Upper Body Posture Estimation Using Handle Force Measurements: Experimental Results

G. Pages 1, N. Ramdani 1, P. Fraisse 1, D. Guiraud 1, M. Eckert 2

1 DEMAR project – Dept. of Robotics, LIRMM / INRIA – 161, Rue Ada 34090 Montpellier - France
2 IMERIR – Avenue Paul Pascot 66000 Perpignan - France
E-mail : gael.pages@lirmm.fr

Abstract

This paper presents our work related to restoring standing in paraplegia induced by functional electrical stimulation (FES) and investigates the relationship between body posture and voluntary upper-body movements. A method is presented for upper-body posture estimation in the sagittal plane from force and torque measurements exerted on supporting handles during standing. In order to validate our methodology, experiments were with spinal cord injured patients with lesions between T5 and T12.

1. INTRODUCTION

Movement generation induced by FES in paraplegia remains mostly open looped and is tuned empirically. In order to design an efficient closed loop control, we need to understand how upper and lower limbs may cooperate. Indeed, generated artificial lower body movements should act in a cooperative way with upper voluntary actions. The so-obtained synergy between voluntary and controlled movements will reduce both patient’s fatigue and electro-stimulation energy cost. A mean to solve this issue consists in characterizing upper body voluntary movements through posture estimation.

Research studies for posture and motion estimation using video or image data to extract parameters of a human body model are actively studied [6], [8]. Since camera-based systems restrict the user to the constrained environment where the cameras are installed, other studies develop real-time posture tracking systems by using miniature sensors such as accelerometers, goniometers or magnetic sensors [3], [4]. However, these types of strategies require to attach devices onto the patient which is not desired in our study case. Indeed, we plan to take advantage of the available walker usually used by the patient.

The use of walkers is investigated by several research teams. In [1] the walker is used for assisting gait, where the measurements of forces and torques applied to the walker’s handles are used to infer navigational intent of the user. However, this method is intended for persons having functional ability but activity difficulties, and are not suitable for paraplegic persons. The measurements of arm forces applied by the patient on handles are also used to determine stimulation patterns to apply on the lower limbs in order to maintain the body in a statically stable state [2].

The method introduced in this paper uses the efforts exerted on the handles of a supporting frame for estimating the posture of a patient. It consists in setting up constraints related to the biomechanical system geometric equations and the hand-handle interactions. In order to insure a reliable estimation of posture, we shall use a guaranteed numerical method which takes in account both, uncertainties within measured forces and model parameters, as well as any modelling error. Experimental results will also be given in the case study of spinal cord injured subjects and show the effectiveness of the proposed approach.

2. METHODS

2.1. Biomechanical model

In this study, the human body is regarded as a 3 degrees of freedom (DOF) kinematic structure in the sagittal plane, as shown on Fig. 1. All links are assumed to be rigid bodies. The segmental model is described in terms of Denavit-Hartenberg coordinate frames. We define \( \mathbf{q} = [\mathbf{q}_1, \mathbf{q}_2, \mathbf{q}_3]^T \) as the joint angle vector, which is a function of time. It is expressed as a
column vector with indices 1, 2 and 3 referring to the hip, the shoulder and the elbow joints respectively. The segments length are denoted by $L_j$. In Fig. 1, the variables $q_1$ and $q_2$ indicate positive angle directions while $q_3$ indicates a negative one, with respect to the zero position. The hand's position in the world frame $W$ is given by the following coordinates:

$$
P_x = L_2 S_1 + L_3 S_{12} + L_4 S_{123}$$
$$
P_z = L_2 C_1 + L_3 C_{12} + L_4 C_{123}$$

with $S_{ijk} = \sin(i+j+k)$ and $C_{ijk} = \cos(i+j+k)$.

Contact between the human hand and the handle creates a closed chain kinematic linkage. This interaction is described by the components of the resultant force vector $f_c$ measured in the $x$ and $z$ directions. Under the assumption of working in the sagittal plane and considering that the orientation of the forearm is collinear to the resultant force $f_c$, which is true for $f_x \geq 0$ and $f_z < 0$, it is reasonable to write:

$$
\tan (\theta) = \frac{f_x}{f_z}
$$

with $\theta = \pi - q_1 + q_2 + q_3$.

