Hierarchical Task Ordering for Time Reduction on KINARM Assessment Protocol

Sayyed Mostafa Mostafavi, Sean P. Dukelow, Stephen H. Scott and Parvin Mousavi, *Senior Member IEEE*

Abstract— Advances in robotic technologies offer objective, highly reliable tools for assessment of brain function following stroke. KINARM is an exoskeleton device that uses a number of behavioral tasks to objectively quantify sensorimotor, proprioceptive and cognitive brain function. As more tasks are developed to more broadly assess different aspects of behavior using the robot, different strategies are required to reduce the overall assessment time. The present study investigates how non-linear hierarchical ordering theory can be applied to determine the ordering on a set of four tasks on the KINARM exoskeleton robot. Evaluation is based on task discretization, which determines whether an individual passes or fails a certain task on the robot. Results of the study suggest an ordering which determines the results of success or failure on a sensorimotor task for the unaffected arm of stroke survivors based on the assessment results of a ball drop object-hit task with 97% confidence. This can be used to reduce the assessment time by over eight minutes for a subgroup of stroke survivors compared to the current KINARM assessment protocol.

Keywords— KINARM, Stroke Assessment, Hierarchical Ordering

I. INTRODUCTION

Stroke is one of the leading causes of permanent disability in Canada, where nearly 80% of stroke survivors suffer from some form of disability [1]. Some 50,000 individuals suffer from stroke every year, and there are an estimated 300,000 individuals living with stroke side effects in Canada [1].

According to previous research, a significant portion of functional recovery occurs within the early weeks and months post-stroke [2]. This leaves clinicians with a short time frame to quantify the impact of the brain damage, and decide on a course of prognostic and therapeutic interventions. A delay in the assessment procedure can, in turn, lead to delays in the course of treatment despite evidence for the importance of early rehabilitation [3].

Traditionally, the stroke assessment procedure is performed by a clinician using a set of clinical scores. These scores suffer from a number of pitfalls including limited inter-rater and intra-rater reliability [4]. Recently, more advanced robotic technologies capable of recording objective, highly reliable data for assessment of brain impairments have been developed. KINARM (BKIN Technologies, Kingston, ON) [4] is one such robotic device that quantifies many areas of brain dysfunction for stroke survivors.

Several tasks are presently performed on the KINARM robot for quantification of sensorimotor, proprioceptive and cognitive brain function. These include, but are not limited to, a visually guided reaching task [5], limb proprioceptive tasks [6], bimanual skill tasks [7], and a rapid target interception task [8]. As more tasks are incorporated on the system, the length of time to assess each subject continues to grow. This leads to the question of whether the length of overall assessment time can be reduced while still retaining the maximal amount of information to quantify subject performance across a broad range of neurological functions.

In the present study, we consider the application of a non-linear hierarchical ordering technique to determine a hierarchy on four robotic tasks on the current KINARM assessment protocol. These tasks include visually guided reaching task performed on both affected and unaffected arms of stroke survivors, arm position matching task and object hit task. The analysis is based on discretized tasks, whereby an individual either passes or fails a certain task on the robot. In particular, we investigate how this ordering can be used to determine the pass/fail results on a certain task based on the results obtained on some other task. This technique can potentially be used to order the robotic tasks in such a way that would eliminate the need to perform a task for a number of subjects when the pass/fail result is known for an earlier task in the hierarchy.

II. MATERIALS

A. Participants and Robotic Assessment

One hundred and twenty stroke patients at St. Mary's of the Lake Hospital (Kingston, ON, Canada) and Foothills Hospital (Calgary, AB, Canada) were recruited for robotic evaluation using the KINARM exoskeleton robotic device in addition to 196 age matched control subjects. The study was approved by the institutional ethics review boards.

This work is supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Ontario Research Foundation –Research Excellence, the Canadian Institutes of Health Research (CIHR) and a Heart and Stroke Foundation of Alberta, Northwest Territories and Nunavut Grant-in-Aid.

Sayyed Mostafa Mostafavi and Parvin Mousavi are with School of Computing, Queen's University, Kingston, Ontario, Canada

Sean P. Dukelow is with the Hotchkiss Brain Institute, and Dept. of Clinical Sciences, University of Calgary, Calgary, Alberta, Canada.

