XIX IMEKO World Congress
Fundamental and Applied Metrology
September 6–11, 2009, Lisbon, Portugal

COORDINATION OF FOCAL ARM MOVEMENTS AND POSTURAL STABILIZATION IN WHOLE BODY REACHING: A COMPUTATIONAL MODEL

Jacopo Zenzeri [1], *Vishwanathan Mohan* [2], *Pietro Morasso* [1],

[1] Neurolab, DIST, via Opera Pia 13, University of Genova, Genova, 16145, Italy,
jacopo.zenzeri@email.it, pietro.morasso@unige.it
[2] Human Behaviour Laboratory, Italian Institute of Technology, via Morego 30, Genova, Italy,
vishwanathan.mohan@unige.it

Abstract − In this paper, we present a biomimetic, force field based computational model for whole body reaching (WBR) using the approach known as passive motion paradigm. The proposed computational model is based on non-linear attractor dynamics where the attractor landscape is obtained by combining multiple force fields in different reference systems. Simulation results for a range of reaching tasks using a simplified body model composed of 5 joints (Ankle-Knee-Hip-Shoulder-Elbow) are presented. We compare the model-generated patterns (final posture, velocity profile and trajectories in the distal/proximal spaces) with the movements of a human subject performing similar WBR tasks.

Keywords: Passive motion paradigm, whole body reaching, postural synergy

1. INTRODUCTION

Postural stabilization during quiet upright bipedal standing essentially involves a single degree of freedom, i.e. the ankle [1]. However, the simple act of reaching an object starting from the quiet standing posture recruits virtually all the joints of the upper limbs, lower limbs, and trunk, binding together a large number of degrees of freedom into a functional unit that combines a focal task (reaching a target with the hand) and a postural task (keeping the projection of the center of mass within the bipedal support area). The fact that the two tasks are part of the same functional unit is proved by the anticipatory postural adjustments [2] that have been described at the kinematic and electromyographic levels. A further step in this direction was the study of whole body reaching (WBR) movements in which the target is beyond the arm's length and thus only the coordinated recruitment of all the joints allows a subject to carry out the task [3-5].

Different approaches have been attempted to quantify the coupling among the joints, in order to identify sub-components in the global reaching synergy: a typical example is the PCA analysis [5]. However, no generative computational model has been investigated so far. paper we describe a preliminary extension to the whole body reaching problem of a computational model that is based on an artificial potential field approach (Passive Motion Paradigm: [6]) combined with terminal-attractor dynamics [7] that has also been applied to robot reasoning [8]. The power of the approach comes from the generality of potential field based methods: the focal and postural components of WBR can be associated to two force fields and the complex, multi-joint coordinated patterns are a "side-effect" of the relaxation to equilibrium of the overall internal model. In this paper, we present the basic computational model and simulation results obtained by using the model for whole body reaching tasks using a simplified body model composed of 5 joints (Ankle-Knee-Hip-Shoulder-Elbow). We further compare the patterns generated by proposed nonlinear dynamical model (i.e final posture, velocity profile and trajectories in the distal/proximal spaces) with the movements of a human subject performing similar WBR tasks. Preliminary results suggest indeed a close correlation between the synthetic patterns and experimental data measured by means of a motion capture device. Future developments will include the integration of this synergy formation mechanism with a lower level, intermittent postural control system [9] and a learning mechanism for the optimal choice of the virtual admittance matrix that is at the heart of the coordination model.

