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Trajectory Planning for Functional Wrist Movements in an ADL-Oriented, Robot-Assisted Therapy Environment

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Abstract— **A task-oriented robot-assisted therapy environment to support activities of daily living tasks was developed with the goals of addressing some of the shortcomings of current robotic therapy systems. An important aspect of making these environments work is the implementation of trajectory planning algorithms that support the naturally curving wrist movement seen in real life functional tasks. We explore the challenge of naturally supporting the positioning of the wrist for activities of daily living tasks such as drinking and feeding. In this paper, we examine the minimum jerk model often used to define trajectory planning routines to automatically position the wrist and present the results of fitting these two models to natural wrist movements for a drinking task. Also, we present a case study to examine how an able-bodied experienced the two models as implemented on the ADLER, task-oriented robot-assisted therapy environment.**

I. Introduction

All physical therapy techniques for stroke survivors have the same desired outcome; to train stroke survivors so that they are again able to function independently in their daily lives. Many differing approaches to therapy that have been attempted and there is a debate over which approach is the most effective. Although the most successful paradigm of physical therapy may not be easy to identify, certain aspects of these therapy methods that have proven to be beneficial to the patients can be identified. These are repetition, intense practice, motivation, and task application [1-2].

Repetitive practice of skilled tasks are thought to be particularly beneficial to stroke survivors due to the fact that they cause neuro-remapping and reinforce these plastic changes [4-8]. Patients who perform motivating tasks in enriched environments have been shown to have a significant increase in learning as compared to those who perform tasks that are not motivating [4-7, 9-10]. Highly functional, task-oriented, and purposeful environments have been shown to engage patients and increase motor recovery as well as carryover of function to the home environment [10,11].

Robotic therapy has the potential to address the aspects of physical therapy that have proven to be beneficial to the patients. Some of the robotic therapy environments that have been developed and put to use for experimental purposes include the MIT-MANUS [12], the MIME [13], and the GENTLE/s system [14], just to name a few. These and other similar systems are able to teach patients to perform point-to-point reaching movements to targets located at different points in 2-D or 3-D space. The effectiveness of these robotic therapy environments and other systems has been tested. It has been shown that in general, patients who are given the opportunity to use the repeatable, reliable, and precise robotic therapy show a faster recovery, decreased impairment, increased accuracy of movement, decreased task completion time, and smoother movements than their counterparts who received traditional therapy [12-15]. However, there are still challenges that must be addressed. One of the biggest challenges being faced is increasing carryover of functional gains to the home environment. Patients who use current robotic therapy environments show inconsistent carryover of the gains made in a therapy session to their home environment [15].

With the goals of addressing some of the shortcomings of current robotic therapy systems, the Activities of Daily Living Exercise Robot (ADLER) was created (Figure 1). The ADLER system combines the repeatable, reliable, and precise therapy afforded by robotics with the engaging, motivational, and purposeful ADL therapy [16]. The move to integrate these two techniques is new in the field and has been addressed by few other systems including the AutoCITE and the MIT-MANUS. From preliminary studies this integration of robotics and motivational therapy has potential to be more effective for patients but more research is needed [17, 18].

In order to create a task oriented environment within ADLER, it is necessary to understand how functional tasks are performed in real life and how these tasks can be programmed in the ADLER environment. The ADLER environment consists of a 6 degree of freedom HapticMASTER robot designed by FCS Control Systems which is attached by way of a gimbal and orthosis to patients' forearms or wrists. The system also includes a grasp assist glove with functional electrical stimulation. Trajectories are programmed into ADLER for each task to

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support positioning of the center of the gimbal, which is approximately equivalent to the center of the patient's wrist.

Figure 1: The HapticMASTER robot attached by way of the gimbal and orthosis to the patient's wrist. In this case the center of the gimbal is approximately equivalent to the center of the patient's wrist.

In this paper, we explore the challenge of naturally supporting the positioning of the wrist for activities of daily living tasks such as drinking and feeding. We examine the ability of the minimum jerk model as a trajectory planning algorithm to position the wrist to fit the natural curves noted for a functional drink movement. We present the results of implementing two versions of the model and a case study to examine how an able-bodied experienced the two models as implemented on ADLER.