Stephen H. Scott is with Centre for Neuroscience Studies, Queen's University, Kingston, Ontario, Canada

Sayyed Mostafa Mostafavi is the corresponding author. mostafa@cs.queensu.ca

978-1-4244-7929-0/14/$26.00 ©2014 IEEE

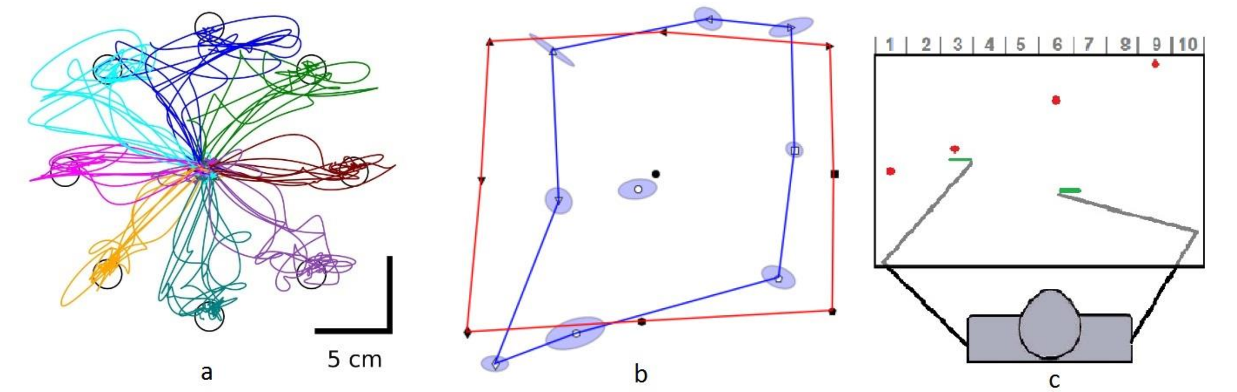

Figure 1: Robotic tasks on the KINARM exoskeleton assessment protocol. a) Visually guided reaching task: hand path trajectory patterns to eight spatial locations for a typical stroke survivor. b) Arm position matching task: The area spanned by the robot-controlled hand is represented by the red boundary, while the area matched by the subject-controlled hand is outlined in blue. c) Aerial view of a subject performing the object hit task.

Four robotic tasks that assess sensorimotor, cognitive and proprioceptive brain function were administered to each subject in a single experimental session [4]. The total assessment time to complete the tasks was approximately 25 minutes. The robotic tasks were as follows:

1. Visually guided reaching task (affected arm).
2. Visually guided reaching task (unaffected arm).
3. Arm position matching task.
4. Ball drop object hitting task.

We briefly describe each of the robotic tasks below:

(i) *Visually guided reaching task (affected and unaffected arm).* This task was used to assess sensorimotor performance. With full vision, subjects were asked to reach “quickly and accurately” from a central target to one of eight peripheral targets located 10 *cm* away, distributed around the circumference of a circle. Each trial began with subjects holding their index finger tip at the central target for 1250-1750 *ms*. Then a peripheral target was illuminated and subjects were given 3000 *ms* to complete the reach. Each target was presented once per block and subjects completed eight blocks for a total of 64 trials. For each subject, the value of each measured parameter over 64 trials was averaged and used. Stroke subjects performed this task with both the affected and unaffected arm (henceforth referred to as *Reaching-Affected* and *Reaching-Unaffected*, respectively). Control subjects performed this task with both hands. A total of twelve movement parameters were recorded in each trial. These parameters can be categorized into five major attributes related to sensorimotor control including upper-limb postural control, reaction time, initial movement, corrective movements, and total movement metrics. Details of these parameters are described in [5].