2. PASSIVE MOTION PARADIGM

The Passive Motion Paradigm (PMP) is a computational model that addresses the problem of coordinating redundant degrees of freedom by means of a dynamical system approach, similar to the Vector Integration to To Endpoint (VITE model: [10]). In both cases, there is a "difference vector" associated with an attractor dynamics that has a point attractor in the designated target. The difference is that the VITE model focuses on the neural signals commanding a pair of agonist-antagonist muscles, whereas the PMP model focuses, at the same time, on the trajectories in the extrinsic and intrinsic spaces. The model exploits the bidirectional mapping between the intrinsic (joints) and extrinsic (end-effector) spaces that characterizes any kinematic chain: (1) the operator that maps incremental motion in the intrinsic space into the corresponding motion in the extrinsic space (i.e. the Jacobian matrix of the kinematic transformation) and (2) a dual operator that maps efforts in the opposite direction (force at the end-effector into joint torques). The "difference vector" of the VITE model becomes, in the PMP model, a virtual "force field" applied to the end-effector: this field is mapped into the corresponding field in the joint space that determines an elementary motion in agreement with the "admittance" of the kinematic chain and then, through the forward kinematic operator, a motion of the end-effector in the extrinsic space until the target is reached. From this comes the nickname of "Passive Motion" for the non-linear dynamic computational mechanism. In fact it is analogous to the mechanism of coordinating the motion of a wooden marionette by means of attached strings. By simply moving the tip of the marionette's hands or legs by the attached strings, once the tip reaches the intended position, the joint angles automatically reach the related values. The strings, in metaphorical terms, are the virtual force fields generated by the intended/attended goal and the other task dependent combinations of constraints involved in the execution of the task.

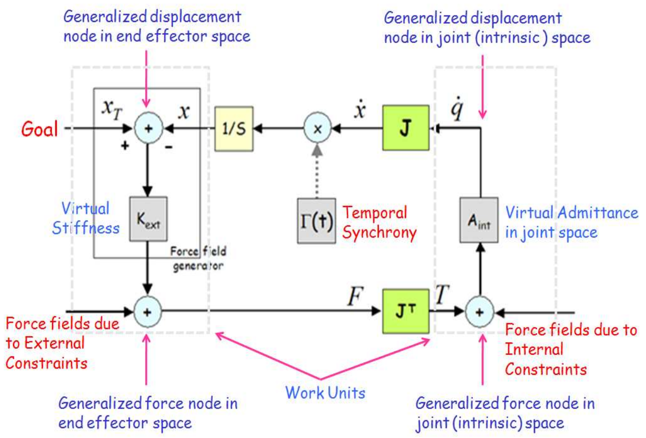

Fig. 1. Basic computational scheme of the PMP for a simple kinematic chain. x is the position/orientation of the end-effector, expressed in the extrinsic space; x_T is the corresponding target; q is the vector of joint angles in the intrinsic space; J is the Jacobian matrix of the kinematic transformation $x = \mathrm{f}(q)$; K_{ext} is a virtual stiffness that determines the shape of the attractive force field to the target; "external constraints" are expressed as force fields in the extrinsic space $F = F(x, \dot{x}, \ddot{x})$; "internal constraints" are expressed as force fields in the intrinsic space $T = T(q, \dot{q}, \ddot{q})$; A_{int} is a virtual admittance that distributes the relaxation motion to equilibrium to the different joints; $\Gamma(t)$ is the time-varying gain that implements the terminal attractor dynamics.

As shown in Fig. 1, the basic structure of the PMP network is composed of a fully connected network of nodes representing either forces or flows (displacements) in different motor spaces (end-effector space, joint space, muscle space, tool space etc). For simplicity, we just consider the end-effector and joint spaces for discussion in this section. A displacement and force node belonging to each motor space can be grouped as a work (force. displacement) unit (WU). This mechanical work is in fact a scalar invariant across the different motor spaces. There are only two kinds of connections: 1) between a force and displacement node belonging to each WU that describes the elastic causality of the coordinated system (represented by the stiffness and admittance matrices) and 2) horizontal connections between two different motor spaces that describes the geometric causality of the coordinated system (represented by the Jacobian matrices). Every node in the simple computational chain of Fig. 1 (and more complex PMP networks) can be reached from every other node and the choice of the elastic transformation is based on this notion of circularity. As shown in Fig. 1, in addiction to an attractive force field pulling the end effector (and connected task relevant parts of the body) towards the goal, multiple constraints (internal/external) can be concurrently imposed in a task-dependent fashion into the dynamics by simply switching on/off different task relevant force field generators. Computationally this implies that the net attractor landscape is obtained by combining multiple force fields in different reference systems.