One of the ideal goals of model development is to create an algorithm that can operate robustly and accommodate for varying movement requirements just as the central nervous system (CNS) can, i.e., an algorithm that receives as input all visual and spatial information about each task and outputs motor control schemes based on these inputs [19]. To develop a model that acts in this way, the movement requirements for each type of task must be analyzed for patterns that can be used as inputs to the model.

The functional requirements for the drink tasks were grouped into model inputs according to Table I. The functional requirements for the drink tasks were grouped as follows: Events 1 and 4 help define the Table Constraint (TC) and TC + Cup Type Object Manipulation. Events 2 and 3 help define the Movement Out of the Plane (MOP) and MOP + Cup Type Object Manipulation. In the analysis of these functional requirement groups, it was found that the critical time point (usually 40% of the event) correlated not only to the velocity and curvature maxima and minima but also to the maximal deviation from the predicted minimum jerk path in Cartesian coordinates. The magnitude of the Cartesian deviation from the original implementation of the minimum jerk trajectory thus can be used as the Cartesian inputs for the model. Table 1 presents a summary of all of the model input groups as well as the applicable events, the critical time for the via point (t1), and the Cartesian inputs (X1, Y1, and Z1).

II. Possible Trajectory Models for Supporting ADLs

A. *Minimum Jerk Model (Basic)*

When determining how to model the functional trajectories for the ADLER environment the minimum jerk trajectory theory was tested, as it is arguably the most used trajectory scheme in robot therapy environments [14, 20].

The minimum jerk theory was developed by Hogan and Flash [21-23]. They proposed that when humans executed a point-to-point reaching movement they maximized the smoothness of the movement. The Cartesian equations that were developed based on this theory are 5th order polynomials scaled to time and can be implemented in the ADLER environment. The model uses the boundary conditions of zero beginning and ending velocity and acceleration and supplying the initial and final points of the movement in the x, y, and z planes. The entire trajectory for the center of the gimbal and thus the center of the patient's wrist can be predicted by way of the following set of equations:

$$\begin{aligned} x(t) &= x_o + (x_o - x_f)(15T^4 - 6T^5 - 10T^3) \\ y(t) &= y_o + (y_o - y_f)(15T^4 - 6T^5 - 10T^3) \\ z(t) &= z_o + (z_o - z_f)(15T^4 - 6T^5 - 10T^3) \end{aligned} \quad (2)$$

In Equation 2, x_o, y_o, and z_o are the starting points of the movements (at t = 0) x_f, y_f, and z_f are the final points (at $t = tf$). T is the time scaled by the final time.

The results of these equations for modeling point-to-point reaching movements were verified by many different experimenters [14, 21, 22, 24]. This model predicts straight lined movements between two points and a bell shaped velocity curve.

B. *Minimum Jerk Model with Curvature*

In order to accommodate for movements that have curvature, Flash and Hogan took the minimum jerk trajectory theory one step further and developed a set of equations that can be used to model curved movements (Eqs. 3 and 4) [23]:

$$x^-(\tau) = \frac{t_f^5}{720}\begin{pmatrix} \pi_1\left(\tau_1^4\left(15\tau^4 - 30\tau^3\right) + \tau_1^3\left(80\tau^3 - 30\tau^4\right) - 60\tau^3\tau_1^2 + 30\tau^4\tau_1 - 6\tau^5\right) \\ + c_1\left(15\tau^4 - 10\tau^3 - 6\tau^5\right) \end{pmatrix} + x_0 \quad (3)$$

$$x^+(\tau) = x^-(\tau) + \pi_1 \frac{t_f^5(\tau - \tau_1)^5}{120} \quad (4)$$

Here, $\tau = t/t_f$, $\tau_1 = t_1/t_f$, and π_1 and c_1 are constant coefficients that depend on the position coordinates at the boundaries and at the interior point and on t_1 (Eqs. 5 and 6)

$$c_1 = \frac{1}{t_f^5\tau_1^2(1-\tau_1)^5}\begin{pmatrix} (x_f - x_0)(300\tau_1^5 - 1200\tau_1^4 + 1600\tau_1^3) \\ + \tau_1^2(-720x_f + 120x_1 + 600x_0) + (x_0 - x_1)(300\tau_1 - 200) \end{pmatrix} \quad (5)$$

$$\pi_1 = \frac{1}{t_f^5\tau_1^5(1-\tau_1)^5}\left((x_f - x_0)(120\tau_1^5 - 300\tau_1^4 + 200\tau_1^3) - 20(x_1 - x_0)\right) \quad (6)$$

The above equations can be expanded to apply to the Y and Z directions. These equations predict a movement passing through the prescribed via point at a given time and take as inputs the Cartesian location of the start and end points of the path. For the trajectories tested using these equations, the minimal velocity corresponded to the point of maximum curvature [23].

