A framework to aid adoption of automated rehabilitation devices into clinical practice

Synthesising and Interpreting Language for Clinical Kinematics (SILCK)

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Abstract— **The Synthesising and Interpreting Language for Clinical Kinematics (SILCK) is an informatic framework for developing software to control automated rehabilitation devices. It aids adoption of devices into rehabilitation practice, by bridging the gap between clinical practice and internal device operation. SILCK defines data entities and processes for capturing clinical observations of patients and their rehabilitation goals in formats which can be used to direct the tailoring of device parameters to the individual patient's needs.**

Keywords— robotic rehabilitation; medical information systems

I. INTRODUCTION

Automated devices, such as robots, have potential to assist therapeutic exercises in patients with stroke and other neurological diseases [1]. However, they must meet the following requirements for successful adoption into rehabilitation practice:

(a) Devices should offer treatment options covering the wide variety of clinical situations in neurological diseases. This requires that control parameters are individually set to the patient's needs.

(b) Devices should be operable without excessive training requirements. There should be minimal need to learn device-specific control parameters.

(c) Device treatment must fit into the patient's rehabilitation programme. Treatment options should be presented in clinically-meaningful terms, related to the patient's rehabilitation goals.

(d) Devices should operate without frequent therapist intervention, by adapting to the patient's evolving performance. However, the therapist should retain overall control.

(e) Treatment delivered by devices should be readily documented in the patient's rehabilitation record.

Task oriented robotic systems such as ADAPT [2, 3] address several of these requirements, particularly (c) and (d), by offering practice of functional tasks. This approach exploits the therapist's knowledge of the patient, by enabling her/him to select tasks relevant to the patient's rehabilitation programme; parameters governing task difficulty are set by an adaptive algorithm which acts upon previous performance. This paper takes a further novel step, by introducing an informatic framework for designing device software that interprets therapists' clinical observations to support the setting of device control parameters.

The framework presented here is termed "Synthesising and Interpreting Language for Clinical Kinematics" (SILCK). It has been developed by a team which includes experienced physiotherapy, occupational therapy and medical practitioners. Allowance has been made for the uncertainties of clinical practice, and for the framework to evolve as clinical experience with treatment devices grows; the version presented here is designated "Alpha".

II. DESCRIPTION OF SILCK FRAMEWORK

SILCK comprises a generic "Main framework", which is designed to be used with "Framework extensions" for specific device modalities, such as robotic exercise therapy or functional electrical stimulation. Extensions define the principles for using generic data from the main framework to set specific device parameters. For example, the iPAM robot [4] is based on the extension for robotic exercise therapy.

This paper describes the main framework; extensions will be considered later.

A. Overall architecture

Fig. 1 shows the main framework. It handles three types of clinical information about the patient – clinical observations, patient goals and device measurements:

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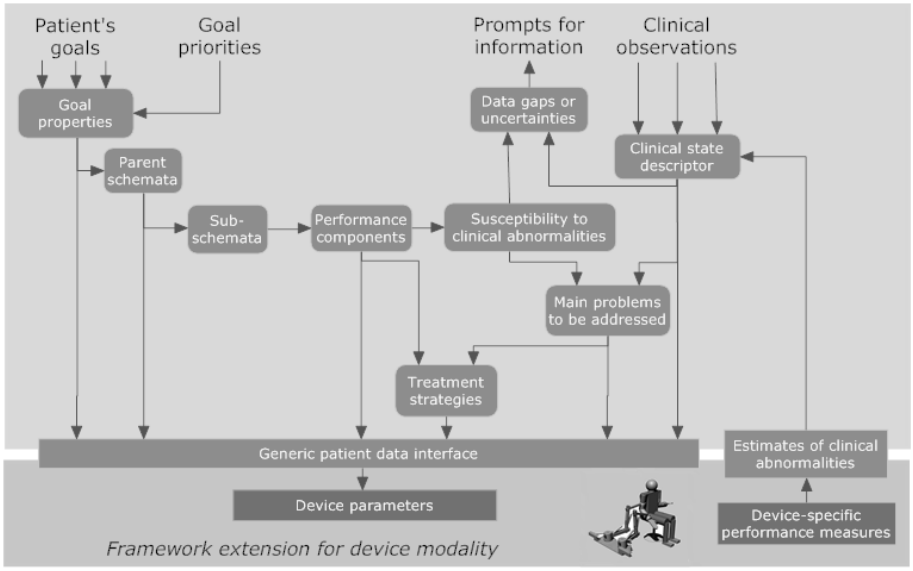