(ii) *Arm position matching task* (henceforth referred to as *Matching* task). Proprioceptive function was assessed by an arm-position matching task: subjects allowed the robot to passively move one hand to one of nine different spatial locations on one side of the body with vision occluded. When the robot stopped, subjects attempted to move the opposite (active) hand to the mirror location in space. When subjects reported they attained the mirror location, the next trial began. Target locations were such that the outer eight targets were separated by 10 *cm*. Each subject completed six blocks (target locations random within a block) for a total of 54 trials. For each subject, the value of each measured parameter over 54 trials was averaged and used. For subjects with stroke the robot moved the affected arm and the subject actively moved the less affected arm to match the limb position. For control subjects, we used the data where subject moved their dominant arm to match the limb position of the non-dominant arm. A total of nine within three major parameter attributes were recorded. These attributes include trial-to-trial variability of the active hand, contraction/expansion of the overall spatial area of the active hand relative to the passive hand and systematic shift between the passive and active hand. A more detailed description of the task and its associated parameters can be found in [6].

(iii) *Object hitting task* (henceforth referred to as *Object Hit* task). This is a bimanual task designed for assessment of visuomotor control and hand coordination. In the object hit task subjects were instructed to use their right or left hands, represented as green paddles, to hit red balls that were moving towards them on the screen. The objective of the task is to hit as many balls as possible. The balls appear on the screen from 10 different (hidden) bins, and a total of 30 balls are released from each bin in random order (all 10 bins release a ball before a bin is reused). Consequently, the game consists of a total of 300 balls falling continuously on the screen. The number of balls that appear on the screen and the speed of the ball movement increases as the task progresses, such that a single ball is moving slowly (~0.01m/s) at the beginning and up to maximum of 16 balls moving on the screen at ~0.05 m/s towards the end of the task. The KINARM robot provides a force feedback each time a paddle hits a ball. During the task, positions of the hands and active balls are recorded with a sampling frequency of 200Hz. A more detailed description of the task and its associated parameters can be found in [8].

	Reach-Unaffected		Match		Object-Hit	
	10	01	10	01	10	01
Reach-Affected	6	44[1]	19	24[3]	19	11[2]
Reach-Unaffected			45	12[2]	50	4[1]
Match					25	12[2]

Table 1. Number of subjects in 01 and 10 cells for each pair of the four robotic tasks.
[1] Pattern indicates strong pre-requisite relation.
[2] Pattern indicates weak pre-requisite relation.
[3] Pattern indicates independence of tasks.

A diagram describing the above three robotic tasks is presented in Figure 1.

III. METHODS

In the present study, we first descretized the robotic parameters for all robotic tasks introduced in the previous section. Based on these descretized parameters we determined whether each subject passes or fails a specific task. We then performed hierarchical task ordering on the descretized tasks to determine the pre-requisite ordering on these tasks as part of the robotic assessment procedure so as to minimize the overall assessment time. We provide details of parameter and task descretization and introduce ordering theory below.

A. Parameter and Task Descretization

A stroke subject is assigned a score of 0 for a certain parameter if their performance score on that parameter falls outside the 95% confidence interval range of controls. We define pass/failure on a task as follows: a stroke subject is assumed to have failed a robotic task, consisting of a group of parameters described above, if they score 0 on more parameters than 95% of control subjects (assigned a score of 0). Otherwise, the stroke subject is assumed to have passed the robotic task (assigned a score of 1).

B. Ordering Theory

Ordering theory extends scalogram techniques [9] to a non-linear hierarchy of tasks. Ordering theory is a fundamental measurement approach primarily applied for two purposes: determination of hierarchy for a set of dichotomous task items or testing a hypothesized hierarchy among a set of binary tasks. In the present study, we applied ordering theory in the context of the first objective.

Although there are many different ways of articulating ordering theory, it is most conveniently expressed as a deterministic procedural model, which identifies linear and non-linear pre-requisite relations among a set of tasks. An item i is a pre-requisite to an item j, if the (0,1) response pattern, where 0 represents the score on item i and 1 represents the score on item j, occurs infrequently. The (0,1) response pattern, as described above, is considered as a disconfirmation that task i is a pre-requisite to task j since this is the only response pattern that implies that a correct response to task i is a pre-requisite to a correct response to task j.

Consequently, ordering theory identifies necessary, but not sufficient, conditions between a set of tasks. The information provided by the application of ordering to a pair of binary scored tasks can be summarized as the following types of relationships:

(i) *Prerequisite Relation*: A task i is found to be prerequisite to another task j, if the score of 0 for task i co-occurs with a score of 1 for task j less frequently than a predefined tolerance level.

