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A Task Description Model for Robotic Rehabilitation

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Abstract— **The desire to produce robots to aid in physical neurorehabilitation has led to the control paradigm *Assistance-As-Needed*. This paradigm aims to assist patients in performing physical rehabilitation tasks whilst providing the least amount of assistance required, maximizing the patient's effort which is essential for recovery. Ideally the provided assistance equals the gap between the capability required to perform the task and the patient's available capability. Current implementations derive a measure of this gap by critiquing task performance based on some criteria. This paper presents a task description model for tasks performed by a patient's limb, allowing physical requirements to be calculated. Applied to two upper limb tasks typical of rehabilitation and daily activities, the effect of task variations on the task's physical requirements are observed. It is proposed that using the task description model to compensate for changing task requirements will allow better support by providing assistance closer to the true needs of the patient.**

I. INTRODUCTION

Robotic rehabilitation aims to improve the efficiency and efficacy of recovery of patients requiring physical neurorehabilitation. The use of robotics has shown to be beneficial [1]–[4] however it is still unclear what is the best rehabilitation paradigm. A good review of control strategies used can be found in [5]. The paradigm Assistance-As-Needed (AAN), sometimes referred to as *performance-based* rehabilitation has shown promising potential [6]–[8]. AAN aims to assist a patient with the minimum assistance required for them to perform physical tasks. Generally, the ideal assistance equals the gap between the capability the patient has and the capability the task requires, illustrated by Fig. 1. It's reasoned that minimizing assistance increases the patient effort essential for neurorehabilitation [9]. Expressing maximum physical effort is also analogous to strength training which aids recovery [10]–[13].

Determining this gap is a challenge. It requires estimation of both task requirement and patient capability. A solution is to derive a measure of this gap empirically by critiquing task execution against performance criteria. Providing assistance based on this measure, combined with a *forgetting factor* will converge to an assistance appropriate for the patient and task [6]–[8]. Although promising, limitations still exits.

The ability of an empirically derived performance measure to reflect the assistance needs of a patient during a task depends on how it was calculated. For example a point-to-point movement task critiqued solely on total time taken does not encapsulate how the patient's capability changed during the task. Assistance adaption is then limited to be task-by-task. Compare this to critiquing continuously during the task (e.g., by movement smoothness) it may be possible to identify segments within the movement requiring more assistance and others requiring less. Secondly, systems that rely highly on a forgetting factor to learn the patient's needs are subject to non-ideal assistance during learning. Changing task requirements will increase learning time. Within the hospital context this is less significant as normally only a few well structured tasks are performed. However it is conceivable (or even desirable) that in the future robotic rehabilitation will make its way into the home, assisting activities of daily living (ADL). In this scenario the variations of tasks performed will be vast, and may require a long time for the robot to learn appropriate assistance levels.

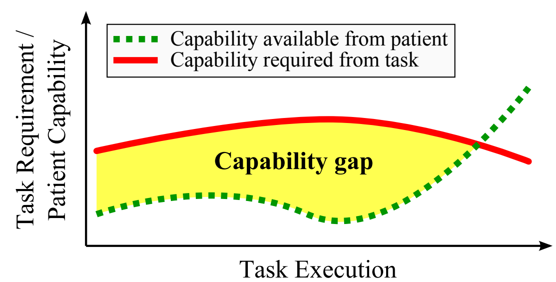

Fig. 1: Generalization of the gap between the capability the task requires during its execution, and the capability available from the patient. The AAN paradigm aims to provide assistance to fill this gap.

This paper presents a model for defining tasks performed by a patient's limb, allowing task requirements to be estimated. It is proposed that by using a task model to compensate for changes in task requirements, rehabilitation efficacy may be improved by providing assistance truer to the patient's needs. Section II develops the model used to define the task, compute task requirement and task performance measures. Section III defines and simulates two upper limb tasks based on existing robotic therapies. The effect of task variation consistent with ADLs are also investigated. Section IV discusses the results in relation to AAN efficacy.