Solving (4) when $y$ is subject to uncertainty with classical techniques based on possibly weighted least squares optimisation for instance, derives reliable results only if the errors are stochastic and with known probability laws. In fact the measured data are subject to either stochastic or deterministic uncertainties and it is not easy to derive a reliable characterization of the probability distribution for these errors. Moreover, the model used may be based on some simplifying hypotheses for which a full probabilistic description might not be reliable. Consequently, it is more natural to assume all the uncertain quantities as unknown but bounded with known bounds and no further hypotheses about probability distributions. In such a bounded error context, the solution is no longer a point but is the set of all acceptable values of the $q$ vector which makes the model output $g(q)$ consistent with actual data $y$ and prior error bounds. We are therefore proposing a methodology based on interval analysis techniques [7] that allows to manage these uncertainties and ensure reliable posture estimation. The results are obtained in a guaranteed way using a set inversion algorithm based on space partitioning, interval analysis and constraint propagation (SIVA) [5].

3. RESULTS

Four spinal cord injured male subjects, with complete spinal lesions between T5 and T12, and of age between 18 and 50, participated in the study. The experimental arrangement includes a handle reaction measuring system, comprising two six-axis force/torque transducers located underneath each handles, and mounted on parallel bars. The six components of the reaction force exerted on each handle are measured and displayed throughout a real time implemented force sensor interface software. A VICON 370 motion analysis system, which includes four infrared cameras, was used to acquire kinematic data. To collect plantar pressure distribution and determine ground reaction force, two flexible pressure insoles were used. The body segment lengths were taken from literature [9]. They are expressed as a percentage of body height and serve as a good estimate in default of better data. During the experiments, the patients, under FES, were instructed to stand up from a chair, assisted by parallel bars, and stay in standing position and sit back down. The standing phase was as long as 1 minute.
Measurements were carried throughout the whole trial. Posture estimation was then done off-line during the standing phase, using MATLAB and the SIVIA algorithm implemented with the PROFIL/BIA
d interval library. An example of the results obtained with the methodology is described here with one of the subjects. The feasible domains for model output are taken as:

\[
\begin{align*}
P_x & \in [-0.02,0.02] \text{ meters} \\
P_y & \in [0.895,0.995] \text{ meters} \\
\theta & \in [-18.6°, -15.6°]
\end{align*}
\]

The prior search space, corresponding to the joints articular motion limit, is taken as:

\[
\begin{align*}
q_1 & \in [-11°, 90°] \\
q_2 & \in [90°, 210°] \\
q_3 & \in [-103°, 0°]
\end{align*}
\]

The projections of the computed inner and outer solution sets onto the \(q_1 \times q_2\) planes are given in Table 1. The solution sets obtained contain the actual posture and are consistent with the modelling (4) and prior domains (5) chosen for model output.

<table>
<thead>
<tr>
<th>Joints</th>
<th>Actual Posture (deg)</th>
<th>Inner enclosure (deg)</th>
<th>Outer enclosure (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(q_1)</td>
<td>0</td>
<td>[-3.56, 21.13]</td>
<td>[-3.85, 27.92]</td>
</tr>
<tr>
<td>(q_2)</td>
<td>192</td>
<td>[191.25, 214.37]</td>
<td>[190.93, 214.66]</td>
</tr>
<tr>
<td>(q_3)</td>
<td>-36</td>
<td>[-75.79, -30.13]</td>
<td>[-76.41, 29.71]</td>
</tr>
</tbody>
</table>

Table 1 : Projection of solution posture sets.

4. DISCUSSION AND CONCLUSIONS

A method for reliable upper body posture estimation, based on measuring forces exerted on handles, has been introduced. The problem is solved by interval analysis tools. Experimental studies were carried out onto paraplegic subjects in order to validate the proposed methodology. Satisfactory results were obtained using a 2D model of the human body since we were able to guarantee that the real posture, i.e. joint positions, was included in the estimated domains. We were also capable of computing guaranteed bounds on the estimated postures which take into account all source of uncertainty. Further studies will take into account a 3D-based model of the human body including the three dimensional resultant force vector of each handle and the interactions between the feet and the ground by measuring ground reaction forces. Moreover, a new supporting frame, replacing the parallel bars, has been designed and manufactured. It consists in a walker equipped with the six-axis force/torque transducers allowing a paraplegic user to stand up and take steps while achieving posture estimation and independent mobility.

References


Acknowledgements

We gratefully acknowledge the patients and Propara rehabilitation centre for giving us the opportunity to work in the best conditions during the experiments. Also thanks to industrial partner MXM (Vallauris, France) for technical and financial support as well as ANR-RNTS, MIMEs project. We also would like to acknowledge the contributions made to this study by our partners from the EDM (Efficience et Déficiences Motrice) laboratory, Université de Montpellier I (France), and funding from COLOR INRIA, Posture project.

1 www.ti3.tu-harburg.de/