This model was tested for various locations of the via point. Flash and Hogan found that the shape of the trajectory depended on the location of the via-point. When the via point was moved closer to the start or end locations, the other segment of the movement became elongated [23]. They also found that bimodal velocity curves had a higher peak velocity for the longer segment of the movement. And finally, they found a relationship between the depth of the velocity valley and the magnitude of the curvature, which is in agreement with the results obtained by Abend and colleagues [24].

This curved minimum-jerk trajectory approach preserves many of the features of the basic minimum-jerk model. It was developed using the same optimization approach and therefore should create trajectories that mimic natural movement. In order to use this model for the functional movements on the ADLER environment, the via point between the segments of the task trajectory were chosen.

III. EXPERIMENTAL METHODS

A. *Method Used to Derive Wrist Data for Testing Models*

The drinking functional task was evaluated (Table 1). Eight right-handed, able-bodied subjects were asked to complete this and other functional tasks such as feeding and hair combing. They ranged in age from 20 to 72 years and all gave informed consent to participate in our IRB approved protocol. Figure 2 shows the layout of the drink task on the table top and Table II shows the four events that comprised the drinking task. When completing the tasks, subjects were instrumented with 12 reflective markers attached over specific bony landmarks on the upper extremity and seated in the motion analysis lab (Froedert Hospital, Milwaukee, WI).

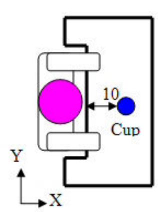

Figure 2: A top view of the activity table set up for the drink task. The cup is 10 inches from the table edge along the subject's midline.

The subjects were given instructions for each functional task and were asked to perform each task at a self selected comfortable pace three times. Fifteen Vicon cameras (Vicon Motion Systems Inc.; Lake Forest, CA) recorded the data at 120 Hz by tracking infrared light that was reflected from the markers worn by the subjects. The Vicon 524 motion analysis system provided the three-dimensional coordinates of the markers in space and it was then possible to reconstruct the patients' upper body. The Cartesian data was obtained from kinematic model for the upper extremity [25]. The Cartesian trajectory information for the wrist center is used in the data analysis. Events were separated based on analyzing subject's velocity profiles (Table II).

The data was filtered via a Woltring filter with a predicted mean square error of 20. Task trajectories were normalized to (0, 0, 0) starting location. Data was then processed by way of a custom MatLab program. Trajectories for each task and event were then averaged using the polyfit and polyval functions in MatLab.

The curvature and velocity were also analyzed to help identify the logical locations of the via points for each of the events defined in Table II. We located the locations by examining the temporal correlation between the tangential velocity profiles and curvature. In order to identify Cartesian inputs at the via point, functional aspects of the tasks were grouped according to their requirements and the resulting sets of trajectories were analyzed to obtain patterns that can be used as inputs. The events were then grouped by patterns of deviations from the basic minimum jerk trajectory scheme and these deviations were quantified. Using these deviations as inputs, functional curvature was added to the minimum jerk predictions using the more advanced paradigm of the minimum jerk theory (Eqs. 3-6). The trajectories generated using this approach were programmed into the ADLER environment and used to test the viability of this model for functional task trajectory generation in this robotic therapy environment.

