2011 IEEE International Conference on Rehabilitation Robotics
Rehab Week Zurich, ETH Zurich Science City, Switzerland, June 29 - July 1, 2011

# Influence of Planar Manipulandum to the Hand Trajectory During Point to Point Movement

Miloš D. Kostić, Dejan B. Popović, *Member IEEE*
University of Belgrade, Faculty of Electrical Engineering, Belgrade, Serbia
Aalborg University, Dept. Health Sci. & Techn., DK

Mirjana B. Popović
University of Belgrade, Institute for Multidisciplinary Research, Belgrade, Serbia
Aalborg University, Dept. Health Sci. & Techn., DK

*Abstract*—**We present the analysis of the planar manipulandum effects to the trajectory of point to point movements in horizontal plane. This analysis is of significance for the control of a haptic robot that can be used for the rehabilitation of hemiplegic patients. The effects were assessed by comparing data collected in experiments with healthy subjects when performing simple movements that are used in the therapy of stroke patients. We found significant differences between the preferred trajectories and the deviations from the preferred trajectories ($p<0.01$) when moving with and without the manipulandum. This result suggests that for the design of the controller of a robot assistant inertial properties of the robot mechanism must be considered even in the case that it is used only for the assessment (passive) or within the bio-feedback.**

***Keywords*- control, movement, haptic robot, inertia**

## I. INTRODUCTION

The re-establishment of movement of the arm in a hemiplegic patient can be enhanced by the increased task related exercise [1]. Haptic robots are assumed to be the ideal tool for assisting patients during the task related exercise [2-5]. The robot for re-establishment of upper extremities movement should be considered as the teacher. This movement teacher can actively drive the movement, prevent deviations from the desired trajectory, or only assess the performance. In this scenario the trainee (patient) is asked to maximize his/her efforts and the robot should only operate when the performance is not adequate. Precisely, the role of the robot is to assist the patient to “learn the next to natural version of the skill”.

In this paper we address the consequence of the use of mechanisms that are the core of some systems used the training of upper extremities [2-5]. The mechanism that is the point of interest is a planar two degrees of freedom unilateral manipulandum. The question that we are answering in this paper is how different are the trajectories of the hand when holding the handle fixed at the end of the manipulandum and when freely moving hand. The task analyzed was a set of point to point movements in the horizontal plane. This is an important question because if the manipulandum affects the movement, then its action should be considered as the disturbing force, and the net result will be a modified motor control strategy [6]. In parallel, if we became aware about the inertial effects, then we should be able to design the control law for the robot assistant which would eliminate or at least minimize these effects.

We will first present some basic facts related to the motion of the hand when holding the handle of the manipulandum. The model of the system is presented in Fig. 1.

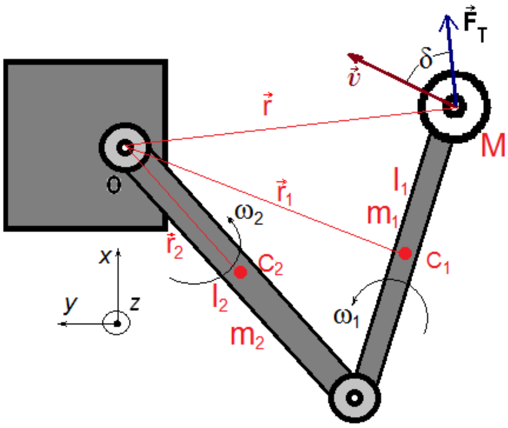

Figure 1: $m_1$, $m_2$ $I_1$ and $I_2$ are masses and inertia moments for the centers of masses of manipulandum segments. $C_1$ and $C_2$ are centers of masses of the segments. M is the end point (handle). m is the mass of the handle and the magnetic mouse. $\omega_1$ and $\omega_2$ are absolute angular velocities of the manipulandum segments. r, $r_1$ and $r_2$ are distances to the center of masses with respect the reference point.