II. TASK FRAMEWORK

Tasks need to be defined such that measures representing the task requirements and evaluating task performance can be derived. Rehabilitation tasks are often critiqued by the limb's trajectory, for example a minimum-jerk movement for the hand or a conventional walking gait for the lower limb. Force interactions with the environment may also be

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part of the task or used to evaluate performance. With this in mind we define the task by decomposing limb dynamics into two components; movement and external load. The task requirement may be generalized by (1) where S_T is the requirement from the task for it to be adequately performed, Q is the limb motion, and F are external forces. Disturbances during task execution, such as unexpected changes in limb trajectory or external force, are represented by d.

$$S_T = f(Q, F, d) \tag{1}$$

Limb movement (Q) cannot always be fully defined by the end point due to kinematic redundancy. We therefore use vectors $\mathbf{q}$, $\dot{\mathbf{q}}$ and $\ddot{\mathbf{q}}$ to represent the position, velocity and acceleration of the degrees of freedom (DOF); e.g., $\mathbf{q} = [q_1, q_2, \cdots, q_k]^T$ for k-DOF.

Force interactions (F) with the environment are represented by scalar magnitude F^E and workspace direction unit-vector $\mathbf{u} = [u_x, u_y, u_z]^T$. For simplicity we assume interaction occurs only at the end point of the limb and has no moment component. Tasks may be defined as involving one or both of these components. An example is shown in Fig. 2.

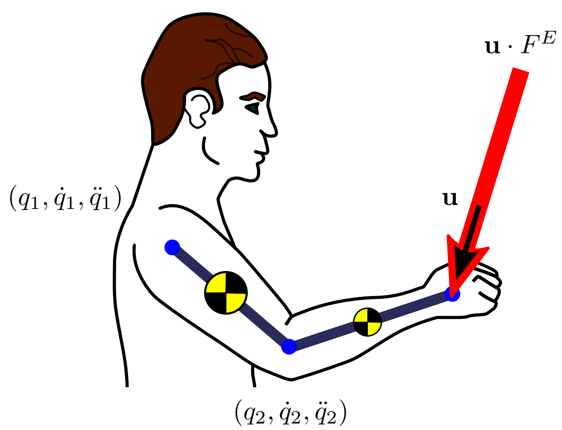


Fig. 2: Example of a task utilizing the upper limb.

This task model can be utilized in an AAN paradigm to represent task requirements and evaluate task performance. For example, consider a robot assisting a patient performing point-to-point movements of the hand whilst opposing external forces. Task performance may be critiqued against a minimum-jerk movement profile using forward kinematics based on $\mathbf{q}$. Task requirement may be defined as the limb joint torques required to perform the task. Using inverse dynamics dependent on $\mathbf{q}$, $\dot{\mathbf{q}}$ and $\ddot{\mathbf{q}}$ and the external force represented by $\mathbf{u} \cdot F^E$, the required torques can be computed.

III. Simulation of Tasks Typical of Rehabilitation and Daily Living

To demonstrate using the task model in a realistic context two scenarios typical of robotic rehabilitation are simulated. The task model is used to observe how task requirements change as the limb is moved during execution. Secondly, a comparison of task requirement with and without an external force typical of ADLs is performed. In terms of (1) we are observing the change in task requirements (S_T) in response to the task's limb movement (Q) and ADL external force (F). Disturbances are considered random and their effects are not simulated.

In Task 1 (Fig. 3a, based on [8]) the patient's hand follows trajectories from a home position to one of seven spatially distributed targets in the frontal workspace. This mimics activities such as lifting, carrying, and putting down objects. An external force is used to compare task requirement with and without an object being carried in the hand. A force of 3N in the direction of gravity is used as 90% of ADL objects lifted weigh 300g or less [14]. Task 2 (Fig. 3b, based on [6]) is similar to the first except the home position and eight targets are located in a horizontal plane at table height. This mimics someone sliding an object across a table top. Task requirements are compared with and without a 2.5N horizontal force opposing movement at the hand, representing a 700g bowl being slid [15].

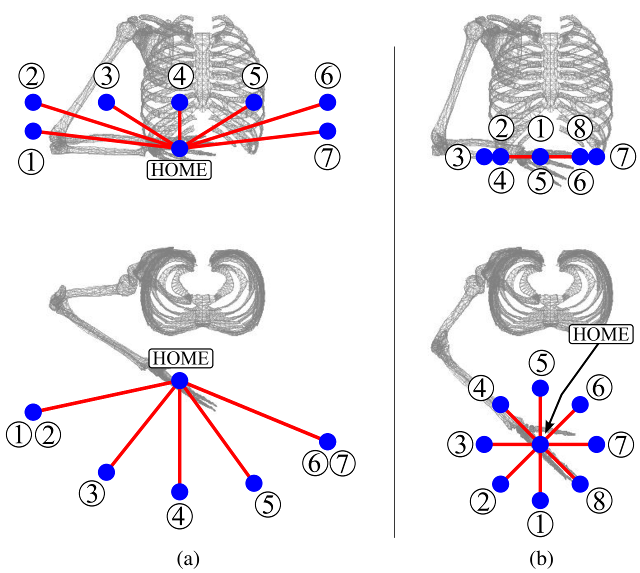


Fig. 3: Two tasks simulated; (a) Task 1 based on [8]. (b) Task 2 based on [6].