B. *Method Used to Evaluate Models on ADLER*

For the testing of the models, a case study was performed in which one normal healthy subject participated. The subject was right handed and age 22. The subject's arm was secured in the wrist orthosis (Fig. 1), which allows for hands free motion. The subject was then seated at the activity table, which was adjusted to a comfortable distance. The subject was asked to perform the 'Drink' and other tasks with both the original minimum jerk model and the model that considered curvature in form and normal modes, three times in each mode. The subject was not cued as to the differences in the models nor when either one was being used. In form mode, ADLER provided forces to keep the subject on the prescribed trajectory as well as assistance in the forward direction of movement for task completion. In normal mode ADLER does not provide any forces or assistance. The cup was placed in the same locations as were used in the motion analysis data collection. The instructions for task completion were the same as those given in the motion analysis setting, and the events for each task were the same as well.

ADLER was initialized to offset the weight of the robotic arm. All tasks were customized to the subject. A task database was used to load the relevant input points that were chosen apriority. Position and force data were recorded for each task but only the position data is treated here. The subject was asked a set of questions at the completion of each task to help to determine the 'feel' of the task. The data collected was analyzed to determine the area between the curves of the model data from the old and new paradigm and the data collected in normal mode (considered as the desired trajectory).

IV. Results and Discussion

A. Drink Task with Basic Model

Figures 3 and 4 show the wrist paths created for the four events of the drink task in the XY and XZ planes. The figures also show the straight-lined trajectories using the basic minimum jerk model in section II-A. It is clear that the difference between the actual movement and model 1 was significant especially in the XZ plane. In a previous study, we showed that this scheme does not appropriately model functional task oriented movements [26]. Tasks were performed under three conditions; object present, object imagined, and object absent were compared, and it was found that the presence of functional objects as well as task oriented goals caused significant deviations from the straight line trajectories predicted by the basic implementation of the minimum jerk trajectory theory. When an object was present as a functional goal, trajectories became significantly more curved than the minimum jerk trajectory predicted. This curvature was shown to depend on object orientation, placement, functional goal, as well as plane of movement.

B. Differences Accounted for with New Model

The minimum jerk model with curvature considerations combined with the model inputs for via points was a better fit than the basic model. The model inputs lead to significant reduction of area between data curves was seen for all events as compared to the original minimum jerk paradigm (old). An example of this can be seen in Figures 5 and 6, which shows the XY and XZ plane data for event 1 ('Reach') and event 4 ('Rest') of the drink task in the object present condition. The data collected from the motion analysis lab is plotted along with data generated from the implementation of the old paradigm of the minimum jerk model as well as the new paradigm of the minimum jerk model. Table III shows the comparison of the area under the position curves for the new and old models.

C. Case Study of the Model Implemented on ADLER

The two versions of trajectory generation (new and old) were used on the ADLER environment for the drink as well as a feed and comb task. The results from the case study are presented in Figures 7 and 8. The area between curves was significantly reduced for all the drink events. The new model provides a more accurate prediction of the desired functional trajectory than the old paradigm of the minimum jerk model. These results show that this trajectory generation scheme provides more appropriate wrist center paths for implementing functional tasks in the ADLER environment. This improvement was noted by the subject as well. Table IV shows the average responses to the questions presented to the subject after each trial. When using the new model and asked if the robot was moving the way he would have liked to move he answered with an average value of 7. This is a more positive response than for the old model, with which he answered 3. When using the new model and asked if he felt as though he had to work against the robot to complete the task he answered with an average value of 2. This is a more positive response than for the old model, with which he answered 5. His comments reveal that the old model did produce movements that did not feel natural. The results from the questionnaire show that the differences seen between the new and old model can be felt by the subject and that using the new model provides for a more comfortable experience and more natural feeling movements.

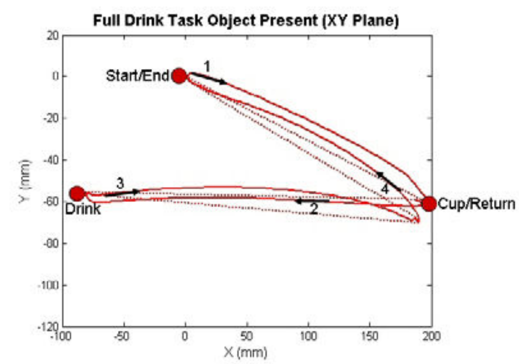

Figure 3: Average wrist trajectory for the drink task along with the basic minimum jerk model (light dash lines) for the XY plane. The arrows indicate how the events unfold.