(ii) *Equivalence Relation*: A task i is found to be equivalent to another task j, if different response patterns for the two tasks i and j (i.e. (0,1) or (1,0) response patterns) occur less frequently than a predefined tolerance level.

(iii) *Independence Relation*: A task i is found to be independent of another task j, if the response pattern of scores for task i is unrelated to the scores of task j.

Ordering theory is a deterministic, and not probabilistic, modeling technique. This means that ordering theory does not intrinsically deal with the probability of encountering random error in the observed response patterns. Instead, it relies on using a preset tolerance level of error. The tolerance level is often preset and determines the number of acceptable disconfirmations in establishing a prerequisite or equivalence relation between two tasks. Thus, for a *5%* tolerance level and n subjects, for instance, one would tolerate at most $\lfloor 0.05 * n \rfloor$ disconfirmatory response patterns between two tasks before accepting a pre-requisite relation.

In order to determine the hierarchy among the set of four robotic tasks, we first applied task descretization to determine a 0 or 1 score for every stroke subject on all tasks. We then performed an analysis to determine the number of 01 and 10 response patterns for every possible pair of tasks among the four robotic tasks. Based on this, we determined the pre-requisite relationships between the associated task pairs at 5% and 10% tolerance levels. We refer to these as strong pre-requisite and weak pre-requisite relationships, respectively.

IV. RESULTS

Results of our task ordering analysis are summarized in Table 1. Based on the results presented, it can be observed that there are three distinct types of relationships that can be inferred among the pairs of tasks: strong pre-requisite (5% tolerance level), weak pre-requisite (10% tolerance level) and independence among task pairs. The relationship corresponding to each task pair is indicated in Table 1.

Based on the results obtained in Table 1, we determined a hierarchy of pre-requisite relationships between different robotic tasks at 5% and 10% tolerance levels and depicted a diagram showing the orderings in Figure 2. It is shown that the *Reaching-Unaffected* task is a pre-requisite to the other three tasks. The relationship is strong for *Reach-Affected* and *Object-Hit*, and a weak pre-requisite relation for the case of *Match* task. There are also two weak pre-requisite relations inferred between *Reach-Affected* and *Object-Hit* task and *Match* and *Object-Hit* task.

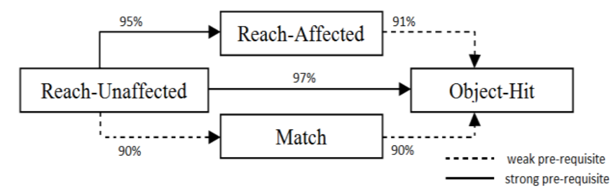

Figure 2. Pre-requisite dependencies among four robotic tasks.

V. Discussion

The logical relationships inferred between the pairs of tasks lead us to a few important observations. The first observation is regarding the overall hierarchical structure inferred from the data. As can be observed from Figure 2, the *Object-Hit* task appears at the top of the hierarchy. This task requires greater participation of neural circuits that span the occipital, parietal, and frontal lobes [10]. The distributed circuit involved in this task makes it a "dirty" one, in the sense that impairments in the task may reflect deficits or injury across many brain regions. It follows that failure in the *Object-Hit* task might be the result of failure on the sensorimotor or proprioceptive skills or both. This is yet another reason to suggest that this task should be placed as a discriminatory task at the beginning of the assessment procedure, and the rest of the assessment procedure should be decided based on the outcome of the assessment on the *Object-Hit* task.

Secondly, the fact that the *Reach-Unaffected* task appears at the base of the hierarchy means that we can use other tasks (for which *Reach-Unaffected* is a pre-requisite to) to determine whether a specific subject will pass this task. For instance, if a particular subject with stroke passes the *Object-Hit* task, we can be sure (with a 97% confidence) that they will also pass the *Reach-Unaffected* task. This is practically important as it allows us to save vital robotic assessment time for those subjects who satisfy this condition. If the assessment procedure is performed such that the *Object-Hit* task is performed prior to the *Reach-Unaffected* assessment, this ordering hierarchy can be used to overlook the *Reach-Unaffected* assessment for those subjects who happen to pass the *Object-Hit* task. Given the fact that in our group of 120 subjects with stroke, 32 subjects pass the *Object-Hit* task, this means that we can potentially save a total of 8 minutes of the time requires to assess the unaffected arm in the reaching task for many subjects by skipping the *Reach-Unaffected* assessment.