Considering the choice of mechanism by which the need for assistance is determined and consequently administered, there is debate as to weather using motion or force is best [9]. We choose strength (force) as it best suits our simulation. Supporting this rationale are studies showing limb strength is a large factor in limb functionality [16], [17].

To calculate the strength required to perform Task 1 and Task 2 we compute the joint torque loading on the limb at the shoulder and elbow. Joint loads are calculated as the hand is moved from the home position to each of the task's targets. Elbow redundancy is resolved using the method proposed in [18]. A musculoskeletal model [19] using 4 DOF relating to the shoulder and elbow, with mass properties equivalent to a 50th percentile male [20] [21] is used. For typical upper limb ADLs the loads resulting from inertial, centrifugal and

Coriolis effects are insignificant in comparison to the gravity loading [22]. We therefore calculate the task requirements as the shoulder and elbow strengths required to oppose gravity and external forces during the task. Load torque on the 4 DOFS are calculated using OpenSim [23], with the three shoulder torques combined into a single load torque of equivalent direction and magnitude. The task requirement is then represented by the two magnitudes of torque required at the shoulder and elbow joints.

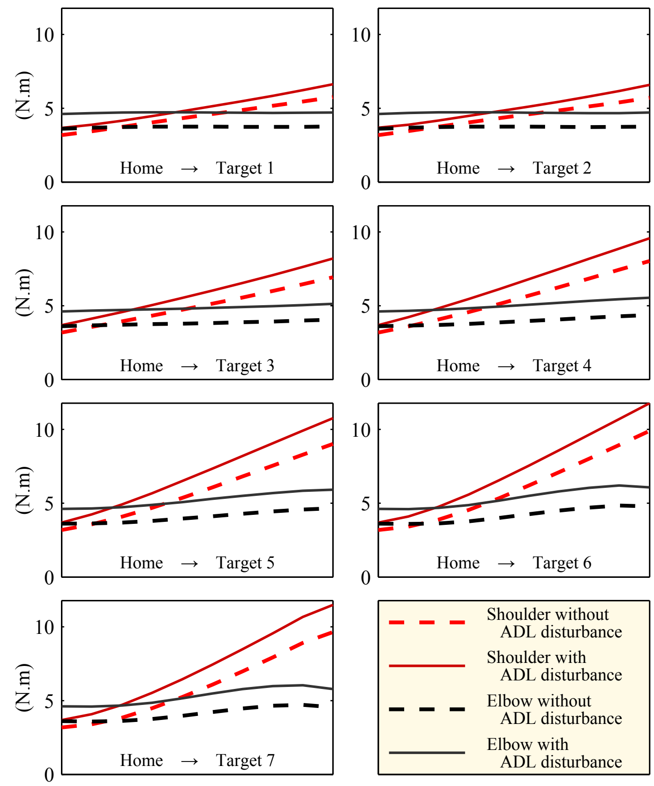
IV. RESULTS AND DISCUSSION

Results for Task 1 (Fig. 4a) show the shoulder and elbow strength requirement increases as the hand is extended towards each target. Largest change was when reaching for target 6. Shoulder strength requirement increased from 3.18 N.m to 9.89 N.m, a change of 6.71 N.m. Elbow requirement increased from 3.61 N.m to 4.78 N.m, a change of 1.17 N.m. The largest change in strength requirement with and without external ADL force was also for target 6, 1.87 N.m and 1.35 N.m for shoulder and elbow, respectively.