Fig. 1. Main SILCK framework (upper section), showing its interface with a framework extension for a device-based treatment modality

1) Clinical observations by therapists, such as assessments of voluntary muscle power. To make efficient use of staff time, SILCK accepts observations from standard clinical assessments. This is a challenge, because various assessment methods are in use globally, depending on clinician's experience, preference, and local policy.

2) The patient's rehabilitation goals. These guide SILCK towards a realistic patient-centred interpretation of the clinical observations.

3) Framework extensions define processes whereby the severities of clinical abnormalities, such spasticity, may be estimated from device measurements of patient performance. These can inform adaptions during treatment.

Each type of information carries uncertainty, arising from observer (device) variability and inherent clinical instability. The architecture of SILCK enables it to handle these uncertainties.

B. Clinical State Descriptor

To accommodate alternative assessments used in rehabilitation practice, SILCK defines an intermediate data structure, the "Clinical State Descriptor" (CSD). The CSD summarises the patient's state in terms of underlying biological constructs, regardless of the assessment methods used to make clinical observations.

The CSD has the seven-ranked structure shown in Table I. This begins with "Clinical factors", mapped onto the International Classification of Functioning, Disability and Health [5]. Intermediate ranks are flexible, according to the factor. Finally, the "Severity profile" quantifies the extent to which the patient exhibits any abnormality of the factor – on a scale from 0 (not present) to 1 (worst possible severity).

TABLE I. RANKS OF THE CLINICAL STATE DESCRIPTOR

Rank	Example
Clinical factor	Muscle tone
Context	Sitting
Secondary context	At rest
Spatial domain	Elbow flexion
Secondary domain	Not required for this factor
Abnormality	Hypertonia
Severity profile	11 membership indices

To handle clinical uncertainty, the severity profile comprises fuzzy membership indices, each denoting the likelihood that the abnormality is at least as severe as the given point on the severity scale.

C. Synthesis of observations into the Clinical State Descriptor

CSD severity profiles are inferred from clinical observations. A separate inference stage is defined for each assessment method. Some assessments may inform several severity profiles; e.g. observations of active movement range allow minimum values for passive range to be estimated, as well as crude inference of voluntary muscle power.

For each observation value/category which an assessment might generate, a set of assessment confidence profiles is assigned, relating to all CSD severity profiles which might be inferred from the observation. These profiles have the same format as the corresponding CSD severity profile, thereby accommodating varying degrees of certainty for different assessments, and inconsistent reliability across their measurement ranges. For the alpha version of SILCK,

confidence profiles have been shaped from the authors' personal experience of the following formal assessments: the MRC Oxford Scale for voluntary muscle power [6], passive joint goniometry [7] and the Modified Ashworth Scale for spasticity [8]. SILCK alpha also includes alternative profiles for less formal, categorical, assessments of muscle power and tone which we use in our practice.

When SILCK-based software receives an observation, it identifies all the confidence profiles for the observation value and uses these to infer the corresponding severity profiles in the CSD. If any severity profile has not yet been defined in the patient's CSD, SILCK merely transcribes the values inferred from the confidence profile. Section II.J describes the process for updating the CSD following previous observations.

TABLE II. GOAL PROPERTIES

Property	Example
Goal type	Feeding
Sub-type	Food requiring cutting up
Limb use	Unimanual left
Auxiliary goal	Use right limb for stabilising plate
Environment	At dining table
Postural support	Dining chair with arms
Equipment	Standard cutlery
Setup	Food cut up
Verbal assistance	Prompt
Physical assistance	Manual guidance
Supplementary qualifiers	-

D. Capture of rehabilitation goals

Although rehabilitation goals are necessarily individual to the patient, SILCK defines a set of properties which characterise them for standardised capture and interpretation; see Table II. Property options are held within a tree structure that leads to a unique "Goal ID" for each combination of properties. In SILCK alpha, the tree has been populated for a sample set of goals based on upper limb activity in sitting. Software implementing the tree for goal capture should also collect a ranking to reflect the priority which the patient attaches to the goal.

