Investigating the feasibility of a knowledge engineering approach to develop the clinical reasoning of a hybrid robotic system for upper limb rehabilitation after stroke

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INTRODUCTION

Stroke is a major public health concern in Canada, where the number of stroke survivors has increased from 526,000 in 2004 to 741,800 in 2013. [1] Stroke has lasting, debilitating effects on survivors and their ability to take care of themselves. This leads to a burden on healthcare systems as survivors depend on others for everyday activities. [2] Thus, rehabilitation is an important area of research, so that survivors can regain their functional abilities and independence - leading to improved quality of life and a decreased burden on the public healthcare system.

Motor system impairments are common after stroke, including deficits in the upper extremities (UE). [3] These deficits can chronically limit stroke survivors' functional abilities. [4] Prior research has investigated various technologies for augmenting traditional therapy. [5] Two of these technologies are robotics and functional electrical stimulation (FES), both of which have been shown to improve UE function in stroke survivors. [6,7] However, they both have weaknesses: robotics has better outcomes for patients with some functional ability [8], and when used for passive support, do not provide afferent nervous system feedback; FES systems lack precision since they are open-loop, but can be effective for patients with minimal functional ability. [7] It follows that combining the two modalities - by closing the FES loop with the robot - could result in improved rehabilitation outcomes for a broader potential patient population. [9]

The project's goal was to extend these ideas by initiating development of an intelligent system combining the two technologies to create a multimodal "hybrid" therapeutic device which would have clinical feasibility. The envisioned hybrid system would have two major aspects in terms of its FES control: 1) It should have an ability to clinically reason - in that the hybrid system should intelligently decide when to intervene with FES during a therapy session so as to be most beneficial. 2) It should be a closed-loop system using feedback from the robot end-effector's kinematics to modulate the FES. This would allow it to adjust FES parameters to smoothly move a patient's arm from any arbitrary point in its workspace to a 'goal' arbitrary point.

Prior research in hybrid systems has investigated methods for precisely controlling the FES parameters (item two above). [10] Therapists' clinical reasoning (item one) has been studied, but not FES-specific, and not explicitly and systematically presenting what knowledge and cues therapists make use of during clinical decision making. [11,12] Thus, this study's purpose was to determine the feasibility of using a novel Knowledge Engineering (KE) approach, specifically the CommonKADS methodology [13], to elicit therapists' tacit knowledge of manual FES therapy, and state it explicitly, for development of the hybrid system's clinical reasoning capabilities.

METHODS

Design

This qualitative study took place at Toronto Rehabilitation Institute (TRI), and was approved by the Research Ethics Board of the University Health Network. Informed written consent was obtained from all participants.

Participants

We studied three occupational therapists and one physical therapist, all experienced in manual FES therapy (mean experience of 7.5 years). The therapists were provided information about the study via email. As the therapists were employees of TRI, it was made clear that their participation or non-participation was anonymized and would have no effect on their employment status.

Procedure

The recruitment, screening, and informed consent was an ongoing process which took place throughout the study. Each participant signed the consent form, was assigned a participant number, and completed the demographic questionnaire. Participants completed two sessions, approximately 45 minutes each.

Session one consisted of an unstructured interview (about 15 minutes), followed by the first stage of a formalized, two-stage structured interview (about 30 minutes). The unstructured interview consisted of open-ended questions about manual FES therapy, and was used to build rapport and establish a common context. [13] The structured interview was used to elicit tacit knowledge from the participant. [13] For the first stage, the participant was asked to give an outline of how they would perform UE FES therapy for reaching. Then they were asked to describe the decisions made during therapy, by listing variables of the decisions, and the possible solutions they use to address these variables. Finally, they were asked to list rules which link the variables to the solutions. Interviews were recorded and transcribed, and the transcriptions were analyzed to prepare for the second interview session.

The second interview session was the final stage of the structured interview. Definitions from the previous interview were reviewed with the participant. Then, for each rule elicited in the previous session, the participant was asked further probe questions as suggested by the CommonKADS methodology. [13] The probe questions were intended to determine constraints for the rules, and to generate further rules, variables, or solutions. The same process was followed for each participant. The study was stopped after four participants because no new information was forthcoming.

Analysis

Both stages of the participant's structured interview were recorded and transcribed, with the first stage analyzed prior to the second stage. Variables, solutions, rules (hereafter referred to collectively as concepts), and definitions were extracted from the interview transcriptions. The results from each participant were combined into one Knowledge Model as detailed in the CommonKADS methodology, while also keeping track of repeated concepts across participants. [13]

RESULTS

There was a total of 20 variables (Table 1), nine solutions (Table 2), and 38 rules (Table 3) identified from eight interview sessions. Some concepts were repeated by multiple participants; other concepts were named by only one participant. Generally, when variables/solutions were duplicated, related rules were also duplicated.