3. PMP APPLIED TO WHOLE BODY REACHING

Figure 2 shows the simplified five link body model considered in this study and figure 3 shows the flow diagram of the PMP based computational model for WBR.

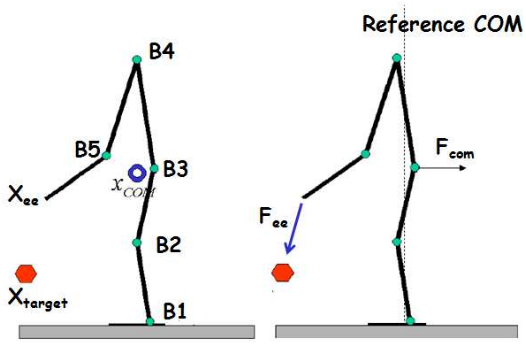

Fig. 2. WBR kinematic model consisting of a 'ankle-knee-hip-shoulder-elbow' chain, with B charecterizing the virtual admittance seen at the different joints.

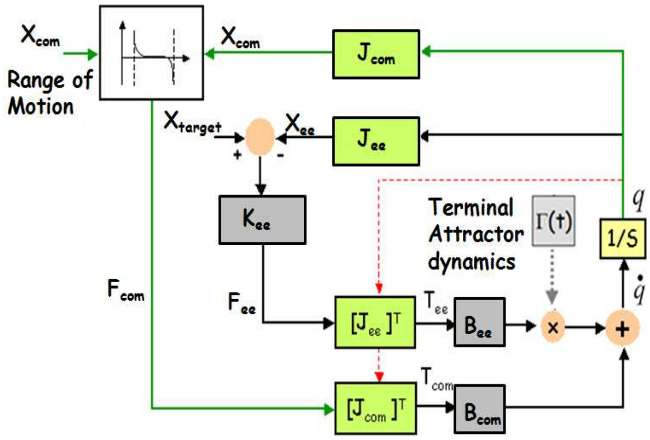

Fig. 3. PMP based computational model for WBR.

In this context, WBR can be defined by the combination of two synergies: a focal and a postural synergy.

Focal synergy:

x_{ee} (the position of the end-effector) must reach the target x_T at a given time t_f.

Postural synergy:

x_{com} (the position of the COM) must remain inside an admissible range of motion.

The motor planner/controller, which expresses in computational terms the passive motion paradigm for whole body reaching task, is defined by the following steps:

1) Define a virtual attractive force field to a designated target (applied to the end-effector) and a repulsive force field (applied to the hip) to keep the COM in an admissible ROM

$$F_{ee} = K_{ee}(x_T - x_{ee}) \quad (1)$$

$$F_{com} = f(x_{com}, x_{\min}, x_{\max}) \quad (2)$$

2) Map the extrinsic force fields into intrinsic force fields:

$$T_{ee} = J_{ee}{}^T F_{ee} \quad (3)$$

$$T_{com} = J_{com}{}^T F_{com} \quad (4)$$

3) Relax the arm configuration in the applied fields, where B is the virtual admittance matrix:

$$\dot{q} = B_{ee} T_{ee} + B_{com} T_{com} \quad (5)$$

4) Integrate to update the "body model"

$$q = \int \dot{q}\, dt \quad (6)$$

5) Extract from the body model the current positions x_{ee} and x_{com}:

$$\dot{x}_{ee} = J_{ee}\, \dot{q} \quad (7)$$

$$\dot{x}_{com} = J_{com}\, \dot{q} \quad (8)$$

A way to explicitly control the time, without using a clock, is to insert in the non-linear dynamics of the PMP model a suitable time-varying gain $\Gamma(t)$ that grows monotonically as x approaches the equilibrium state and diverges to an infinite value in that state. The technique was originally proposed by Zak [11] for speeding up the access to content addressable memories and then was applied to a number of problems in neural networks. Our purpose, however, is not merely to speed up the operation time of the planner but to allow a control of the reaching time as well as the speed profile in order to fit the human reaching patterns. This can be implemented by substituting the relaxation equation (5) with the following one:

$$\dot{q} = \Gamma(t)\left(B_{ee} T_{ee} + B_{com} T_{com}\right) \quad (9)$$

A form of the time-varying gain that implements the terminal attractor dynamics is the following one:

$$\begin{cases} \xi(t) = 6 \cdot (t/\tau)^5 - 15(t/\tau)^4 + 10(t/\tau)^3 \\ \Gamma(t) = \dot{\xi} \big/ (1-\xi) \end{cases} \quad (10)$$

where $\xi(t)$ is a time-base generator (TBG): a scalar function that smoothly evolves from 0 to 1 with a prescribed duration τ and a symmetric bell-shaped speed profile. A simple choice for the TBG is a minimum jerk polynomial function, but other types of TBGs are also applicable without any loss of generality. Systems that have terminal attractor dynamics violate the Lipschitz criteria of ordinary differential equations, i.e., they have point attractors of infinite stability in the sense that the gradient of their Lyapunov function diverges at equilibrium point: a consequence is that they reach equilibrium in finite time (it is a terminal attractor). In this way, the potential function is synchronised with the TBG, so the relaxation converges in finite time. In figure 4 we can see the signal output of a TBG: note the bell-shaped speed profile that we can easily control.

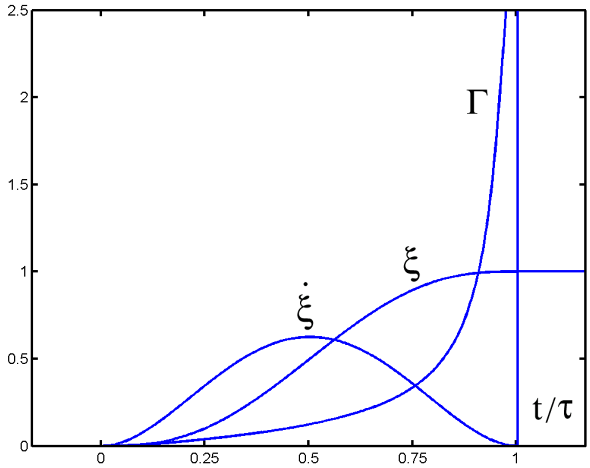

Fig. 4. Output signal for control the time: the time-varying gain $\Gamma(t)$, the time-base generator $\xi(t)$, the speed $\dot{\xi}(t)$.

4. IMPLEMENTATION AND SIMULATION RESULTS

The PMP based computational model for WBR was implemented with respect to a simplified geometrical structure of the body with 5 joints (Ankle-Knee-Hip-Shoulder-Elbow). The timing of the relaxation process is controlled using a neural time base generator as shown in figure 4. A range of reaching tasks mainly using the "Hip Strategy" or "knee freezing" and the "Ankle Strategy" or "normal reaching" were simulated using the computational model. In an extended study, the solutions obtained using the computational model were compared with movements of human subjects performing similar tasks measured by a motion capture device (MOCAP).

Figure 5 shows the behaviour of the model and of a human subject in the knee freezing mode: Panel 5A illustrates the trajectories of the whole body and we note that they are very similar considering the fact that with one subject we don't want to overfit the data; Panel 5B shows the evolution of the joint angles and we note that the mean error between the subject and the model is about 5 degrees and for some joints is even less; Panel 5C shows that the speed profile is bell-shaped in both cases; Panel 5D shows the influence of the stiffness value of the end-effector on the model-generated trajectory of the end-effector. As regards the last panel, we observe that with value of stiffness for the enf-effector larger than 1000N/m, the generated trajectory mimics very well the human behaviour.