The system analyzed is composed of the manipulandum with two segments with masses $m_1$ and $m_2$, with the lengths $l_1$ and $l_2$, and the mass of the handle (m). The force in the tangential direction ($F_T$) which a human needs to generate in order to compensate the inertia can be estimated from the law of momentum

$$\sum_i M_{Ozi} = \frac{dL_{Oz}}{dt}$$

where $L_{Oz}$ it the kinetic moment of the system with respect the Oz axis and $\Sigma(M_{Ozi})$ is the algebraic sum of all moments about the $O_z$ axes. The only force that is generating the moment about the $O_z$ axes is $F_T$, acting at the distance r; hence, the movement is defined with the following equation:

$$M = F_T r = \frac{d[mrv\cos\delta + I_1\omega_1 + m_1 r_1^2(\omega_1+\omega_2) + I_2\omega_2 + m_2 r_2^2\omega_2]}{dt}$$

The force $F_T$ (hand to manipulandum interface) is then:

---

This work was supported by the FP7 EC strep project HUMOUR, No. 231724 and the Project No. 175016, funded by the Ministry for Science and Technological Development, of Republic of Serbia, Belgrade

978-1-4244-9861-1/11/$26.00 ©2011 IEEE

$$F_T = [m\frac{dr}{dt}v\cos\delta + mr\frac{dv}{dt}\cos\delta - mrv\sin\delta\frac{d\delta}{dt} +$$
$$\sum_{i=1}^{2}(I_i\frac{d\omega_i}{dt} + 2m_i r_i\frac{dr_i}{dt}\omega_i + m_i r_i{}^2\frac{d\omega_i}{dt}) + 2m_1 r_1\frac{dr_1}{dt}\omega_2 + m_1 r_1{}^2\frac{d\omega_2}{dt}]/r$$

The last equation shows that the inertia changes along the movement. This change will result in the time varying interface force between the handle of the manipulandum and the hand. In the sections that follow we demonstrate kinematical effects of this interface force action to the trajectories obtained in measurements with healthy individuals.

## II. METHODS AND MATERIALS

### A. *Subjects*

Six healthy right handed subjects participated in this study: four males (age between 24 and 25) and two female subjects (age 24). All subjects signed the informed consent approved by the local ethics committee.

### B. *Experimental Procedure*

The experimental setup followed the typical therapeutic session scenario in which movements in the horizontal plane are practiced. The movements can be categorized into three classes: radial movement from body proximal medial point to body distal medial point; movement from proximal ipsilateral point to distal contralateral point; and movement from proximal contalateral point to distal lateral point. In this experiment we investigated influence of manipulandum on movements belonging to the three classes listed above.

Figure 2: The experimental setup with manipulandim (left panel) and no manipulandim (right panel)

A subject was seating in a chair with adjustable seat height positioned in front of a workspace that was about 30 cm bellow the shoulder level. The trunk was held against the back of the chair by a shoulder harness. The movement analyzed can be classified as the self paced point to point movement. The range of movement was set to study motion of the hand from flexed to about 80% of fully extended arm. All movements were performed with manipulandum (Fig. 2, left panel), and without it (Fig. 2, right panel). Each movement was repeated in total 10 times.

We present here three cases: 1) movement starts at a point in front of the contralateral shoulder (S1), at 15 cm from the projection of the shoulder to the desk plane, and ends at a point of 80% of the maximal reach at the ipsilateral side (T1); 2) radial movement in the central body line, starting 15 cm in front of the sternum (S2) , and ending at 80% of the maximal reach (T2); and 3) movement starts at a point 15 cm in front of ipsilateral shoulder (S3) and ends at 80% of the maximal reach at the contralateral side (T3). The starting and target points were marked with 1cm diameter dots in different colors on the digitizing board.

### C. *Instrumentation*

We used the Wacom Intuos4 and the software developed for the drawing test [7]. The board outputs the absolute position of the magnetic mouse in the rectangular reference system originating in the lower left corner of the quadratic board with the side of about 50 cm. Spatial resolution of the board is 100 points per mm, and the sampling frequency is 100 Hz. The antenna (cupper winding) of the magnetic mouse has the diameter of 1.5 cm. Data transfer to PC was done directly from Wacom Intuos4 using a USB communication. Data acquisition was performed in custom made LABView software.

The manipulandum used in this experiment is a passive mechanical rig with two cylindrical joints with prestressed ball bearings which allow virtually frictionless movement in horizontal plain (Fig. 1). Length of each segment of the manipulandum was 40 cm, and the mass 650 g. The details about the manipulandum are described elsewhere [8].