Table 1. Variables for forward reach UE FES therapy

Variables (in descending order by number of participants who mentioned it)		
Name	**Definition**	**Participants**
Tone	Tone in the patient's UE muscles	4
Volitional effort	How much neuromuscular effort the patient is using to move themselves	4
Movement amplitude	How far the patient reaches on a per-trial basis	4
Physical fatigue	Patient's UE muscle fatigue	4
Movement/synergist pattern	The pattern of co-contractions	3
Spasticity	Spasticity in the patient's UE muscles	3
Range of motion	Patient's range of motion in the shoulder and elbow joints	3
Trajectory	Specifically the reaching trajectory, or path the hand takes on approach to target	3
Patient engagement	Patient's engagement in the therapy as an active participant	3
Assessment	Including strength and functional goals	2
Mental fatigue	Patient's subjective feeling of tiredness or ability to focus	2
Compensations	Dipping trunk, shoulder abduction, arm pronation	2
Movement quality	Quality of patient's reaching movement compared to healthy movement	2
Other[a]	Variables mentioned by a single participant	1

[a] Frustration, force, facial expression, smoothness, patient's cognitive function, historical tracking, unaffected side.

Table 2. Potential solutions for forward reach UE FES therapy

Solutions (in descending order by number of participants who mentioned it)		
Name	**Definition**	**Participants**
Therapist assistance	Movement guidance	4
FES	Usually refers to the FES current amplitude, but can also be the decision to intervene in a non-assisted movement with FES	4
Rest	A break from exercises or the FES	3
Tactile cueing	Physical feedback given to patient, such as pushing against the arm to cue which muscle the patient should be engaging	2
Verbal feedback	Feedback from therapist to patient about how they are performing	2
Change therapy protocol	Change which movements are being practiced, related to rest	2
Other[a]	Solutions mentioned by a single participant	1

[a] Therapist alliance, manual therapy, cognitive strategies.

Table 3. Rules linking variables to potential solutions

Variable	Rule	Participants
Tone	If low tone, then free to use high FES current if needed	4
	If high tone, start with more FES current than usual to fatigue the toned muscle, then bring it back down	2
	If a lot of tone/spastic muscles, use less current - cue to patient to start working that muscle	2
	If patient presents with high tone, then try using manual therapy techniques to release the tone	1
Volitional effort	In general, try to maximize patient's volitional effort by keeping FES current to a minimum	4
	If patient is giving volitional effort but not moving, then they are too weak; use FES or manually assist	2
	If patient is able and not trying, then use cognitive strategies to get them engaged	1
	If using FES and patient is moving well, then decrease FES current to try and maximize patient volition	1
Movement amplitude	If movement amplitude has decreased during therapy session and FES is not on, then use FES	4
	If movement amplitude has decreased during therapy session and FES is on, then patient is fatigued; rest or switch to new exercise/protocol	2
Physical fatigue	In general, if patient is physically fatigued, then rest or switch to a different exercise/protocol	4
	Patient may be fatigued if movement quality diminishes during therapy session	2
	If patient is fatigued from myofascial tension or spasticity, then try manual therapy to alleviate	1
	If physical fatigue has set in after 4-5 repetitions with FES, then rest	1

Note: Only rules involving variables mentioned by all four participants are shown.

DISCUSSION

Use of a KE methodology to develop the automated clinical reasoning capabilities of a therapeutic device is a novel approach for hybrid systems [12]. Two considerations will be accounted for when incorporating this knowledge into a clinical reasoning system for future research. First, the capabilities of the envisioned system should be noted. It may be the case that only a subset of the elicited concepts can be covered by the hybrid system. Indeed, in this study, there were more concepts than are possible to address with the envisioned hybrid system, as the robot's end-effector kinematics can only be used for certain concepts - such as trajectory or movement amplitude. Second, concepts mentioned by multiple therapists may be more important than concepts mentioned by fewer, and this frequency should be taken into account. Overlaps between these two considerations would be starting points for system development. Future research could add other technologies used to cover the gaps (between concepts and hybrid system capabilities), such as motion tracking to detect compensations, computer vision to monitor facial expressions, or EMG to detect muscle fatigue.

The KE methodology was a useful approach since it contributed to a user-centered design process. Therapists are considered the end-users of the hybrid system, so the system should work in a way that helps them to perform their therapy. Along these lines, all the therapist participants stressed the 'holistic' and dynamic nature of FES therapy, in that they are constantly monitoring the patient to adjust therapy on the fly. Thus, the hybrid system would need to be flexible to accommodate patient changes between and during therapy sessions. Future research could continue this user-centered design process to determine how to address this need.

There were two main limitations to this study. First, all the therapist participants were educated through the same hospital, so there may be a bias in what was elicited from these therapists when compared to therapists trained elsewhere. Second, there were some conflicting strategies which can be attributed to differing to the therapists' personal philosophies, such as using manual therapy to address tone as opposed to intentionally fatiguing the toned muscle with FES (Table 3). Future research would need to address these conflicts.

CONCLUSIONS

Therapists must keep in mind a large knowledge base when performing manual FES therapy. This includes variables about their patient that they monitor during therapy - such as patient tone, spasticity, fatigue, movement amplitude, and historical performance. It also includes what solutions they can use to address these variables - such as modifying the FES parameters, providing feedback, or manually assisting the patient to perform the correct movement. This tacit knowledge can be systematically elicited and made explicit, to the point where a system could be designed which makes automated use of this tacit knowledge. These findings have implications both for educating therapists in training, and for developing the clinical reasoning capabilities of therapeutic devices.

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