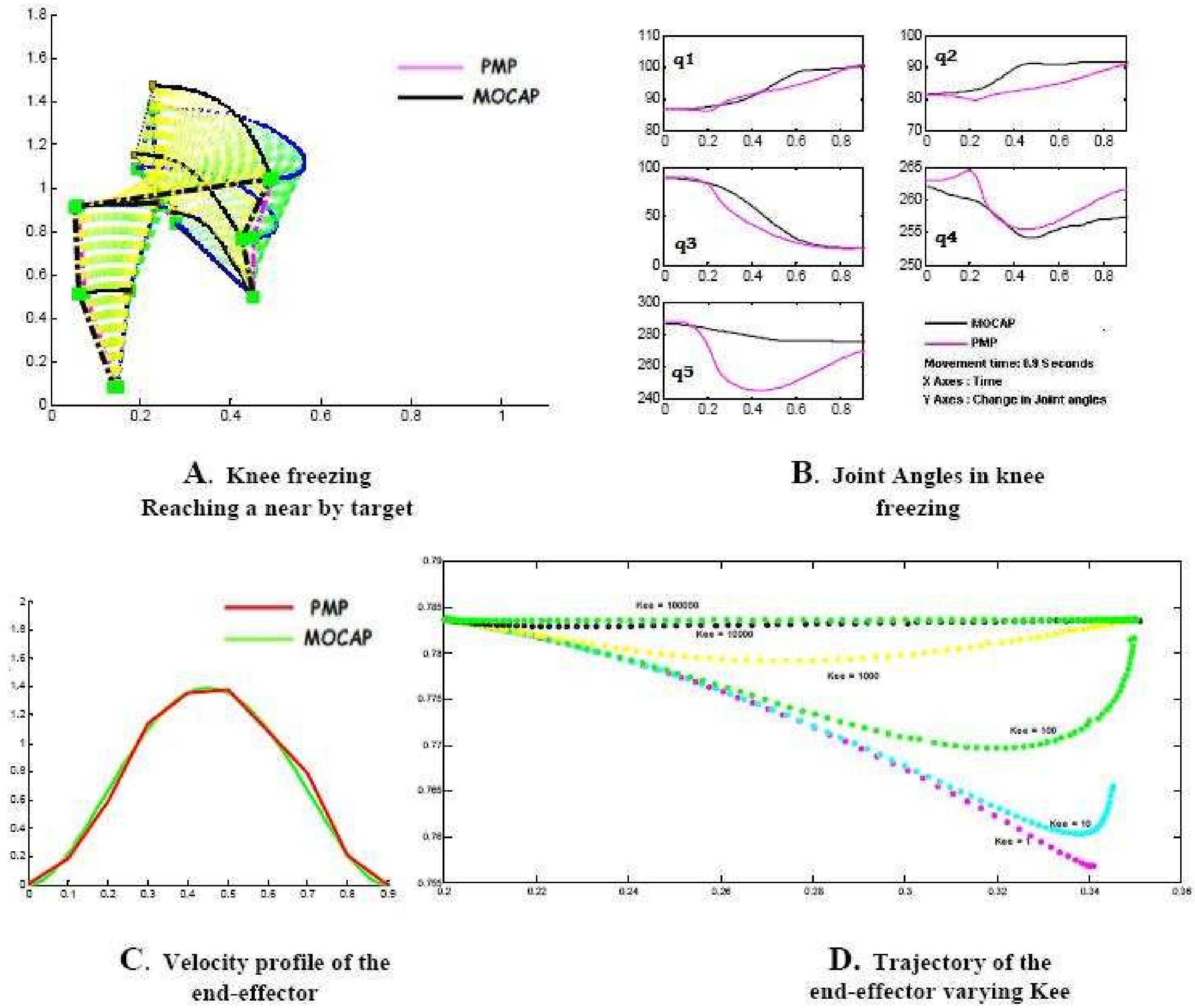

Fig. 5. Comparison of solution obtained using the PMP based computational model for whole body reaching, with data of movements of human subjects obtained using a motion capture device.