E. Goal interpretation

For each goal ID, SILCK associates a set of "Performance components"; these are the skills required to attain the goal e.g "Reach forwards to grasp" is a component of goals involving self-feeding. Because more complex goals have multiple elements, direct mapping of goal IDs onto performance components is not always feasible. Therefore, SILCK resolves goals into stages, using with the Activation-Trigger-Schema approach [9]. These stages are known as parent schemata; each may comprise sub-stages, termed sub-schemata. For example, the goal of making a cup of tea would involve parent schemata for boiling water, brewing the tea and serving it; the schema for boiling water would involve sub schemata for filling a kettle, switching it on etc. Each sub-schema is finally mapped onto one or more performance components.

F. Identification of main problems to be addressed

The clinical abnormalities which are most relevant to the patient's goals are identified as the "Main problems" to be addressed by device treatment. Each performance component has a set of "Susceptibility profiles", describing its liability to disruption by various abnormalities. For example, the component "Reach forwards to grasp" has profiles for weakness of shoulder flexion, weakness of elbow extension, elbow flexor hypertonia etc. Like the CSD severity profiles, susceptibility profiles have fuzzy membership indices spanning the severity scale: each index denotes the extent to which the component would be affected if the abnormality were present to the given degree of severity. Using Occupational Therapy task analysis, susceptibility profiles have been defined for the performance components which underpin the sample goals of SILCK alpha.

The intersection of a susceptibility profile with the patient's CSD severity profile for the corresponding clinical abnormality defines the relevance of the abnormality to the component in this patient. A dimensionless "Relevance index" is extracted by defuzzification; this index will only be high if the performance component is susceptible to the abnormality and the patient exhibits the abnormality to a sufficient degree. For each abnormality, relevance indices are summated across the performance components of all the patient's goals, scaled according to the goals' priority rankings. SILCK denotes the abnormalities with highest relevance index sums as being the patient's main problems to be addressed.

G. Recommendation of treatment strategies

Data entities, termed "Treatment strategies", identify broad approaches to treatment in clinically-recognisable terms, such as "working in outer muscle ranges, gradually reducing assistance". SILCK framework extensions for specific modalities define how each strategy might be translated automatically into an appropriate set of device parameters. At present, the therapist manually selects a treatment strategy, but a decision network is currently under development for recommending strategies based on the patient's main problems, and his/her capacity for active engagement, as indicated by the CSD.

SILCK's inclusion of strategies address several of the device adoption requirements identified in section I, such as minimising need to learn device-specific parameters (requirement b) and presenting treatment in clinically-meaningful terms (requirement c). Because the therapist selects the treatment strategy, overall clinical control is retained (requirement d).

H. Prompts for further data

Initial clinical information is often incomplete. SILCK-based software can request observations relevant to the patient's goals, by comparing susceptibility profiles for the patient's goal(s) with populated CSD profiles, and considering

the abilities which the patient must possess in order to engage with the candidate treatment strategies.

I. Interface with framework extensions

Extensions of the SILCK framework for specific device modalities may use several of the generic SILCK data entities to inform parameters of treatment devices, depending on device capabilities:

Goal properties, schemata and performance components may enable a device to present exercise tasks which simulate the patient's goals; see adoption requirement (c) in Section I

Devices may use suggested treatment strategies to offer pre-set "packages" of control parameters; see requirement (b).

Within a given strategy, the main problems to be addressed may direct the device to focus treatment on specific limb segments or functions e.g. if shoulder flexion weakness is a problem, exercises in outer reach may be given, with parameters pre-set for greater shoulder assistance; see requirement (a).

The CSD provides information about other patient abnormalities which, though not identified as main problems, may help to tailor device settings to the patient's situation e.g. passive joint range could define safe bounds for the exercise workspace, without requiring staff to learn device-specific workspace parameters. See requirement (b).

