fig.6. Comparison of reaction force and moment in model 23 links and 58 degrees of freedom

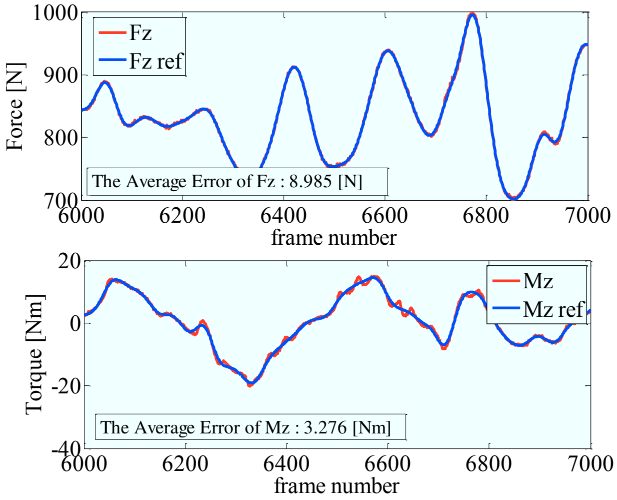


Fig.7. Comparison of reaction force and moment in model 15 links and 34 degrees of freedom with tennis racket

V. CONCLUSION

In this paper we have shown that using more complex models for dynamics identification is possible. We found that regardless of the kinematics model the inertial parameters are estimated accurately. More complex models can describe more precisely the kinematics of human motions, which is extremely complex. And with such models it is still possible to obtain accurate contact forces estimation, thus to perform dynamics analysis of human motion with subject specific parameters. Moreover, we also prove here that not only the human body dynamics can be identified, but also the dynamics of tool human interact with such as tennis racket, golf club or any other tool. This also contributes to subject and task specific dynamics simulation and computation. Further analysis regarding the sensitivity of the results with respect to the inverse kinematics errors and the sensor resolution are needed.

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