Modeling of Joint Synergy and Spasticity in Stroke Patients to Solve Arm Reach Tasks

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Neurological damage caused by stroke can result in motor control impairments [1] such as deleterious joint synergies (involuntary coactivation of joints) and spasticity (involuntary muscular contractions that limit range of motion). These issues reduce the arm workspace, necessitating modified rehabilitation training methods. Task-specific therapies that simulate activities of daily living (ADL) can be used to relearn the requisite motions [2]. However, individuals with joint synergy and spasticity may not know how to complete daily living tasks while compensating for their motor issues. This research focuses on developing an algorithm that finds efficient reach paths by taking into account the joint synergy and spasticity. In addition to helping patients complete ADLs, the algorithm could serve as a tool for classifying the feasibility and painfulness of reach tasks.

The algorithm attempts to minimize overall travel distance, thus counteracting synergy and avoiding movement through penalized spastic regions. To simulate the reach tasks, a 7 degree-of-freedom robotic representation of the arm was developed in MATLAB using the Robotic Vision toolbox [3]. The algorithm performs an iterative branched search in which nodes, representing joint configurations, are created, scored, and evaluated. Initially, a single node stores the starting configuration of the seven joints. Given a node, an angular increment or decrement (set to 3º) is considered for each of its joints. These joint commands can cause up to fourteen "children" nodes to be created. The node data structure stores the current values of the seven joints (the node's joint vector), the sequence of joint commands that led to these joint values, and the current XYZ position of the hand.

It was deemed too computationally intensive to track all possible children nodes as the program progresses. A scoring metric ensures that only the least efficient paths are deleted. A node's score is a weighted sum of the distance to the target from the current hand position and the net path travel distance in XYZ space. As efficient paths minimize travel distance while approaching the target, lower scores are better. When a solution is first found, indicated by the final hand position being within a minimum distance (5 cm) from the target, all nodes with longer travel distances are deleted as being less efficient. Nodes with shorter travel distances have the potential to be more efficient and therefore continue to spawn children. A descendant of these nodes will either reach the target with less travel distance, causing it to replace the previous solution, or will be deleted for exceeding the current solution's travel distance. This process converges to a single solution.

Two types of spasticity, hard and soft, were added to the model to allow for flexibility in future applications. Hard spasticity defines joint limits that cannot be exceeded. Nodes are not created if the specific joint movement taken would result in violation of a hard spasticity limit. Soft spasticity defines regions wherein any joint movement is somewhat difficult for the patient. In the model, this movement results in a penalty that is added to the node travel distance, increasing its score. Using soft spasticity, a penalty weighting can be appropriately assigned so that a path through a spastic region will be selected only when such movement is necessary for task completion. More generally, by varying the penalty weightings for different joints, the algorithm can be used to identify alternative paths for the same reach task.

Each of seven Fugl-Meyer (FM) tasks for which data was collected in [4] primarily utilized just one of the seven joints. The data were analyzed in [4] to develop a synergy matrix whose accuracy was confirmed via a statistical comparison of synergy matrix and FM scores. To derive the synergy matrix, the least squares linear fit was calculated for every pair (i,j) of joint angles using data from the FM task for joint j. The (i,j)th element of the synergy matrix was the slope of the corresponding linear fit. Given a command for joint i, the angular change for all seven joints is the ith column of the synergy matrix scaled by the joint angular increment/decrement.

The algorithm was evaluated by simulating a shoulder reach task both with and without synergy and spasticity. Based on the simulation results, the algorithm successfully minimizes travel distance while taking into account spasticity and synergy. The lowest scoring solution largely avoided spastic regions when possible, took angular steps to counteract synergistic interactions that caused the path to deviate from the target, and minimized travel distance relative to the other feasible paths found. More algorithm details are in the poster, which cites [3]-[9].