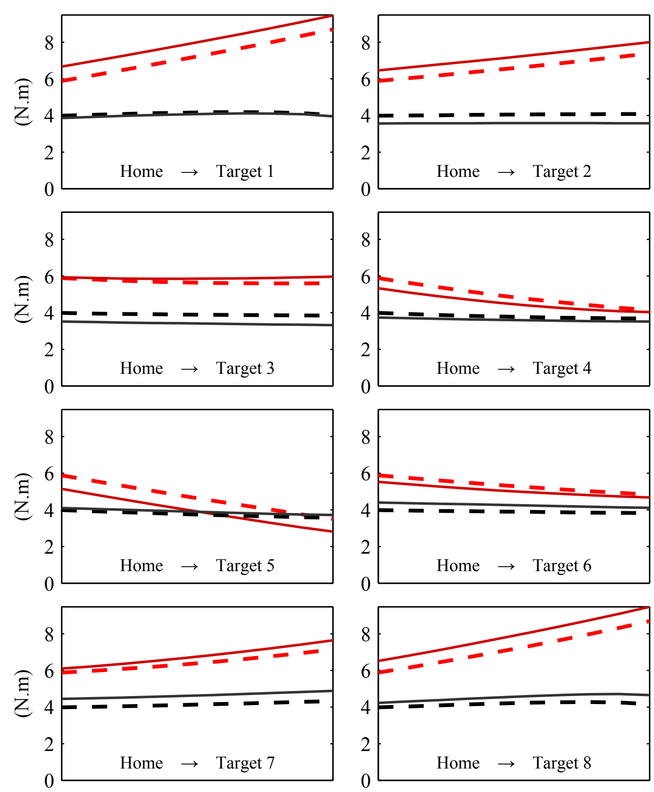
Results for Task 2 (Fig. 4b) show the elbow strength requirement changed little in response to both movement and external force. This is due to little change in forearm orientation during the task, and small moment arm between the horizontal ADL force and elbow joint axis. Change in required shoulder strength was largest when reaching target 1, increasing from 5.89 N.m to 8.71 N.m, a change of 2.82 N.m. Largest change in shoulder strength requirement from the ADL force was 0.79 N.m when reaching target 8. For the elbow the largest change due to the ADL force was 0.56 N.m for target 7.

These results provide insight into the changing needs of the patient due to changes in task requirements as they are performed. They also allow estimation to the extent such task variation can detract from providing true assistance as needed if not accounted for. Consider a simple implementation of an AAN robot that utilizes no task model. Empirically critiquing task execution as a whole (from home to target) results in an estimate indicative of the patient's *average* assistance needs. This scenario applied to Task 1, target 6, providing assistance equal to this task's median requirement will at its worse provide ±51% off its actual requirements. Admittedly this result is based on the task with largest variation, and we have not considered changes in the patient's capability, however it does highlight the potential adversity of not considering a task's changing requirements.

Likewise we consider the effects of a typical ADL external force on providing true AAN. Task 1 requires the patient to oppose gravity, and since the ADL force from carrying an object is also due to gravity, this effectively biases the task requirement. A forgetting factor acting like the integral term of a PID controller should be capable of compensating this bias over time. Compare this to Task 2 where the effect from the ADL force changes direction depending on the interaction with the environment, in this case the direction the object is slid across the table. A forgetting factor would not be as effective in compensating, particularly for



(a) Task 1



(b) Task 2

Fig. 4: Results showing task strength requirements changing during task execution. Required shoulder (red) and elbow (black) strengths, plotted in solid and dashed curves representing with and without ADL external force, respectively.

loads changing often. Such a scenario would occur during interaction with unstructured environments, for example in the household.

V. CONCLUSION

In this paper we presented a task description model for modeling physical tasks performed by a patient. This model can be used to estimate task requirements, providing information that then could be used to adapt the assistance provided by a robot during rehabilitation. Applying the task model to two realistic rehabilitation scenarios we observed how the task requirements changed.

Results showed for the tasks simulated their strength requirements changed significantly, both due to limb movement and from the addition of conservative external forces consistent with typical ADLs. Furthermore, the effect of the ADL external force on task requirements depended on how it was applied, for example the direction an object is slid across a table. This highlights that in unstructured environments where the tasks vary (e.g., picking up or sliding an object) changes in the task requirements are significant and need to be accounted for to provide assistance true to the needs of the patient.

The task model presented here is a step towards developing an AAN framework for providing robotic assistance based on the changing needs of the patient. A model like the one presented here could be used to compensate for changes in task requirements. A future goal is to combine a model that estimates changes in task requirements with a model estimating patient capabilities, for example [24]. The resulting estimate of the gap between task requirement and patient capability may form the basis on which assistance can be provided.

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