The third important finding of our analysis is the independence of *Reach-Affected* and *Match* tasks. This confirms the results of a recent study that suggests independence of deficits in position sense and visually guided reaching following stroke [11]. The fact that no pre-requisite or equivalence relationship could be established between these two tasks suggests that these two tasks should be individually performed to independently quantify sensorimotor and proprioceptive deficits for stroke survivors.

One of the limitations of the present study was information loss as a result of parameter/task descretization. This can be further improved using probabilistic or fuzzy modeling techniques for pass/failure on a certain set of parameters or robotic tasks.

VI. Conclusion

In the present study, a technique for inference of hierarchical ordering was used to determine the hierarchical structure between a set of four tasks on the KINARM exoskeleton robot, designed for quantification of different areas of brain dysfunctions following stroke. It was discussed how the determined ordering could be used to re-order the current assessment procedure in an attempt to reduce the vital assessment time. Results suggest an average reduction of eight minutes of assessment time for a subset of the population of stroke survivors.

For future analysis, we plan to extend our proposed scheme to a larger hierarchy of tasks currently under study on the KINARM robot as more data becomes available. This has the potential to identify possible task redundancies as more tasks are introduced into the KINARM robotic assessment protocol.

References

[1] Public Health Agency of Canada. Tracking heart disease and stroke in canada. 2013.

[2] P. W. Duncan, L. B. Goldstein, R. D. Horner, P. B. Landsman, G. P. Samsa, and D. B. Matchar, "Similar motor recovery of upper and lower extremities after stroke". *Stroke*. 25(6):1181-1188. 1994.

[3] J. Biernaskie, G. Chernenko, and D. Corbett. "Efficacy of rehabilitative experience declines with time after focal ischemic brain injury". *The Journal of neuroscience*, *24*(5), 1245-1254. 2004.

[4] S.H. Scott, S.P. Dukelow. "Potential of robots as next-generation technology for clinical assessment of neurological disorders and upper-limb therapy". *Journal of Rehabilitation Research & Development*, *48*(4). 2011.

[5] A.M. Coderre, A.A. Zeid, S.P. Dukelow, M.J. Demmer, K.D. Moore, M.J. Demers, H. Bretzk, T.M. Herter, J.I. Glasgow, K.E. Norman, S.D. Bagg, S.H. Scott. "Assessment of upper-limb sensorimotor function of subacute stroke patients using visually guided reaching". *Neurorehabil Neural Repair*; 24(6):528-41. 2010.

[6] S.P. Dukelow, T.M. Herter, K.D. Moore, M.J. Demers, J.I. Glasgow, S.D. Bagg, K.E. Norman, S.H. Scott. "Quantitative assessment of limb position sense following stroke". *Neurorehabil. Neural Repair*. 24(2):178-87. 2010.

[7] C.R. Lowrey, C.P.T. Jackson, S.D. Bagg, S.P. Dukelow, and S.H. Scott "A novel robotic task for assessing impairments in bimanual coordination post-stroke". *International Journal of Physical Medicine and Rehabilitation.* (in press). 2014.

[8] K. Tyryshkin, A.M. Coderre, J. Glasgow, T.M. Herter, S.P. Dukelow, S.D. Bagg, and S.H. Scott. "A robotic hitting task to quantify sensorimotor impairments in subjects with stroke". *Journal of Neuroengineering and Rehabilitation* (in press). 2014.

[9] L.A. Guttman. A basis for scalogram analysis. In SA Stouffer, et al., *Studies in social psychology in World War II. Vol 4. Measurement and prediction*. Princeton: Princeton university Press, 1950.

[10] R. Shadmehr, S.P. Wise. The computational neurobiology of reaching and pointing: A foundation for motor learning. Combridge (MA): MIT Press; 2005.

[11] S.P. Dukelow, T.M. Herter, S.D. Bagg, and S.H. Scott. "The independence of deficits in position sense and visually guided reaching following stroke". *Journal of neuroengineering and rehabilitation*, 9(1), 72. 2012.