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MODELING OF JOINT SYNERGY AND SPASTICITY IN STROKE PATIENTS TO SOLVE ARM REACH TASKS

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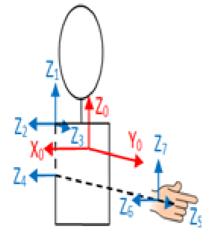
Introduction

- Stroke causes deleterious joint synergies and spasticity. Affected individuals may not know how to complete daily living tasks while compensating for their motor issues.
- Research goal: develop an algorithm that minimizes travel through spastic regions to avoid pain and also counteracts synergy to enable completion of the reach task
  - Can help patients complete activities of daily living
  - Can help classify feasibility and painfulness of reach tasks

Approach



1=shoulder interior/exterior rotation
2=shoulder abduction/adduction
3=shoulder flexion/extension
4=elbow flexion/extension
5=wrist/forearm pronation/supination
6=wrist flexion/extension
7=wrist ulnar/radial deviation

Fig. 1

- 7 degree-of-freedom robotic arm model developed using the Robotic Vision toolbox [3]
- Algorithm performs an iterative branched search in which nodes, representing joint configurations, are created, scored, and evaluated. Node stores vector of 7 joint values, sequence of joint commands (history), XYZ position of the hand
- Given a node, angular step (increment or decrement) considered for each joint, creating up to 14 children nodes
- Node score = weighted sum of distance to target from the current hand position and the net path travel distance in XYZ space. Highest scoring nodes deleted when # of nodes > 1000
- Node not created if potential command has opposite sign of any previous command for same joint
- Node collapsing: when nodes are similar in joint space, the node with greater travel distance is deleted
- Convergence: set the first node within 5 cm of target as the initial solution and delete nodes with greater travel
- Other paths grown until a. deleted because they have greater travel or b. reach target with less travel than the solution, in which case they become the new solution
- Procedure converges to a single feasible path for suitably chosen weights

Synergy

- Data [4] from 7 Fugl-Meyer (FM) tasks, each of which primarily utilized one of the 7 joints
- Synergy matrix: [4] set (i,j)th matrix element to slope of least squares linear fit of data from FM task for joint j
- Given a command for joint j, the angular change for all seven joints is the jth column of the synergy matrix scaled by the commanded angular increment/decrement

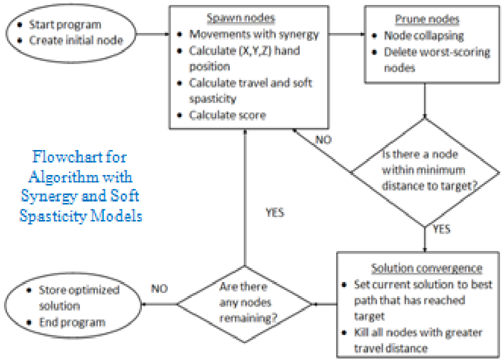
Spasticity

- Hard Spasticity: joint limits cannot be exceeded, so node not created when hard spasticity limit violated
- Soft Spasticity: joint movement is difficult for the patient, so apply node travel distance penalty for angular movement through soft spasticity region
- By varying the penalty weightings for different joints, the algorithm can be used to identify alternative paths for the same reach task
- Research [5], [6] shows a linear relationship between force applied to move a spastic joint during slow stretch and the angular deviation from a threshold, so developed linear spasticity model

$$\text{Soft Spasticity Penalty} = F \times D \times C$$

- F: Average force angle is the average of the initial and final angles in soft spasticity region; these angles are expressed as non-negative delta values relative to the edge of the region, and are based on the initial and final angles of a movement.
- D: Angular distance is the absolute value of the difference between the final and initial angles in the region.
- C: Constant, typically individual- and task-specific, that converts the product of the average force angle and angular distance to a travel distance penalty with units of centimeters.
- Penalty is additive: penalty for a single movement of $x° + y°$ into the spastic region equals sum of the penalties for first moving $x°$ and subsequently an additional $y°$:

$$(\text{initial } 0° + \text{final } x° + y°) \times \text{angular distance } x° + y° =$$
$$(\text{initial } 0° + \text{final } x°) \times \text{angular distance } x° +$$
$$(\text{initial } x° + \text{final } x° + y°) \times \text{angular distance } y°$$



- Start program
- Create initial node

Spawn nodes
- Movements with synergy
- Calculate (X,Y,Z) hand position
- Calculate travel and soft spasticity
- Calculate score

Prune nodes
- Node collapsing
- Delete worst-scoring nodes

Is there a node within minimum distance to target?