Figure 6 shows that the model can replicate a variety of reaching tasks performed by a human. We have tried four type of tasks: knee freezing with a near by (panel 6A) and a far away target (panel 6B) and normal reaching with a near by (panel 6C) or far away target (panel 6D). With high values of the stiffness of the end-effector the only parameters to learn are the elements of the admittance matrix. With some simple search techniques in the five dimensional space of the admittance matrix we can fit very well the human movement as shown in figure 6. We finally note that the values of this matrix have to be positive and it's not important the absolute values of each admittance but the relative values of one with respect to the others.

5. CONCLUSIONS

The action of 'reaching' is fundamental for any kind of goal directed interaction between the body and the world. In this paper we presented a biomimetic, force field based computational model for whole body reaching and presented simulation results obtained using the computational model for a variety of reaching tasks. The power of the approach comes from the generality of potential field based methods: the focal and postural components of WBR can be associated to two force fields and the complex, multi-joint coordinated patterns are a "side-effect" of the relaxation to equilibrium of the overall internal model. Further, the timing of the relaxation can be controlled using a non-linear dynamical timing mechanism that provides terminal attractor properties to the computational model and endows the generated trajectories with human-like smoothness and precise control of the reaching time. Preliminary results suggest close correlation between the solutions obtained using the computational model and the movements of human subjects performing similar tasks (measured through motion capture device). Future developments will include the integration of this synergy formation mechanism with lower level, intermittent postural control [9] and a learning mechanism for the optimal choice of the virtual admittance matrix that is at the heart of the coordination model.