The device used in experiments without the manipulandum was a handle mounted on the top of the magnetic mouse (Fig. 2, right panel). The adapter holding the mouse guarantied that the handle will be vertical during movement. The friction between the board and the device was minimized with Teflon pads mounted at the mouse.

### D. *Data analysis*

The data analysis procedure consisted of four steps (Fig. 3):

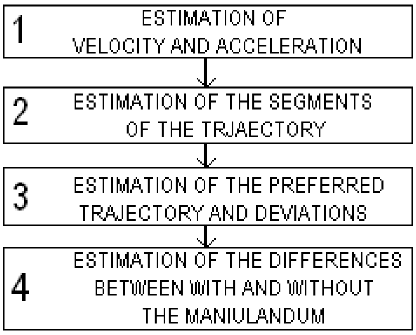

Figure 2. Data analysis flowchart

1) Position data were used to calculate the velocity and acceleration in x and y direction by numerical derivation.

2) Since the point to point movements had parts that do not belong to the same strategy they were truncated in two segments [9]. The first segment comprises about 95% of the movement. The second segment is an adjusting corrective movement which occurred at the late phase of movement to correct for the misalignments of the mouse and the target. In our study we divided the movement to segments by observing the first acceleration zero crossing from negative to positive, after the movement onset.

3) Since the self paced point to point movement belongs to stochastic process we estimated the median trajectory and termed it preferred trajectory. We assessed the deviations from the preferred trajectory.

4) We used the t-test for unequal variances to compare the deviations with and without the manipulandum.

## III. RESULTS

In Figure 3 we show the setup and one class of the movement (S2 to T2). We select this class of movement since it was established that the preferred trajectory for medial radial movement is a straight line [10]. The first important result relates to the first segment of movement (Fig. 4), while the second to the second segment (Fig. 5).

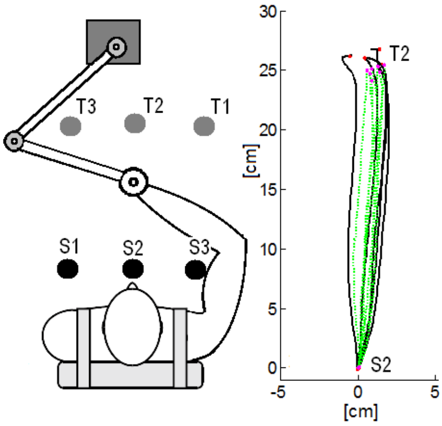

Figure 3: The setup (left panel) and the trajectories for all 10 trials of the radial movement along the central line (right panel): 5 trials, of one subject, without the manipulandum (green dotted lines) and 5 trials with the manipulandum (5 black full lines)

Fig. 3 shows that the end point of movement and the target were not overlapping. The distance between the target position and the end point was in average within a 1cm. This allowed us to use the straight line as the preferred trajectory and calculate the deviations for the first segment of the movement.

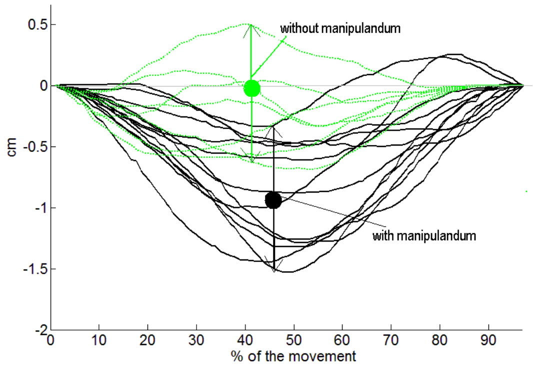

Figure 4. Deviation of the trajectory from the straight line for trials with (black full lines) and without manipulandum (green dotted lines) for central radial movement shown in the right panel of Fig. 3.

Fig. 4 shows enlarged deviations from the straight line for the first segment of the movement (≈ 95%). The abscissa is given in percent of the movement (normalization which eliminates the differences in the duration of the movement). The difference between the median deviations with and without the manipulandum was about 1 degree ($p < 0.01$, $t=1.70$), the standard deviations were 0.87 degrees (no manipulandum) and 1.61 degrees (with manipulandum).