NO

YES

Solution convergence
- Set current solution to best path that has reached target
- Kill all nodes with greater travel distance

Are there any nodes remaining?

YES

NO

- Store optimized solution
- End program

Flowchart for Algorithm with Synergy and Soft Spasticity Models

Simulation Results

- Simulated shoulder reach task with and without synergy and spasticity. Arm starts straight down and ends with hand outstretched in front of body. Fig. 2 shows starting, halfway, and ending configurations with healthy synergy.
- Fig. 3 joint history generated without synergy or spasticity; the efficient path (119 cm) approximates a straight line.
- Fig. 4 shows healthy synergy; final hand position is near target, but path length increases to 120 cm. Dip in joint angle 5 results from a joint 5 decrement to counteract synergy.
- Fig. 5 shows stroke-induced synergy path (132 cm). The pervasive switchbacks seen in the joint history reveal that commands were taken to counteract the deleterious synergy.
- Fig. 6 implemented soft spasticity on joint 3, shoulder flexion, with an upper threshold set at 0°. Shoulder flexion is crucial to completing the task, so the solution utilizes shoulder flexion but minimizes it, compensating with more elbow flexion.

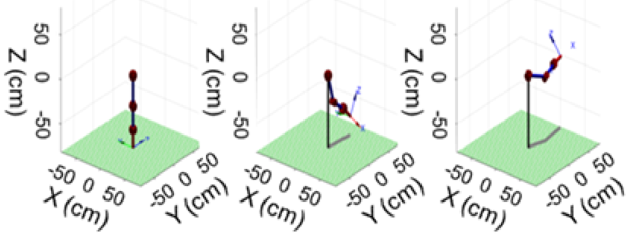


Fig. 2

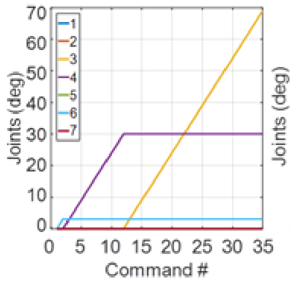


Fig. 3

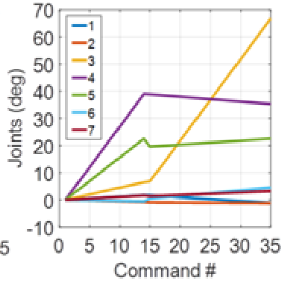


Fig. 4

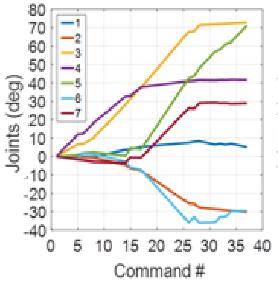


Fig. 5

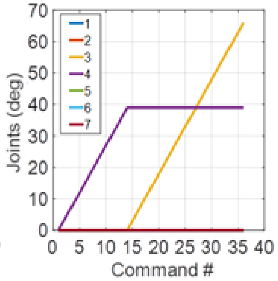


Fig. 6

Conclusions

- Algorithm successfully minimizes travel distance while taking into account spasticity and synergy.
- Although algorithm provides a general framework for generating reach task solutions, enhancements are possible:
  - Dynamics, namely gravity, the mass of the arm, and joint torques [7], would yield a more physical model.
  - Research [8] shows that factors based on the arm position may be involved. Could be taken into account by allowing score weights and factors to vary throughout the task.
  - More sophisticated synergy model could incorporate nonlinear polynomials and allow state-dependence [9].

References listed in abstract