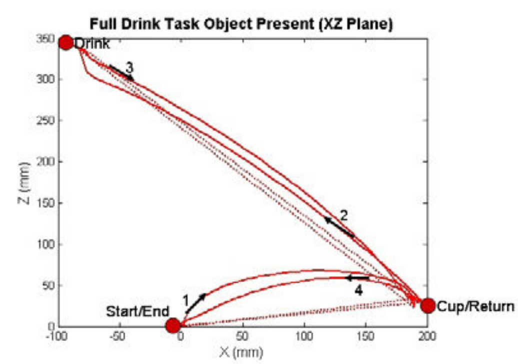

Figure 4: Average wrist trajectory for the drink task along with the basic minimum jerk model (light dash lines) for the XZ plane. The arrows indicate how the events unfold.

V. Conclusion

Based on the analysis of the motion data for the drink and feed tasks, a modeling scheme was developed that utilizes an advanced paradigm of the minimum jerk trajectory theory. This model was implemented on the ADLER environment and was shown to accommodate for much of the curvature that appears to be the result of the presence of the functional object and task specific goals. This model accommodates for the differing curvature as the goal and direction of movement change as well as when the functional object changes. In the case study performed on the ADLER system, the subject reported a "more natural" feel when operating with the new model rather than the old model. This shows that the model appears to meet the goal of providing a more natural prediction of functional wrist paths. Although these results are promising it is understood that much more work to be done.

Overall, this paper has shown that the minimum jerk model with curvature considerations and custom inputs for trajectory generation can be used in robotic therapy to allow stroke patients to train on ADL tasks in a more natural and functional way. Ideally, the implementation should be more robust. To achieve this, we will use visual servoing algorithms to improve automatically define the model inputs and the trajectory planning during robot-assisted therapy.

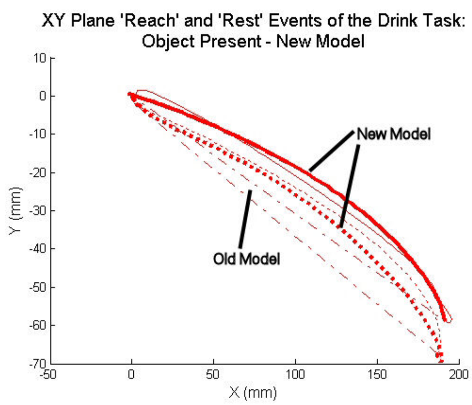

Figure 5: XY plane data for the 'Reach' and 'Rest' events of the Drink task. The new model is represented by heavier lines (solid = reach, dotted = rest), the average data is represented by lighter lines (solid = reach, dotted = rest), and the old model is represented by dashed lines.

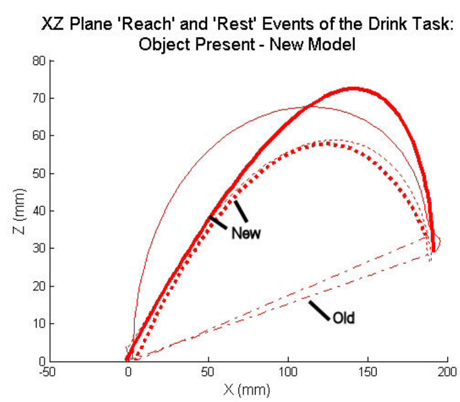

Figure 6: XZ plane data for the 'Reach' and 'Rest' events of the Drink task. The new model is represented by heavier lines (solid = reach, dotted = rest), the average data is represented by lighter lines (solid = reach, dotted = rest), and the old model is represented by dashed lines.

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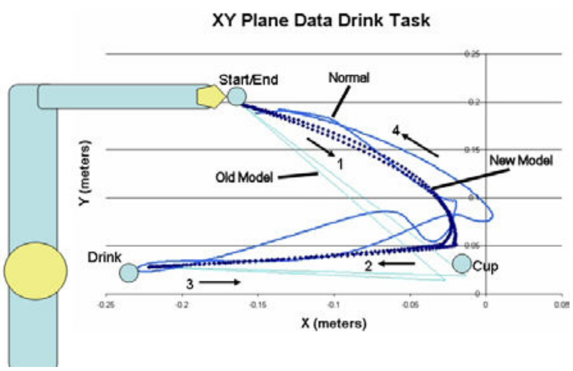

Figure 7: XY plane data of (from top to bottom) the drink task. The data collected in normal mode is represented by a thick solid line, the data collected when using the old model is represented by a thin solid line, and the data collected when using the new model is represented by a dotted line.