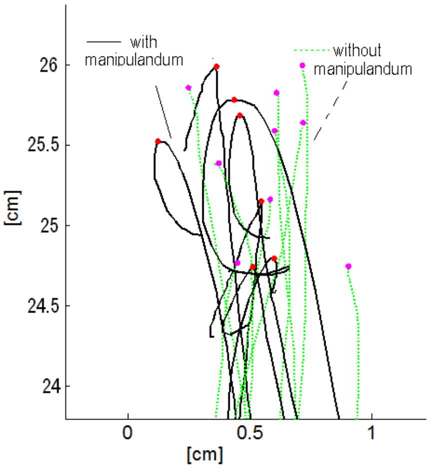

Figure 5. Final part of movements for trials with (black full ines) and without manipulandum (green dotted lines)

Fig. 5 shows the second segment (end of trajectory) for movements without and with the manipulandum in a lager scale compared with the scale used in Fig. 3.

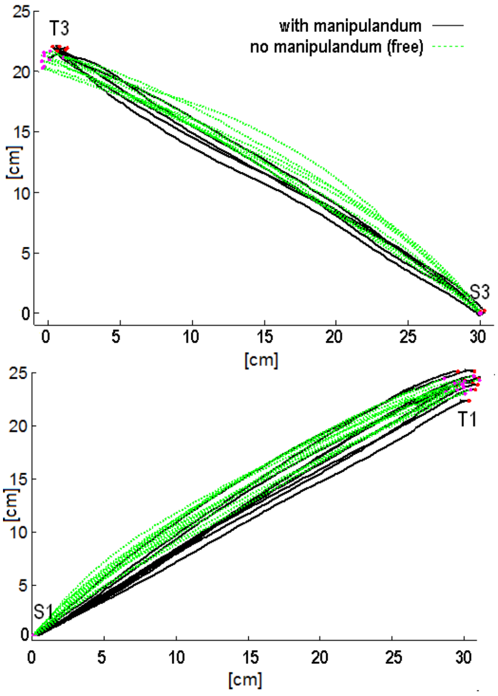

Figure 6. Trajectories for the movements S1-T1 (bottom panel) and S3-T3 (top panel) recorded during one subject's movements with (black fill lines) and without the manipulandum (green dotted lines).

In the movement with the manipulandum the corrective maneuver was “returning from the overshoot”, and without the manipulandum there were almost no corrections.

The findings for the class of movement S1-T1 are valid for two other classes of movement studied (Fig. 6). Trajectories for the movement starting at ipsilateral and contralateral sides significantly differ between the movement with and without the manipulandum by using the same measures as used for the medial radial movements.

One of the main differences observed in these two classes of movement is that when performed without the manipulandum they cluster around the trajectory which is different from the preferred trajectory with manipulandum. In addition, the deviations from the preferred trajectory when using the manipulandum, are larger compared with the deviation without the manipulandum.

The finding for the corrective movement with the manipulandum holds also for the two classes of movement shown in Fig. 6.

## IV. DISCUSSION

It is known that there is an approximately linear relation between elbow muscle torque and shoulder muscle torque when a human is free to choose the path of the hand to a target which is in front of him/her [11-16]. This behavior is translated into the selection of the straight line trajectory of the hand during medial radial movements as the preference (natural optimization) as shown by Burdet and colleagues [9]. By moving the hand along a straight line arm forms an isosceles triangle in which the angle in shoulder and elbow change in reciprocal manner, following the innate principle of muscle torque minimization [17].

When the movement is constrained with the manipulandum, the mechanical structure is changed, and additional forces act on the hand during the movement. This affects the motion, and the optimal path is not longer the straight line. Deviations (Fig. 4) suggest that when the movement is performed without manipulandum there is no prevalence of deviation on either side. Deviations are randomly distributed to both sides. On the contrary when the manipulandum is used there is the prevalence of to deviation to one side. This indicates that the neural system forms a new optimal trajectory which is slightly curved to the preferred side, and all trials cluster around it. This behavior was found in all subjects; yet, with the various degrees. Depending on subject’s individual motor control strategy and limb impedance the size of deviation is smaller or larger, but always present. Similar changes were assessed for the other movements as it can be seen from Fig. 6.

The final part of the movement with and without manipulandum showed the biggest difference. Namely, the last part of the movement with the manipulandum shows that there was a need to correct the overshoot. In the trials performed without manipulandum we found only very small or no corrective maneuvers. Fig. 5 shows that in these “freehand” trials even in the cases where the pointer was not precisely at the target subjects readjusted the position minimally. We suggest that this difference comes because of the inertia which the manipulandum adds to the arm/hand.