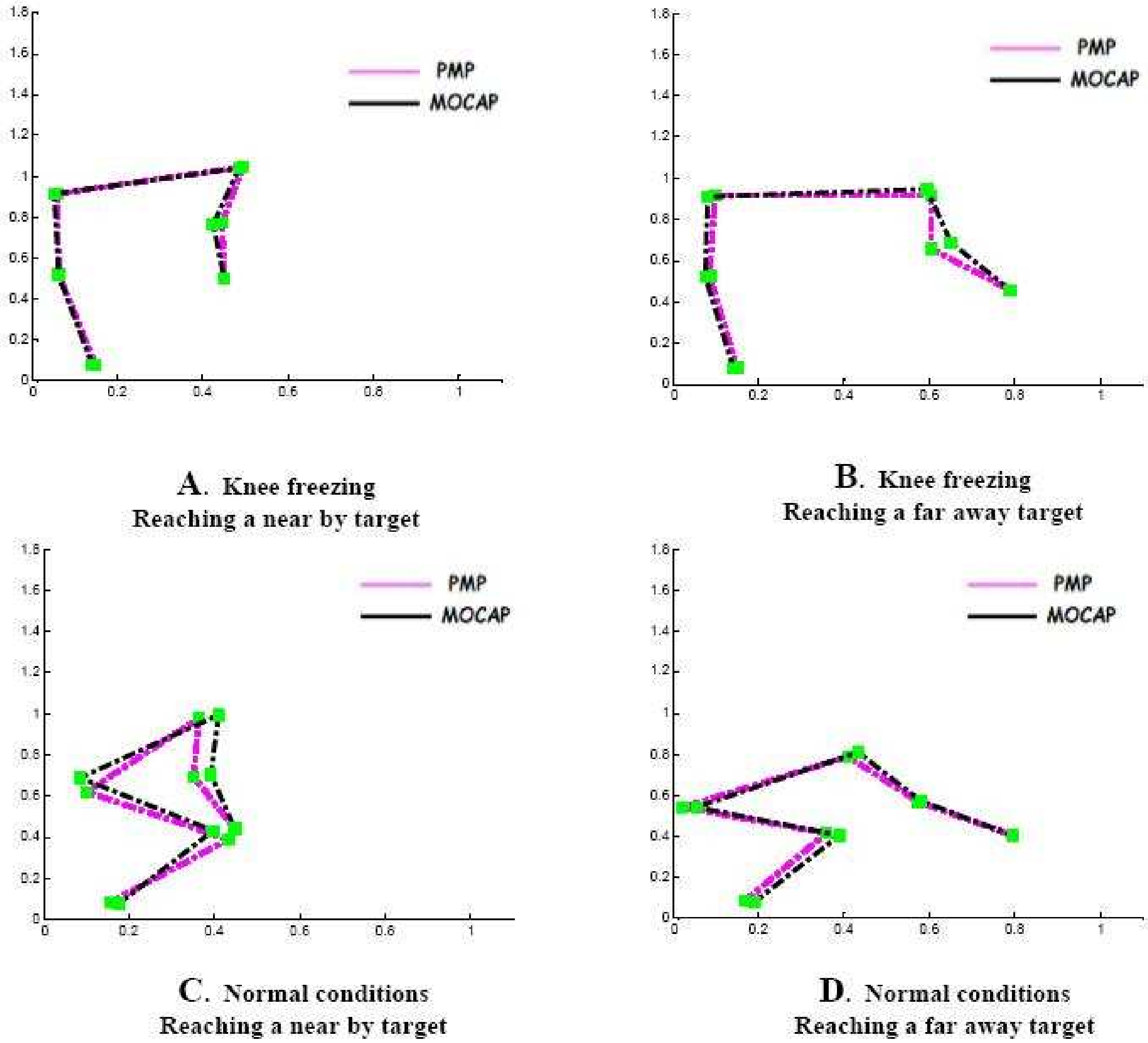

Fig. 6. Comparison of final postures obtained using the PMP based computational model for whole body reaching, with data of movements of human subjects obtained using a motion capture device.

ACKNOWLEDGMENTS

This research was partly supported by IIT (doctoral fellowship to Dr. Mohan), the EU FP6 Project GNOSYS and the EU FP7 Project HUMOUR.

REFERENCES

[1] [1] P. Morasso and V. Sanguineti, "Ankle muscle stiffness alone cannot stabilize balance during quiet standing", *J. Neurophysiology*, 88, 4, 2157-62, 2002.

[2] S. Bouisset, M. Zattara, "Biomechanical study of the programming of anticipatory postural adjustments associated with voluntary movement", *J Biomech* , 20:735–42, 1987.

[3] T. Pozzo, P. J. Stapley and C. Papaxanthis, "Coordination between equilibrium and hand trajectories during whole body pointing movements", *Exp Brain Res*, 144:343‑350, 2002.

[4] J. Patron, P. Stapley and T. Pozzo, "Human whole-body reaching in normal gravity and microgravity reveals a strong temporal coordination between postural and focal task components", *Exp Brain Res*, 165:84‑96, 2005.

[5] T. R. Kaminski, "The coupling between upper and lower extremity synergies during whole body reaching". *Gait & Posture*, 26, 2007.

[6] F. A. Mussa Ivaldi, P. Morasso and R. Zaccaria, "Kinematic Networks. A Distributed Model for Representing and Regularizing Motor Redundancy", *Biological Cybernetics*, 60, 1-16, 1988.

[7] T. Tsuji, P. Morasso, K. Shigehashi and M. Kaneko, "Motion Planning for Manipulators using Artificial Potential Field Approach that can Adjust Convergence Time of Generated Arm Trajectory", *Journal Robotics Society of Japan*, 13, 285-290, 1995.

[8] V. Mohan and P. Morasso, "Towards reasoning and coordinating action in the mental space", *International Journal of Neural Systems*, 17, 4, 1-13, 2007.

[9] A. Bottaro, Y. Yasutake, T. Nomura, M. Casadio and P. Morasso, "Bounded stability of the quiet standing posture: an intermittent control model", *Human Movement Science*, 27, 473-495, 2008.
[10] D. Bullock, S. Grossberg, "Neural dynamics of planned arm movements: emergent invariants and speed-accuracy properties", *Psychol Rev*, 95, 49-90, 1988.
[11] M. Zak, "Terminal attractors for addressable memory in neural networks". *Phys. Lett. A*, 133, 218–222, 1988.