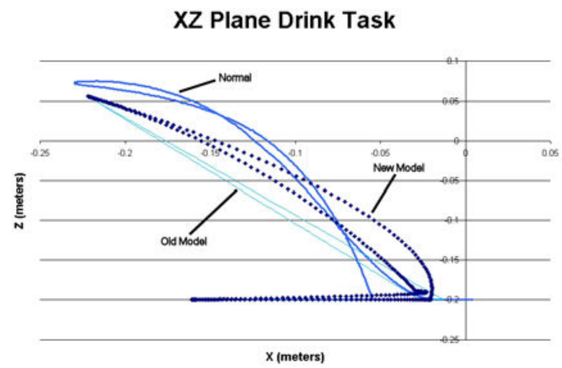

Figure 8: XZ plane data of (from top to bottom) the drink task. The data collected in normal mode is represented by a thick solid line, the data collected when using the old model is represented by a thin solid line, and the data collected when using the new model is represented by a dotted line.

TABLE I: SUMMARY OF ALL MODEL INPUTS
THE CRITICAL TIME FOR THE VIA POINT IS LISTED AS T1 AND THE CARTESIAN INPUTS ARE LISTED AS X1, Y1, AND Z1.

Model Input#	Purpose	Applicable Events	*t1*	X1	Y1	Z1
1	Table Constraint (TC)	'Reach' 'Rest'	.40 .40	N/A N/A	N/A N/A	42 mm 28 mm
2	TC+Cup Manipulation	'Reach' 'Rest'	.40 .40	39mm 39mm	N/A N/A	T.C. + 12 mm T.C. + 7mm
3	TC+Spoon Manipulation	'Reach' 'Rest'	.40 .40	N/A N/A	N/A N/A	T.C. - 15 mm T.C. + 6mm
4	Movement out-of-the-plane (MOP)	'To Mouth' 'Return Object'	.40 .40	N/A N/A	N/A N/A	59mm 59mm
5	MOP + a cup-type object	'To Mouth' 'Return Object'	.23 .40	16mm 16mm	N/A N/A	10.5mm 10.5mm

TABLE II: FUNCTIONAL TASK ANALYZED

	Object Present
Events 1-4 Drink	Reach to cup (E1), Bring cup to mouth (drink) (E2), Return cup to table (E3), Return to rest (E4)

TABLE III: SUMMARY OF AREA REDUCTION WHEN IMPLEMENTING THE NEW MODEL FOR THE DRINK TASK

	Old Model **XY**	New Model **XY**	Diff. **XY**	Old Model **XZ**	New Model **XZ**	Diff. **XZ**
	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
E1	**2189** (179)	**52** (15)	**2137**	**4589** (97)	**157** (29)	**4432**
E2	**584** (42)	**398** (43)	**186**	**57** (5.8)	**21**(12)	**36**
E3	**584**(42)	**398**(43)	**186**	**57** (5.8)	**21**(12)	**36**
E4	**2189** (179)	**52** (15)	**2137**	**4589** (97)	**157** (29)	**4432**

The areas between the old and new model curves as well as the difference are presented in each plane for events 1-4 of the drink task. Difference data is in shaded columns.

TABLE IV: SUBJECT SURVEY AT THE END OF EACH TRIAL

Question	Response Range (1-10)	Average Response
Do you feel as though the robot is moving the way you would like to move?	10 = Yes, completely; 5 = About half the time; 1 = No, not at all	Old Model: 3 +/-1 **New Model: 7 +/- 1 ***
Do you feel as though you need to fight against the robot to complete the task?	10 = Yes, all the time; 5 = About half the time; 1 = No, not at all	Old Model: 5 +/- 1 **New Model: 2 +/- .5 ***

The questions, possible responses, and average responses are listed. Representative comments were chosen for each model. If a result was statistically more successful by means of a T-Test it is marked with an asterisk and in bold.