We also analyzed shorter movements in the range of 10 to 15 cm (results not presented in this paper) and found that the deviations from the preferred trajectories and the corrective movements are less expressed.

## REFERENCES

[1] D. B. Popović, T. Sinkjær, M. B. Popović, „Electrical stimulation as a means for achieving recovery of function in stroke patients,” J NeuroRehabilitation. 25:45-58, 2009.

[2] S. Hesse, H. Schmidt, C. Werner, A. Bardeleben, “Upper and lower extremity robotic devices for rehabilitation and for studying motor control”, Current Opinion in Neurology 16 , 6 : 705-710, 2003.

[3] N. Hogan, H. I. Krebs, J. Charnnarong, "MIT-MANUS: a workstation for manual therapy and training. I", Proc. IEEE International Workshop on Robot and Human Communication, Tokyo, Japan, ISBN: 0-7803-0753-4, 1992.

[4] N. Hogan, J. I. Krebs, J. Charnnarong, P. Srikrishna, A. Sharon, "MIT-MANUS: a workstation for manual therapy and training. II", Proc. SPIE 1833, 28 (1993), doi:10.1117/12.142124, 1993.

[5] M. Casadio, V. Sanguineti, P. G. Morasso, V. Arrichiello, “Braccio di Ferro: A new haptic workstation for neuromotor rehabilitation”, Technology and Health Care 14:123–142, 2006.

[6] R. Osu, E. Burdet, D. W. Franklin, T. E. Milner, M. Kawato, "Different Mechanisms Involved in Adaptation to Stable and Unstable Dynamics", J. Neurophysiol. 90: 3255–3269, 2003.

[7] C. Eder, M. B. Popović, D. B. Popović, A. Stefanović, L. Schwirtlich, S. Jović, “The drawing test: a tool for assessing motor coordination in post-stroke hemiplegic subjects”, Arch Phys Med Rehab, 86(2):289-295, 2005.

[8] M. D. Kostić, D. B. Popović, “Action Representation for Wii Bowling: Classification”, Proc of the 10th Symp on Neural Network Applications in Electric Engineering, NEUREL 2010, Belgrade, Serbia, pp. 23-26, ISBN 3-900928-09-5, 2010

[9] L. Fradet, G. Lee, N. Dounskaia, “Origins of submovements during pointing movements”, Acta Psychologica,129: 91–100, 2008.

[10] E. Burdet, R. Osu, D. W. Franklin, T. E. Milner, M. Kawato, "The central nervous system stabilizes unstable dynamics by learning optimal impedance", Nature 414: 446-449, 2001.

[11] G.L. Gottlieb, Q. Song, D. Hong, G. L. Almeida, D. Corcos, “Coordinating movements at two joints: a principle of linear covariance”, J. Neurophysiol. 75: 1760–1764, 1996a.

[12] G. L. Gottlieb, Q. Song, D. Hong, D. Corcos, “Coordinating two degrees of freedom during human arm movement: load and speed invariance of relative joint torques”, J. Neurophysiol. 76: 3196–3206, 1996b.

[13] J. T. Francis, “Error generalization as a function of velocity and duration: human reaching movements”, Exp Brain Res, 186:23–37, 2008.

[14] J. P. Spencer, E. Thelen, “Infants use different muscles in the same spatial regions before vs. after they learn to reach”, Poster presented at the 26th Annual Meeting of the Society for Neuroscience, Washington, DC, 1996.

[15] F. Zaal, K. Daigle. G. L. Gottlieb, E. Thelen, “An Unlearned Principle for Controlling Natural Movements”, J.Neurophysiol. 82: 255–259, 1999.

[16] M. B. Popović, D. B. Popović, R. Tomović, “Control of Arm Movement: Reaching Synergies for Neuroprosthesis with Life-Like Control”, J. Automatic Control, University of Belgrade, 12: 9-15, 2002.

[17] D. B. Popović, M. B. Popović, “Tuning of a Nonanalytic Hierarchical Control System for Reaching with FES”, IEEE Trans Biomed Eng, BME-45: 203-212, 1998.