Conversely, devices based on SILCK framework extensions may estimate severities of clinical abnormalities, from data gathered during treatment e.g. increasing muscle tone might be detected if the device can quantify resistance to movement. New abnormality severity profiles can be inferred from these estimates, and used to update the CSD (see below). This approach supports automatic device adjustments during therapy, thereby addressing adoption requirement (d).

J. Updating the Clinical State Descriptor

After the CSD has been populated from initial clinical observations, further patient data may become available if clinicians supplement preliminary observations with more detailed assessments, or the patient is reviewed after therapy. SILCK-based devices may infer new abnormality severity profiles from patient performance data.

The CSD should be updated to reflect this new information, but existing CSD severity profiles should not be discarded, given the uncertainty associated with all observations. The SILCK framework defines a process for partially modifying the CSD, by synthesising new profiles into the extant profiles using weighted Hadamard product. Weighting reflects the intrinsic biological stability of the abnormality, and the interval between the latest and previous assessment data. It ensures that CSD severity profiles for relatively stable abnormalities, e.g. passive movement ranges, are less influenced by new observations than profiles for abnormalities that may be expected to change rapidly e.g. muscle tone.

III. IMPLEMENTATION – "SILCK CLINIC"

The main SILCK framework described here has been used as the template for a software application, "SILCK clinic", which is being developed by Skene Software Ltd. - www.skenesoftware.co.uk. As a stand-alone application, this provides an electronic rehabilitation record, with a flexible interface for capturing patient goals, and clinical observations using a range of alternative assessment tools. This information is synthesised into the patient's CSD and used, together with goal performance components, for identifying the main problems to be addressed, as defined by the SILCK framework. Reference data for SILCK processing, e.g. confidence profiles, are held in an embedded database.

SILCK clinic can host multiple plug-in software modules, for treatment devices based on extensions of the SILCK framework. It implements the interface described in section I, and supports direct logging of device treatment in the patient's rehabilitation record; this addresses adoption requirement (e). By providing a common point of access, it minimises training requirements for new devices – see adoption requirement (b). If more than one device is used by a patient, SILCK clinic can share data between devices, thereby reducing the time taken for clinicians to set subsequent device parameters; this could be particularly useful if patients progress from inpatient systems to home-based devices. The first plug-in module has been developed for the iPAM therapeutic robot [4]. A version with partial SILCK functionality is currently on clinical trial.

IV. DEMONSTRATION

The operation of SILCK processes is demonstrated by using SILCK clinic to analyse three typical sets of clinical observations given in Tables III - V; these were devised to represent some of the mild, moderate and severe patterns of impairment seen after stroke. For clarity, only sufficient observations are given to illustrate SILCK operation; normal right side function is assumed. A complete clinical description would include more observations of all limbs, as well as assessments of the patient's truncal posture, perception and cognitive functions (praxis, attention, midline sense); the SILCK framework has the potential to accommodate such observations in due course.

TABLE III. DEMONSTRATION SETS: POWER

Voluntary power in left upper limb MRC [6]: 0-5	*Set #1 Mild*	*Set #2 Medium*	*Set #3 Severe*
Shoulder – flexion	4	3	1
- extension	3	2	0
- ext. rotation.	2	2	0
- abduction	3	2	0
Elbow – flexion	3	2	2
- extension	2	1	0
Wrist – extension	2	1	0
Digits - flexion	3	2	1
- extension.	2	1	0

TABLE IV. DEMONSTRATION SETS: TONE

Tone in left upper limb mAS [8]: 0-5	*Set #1 Mild*	*Set #2 Medium*	*Set #3 Severe*
Shoulder – adductor	1	2	4
Elbow – flexor	1	2	4
Wrist – flexor	2	2	3
Digits – flexor	2	2	3

TABLE V. DEMONSTRATION SETS: JOINT RANGES

Passive ranges in left upper limb Degrees	*Set #1 Mild*	*Set #2 Medium*	*Set #3 Severe*
Shoulder – flexion	140	100	60
- extension.	50	50	0
- ext. rotation.	50	20	0
- abduction	90	70	50
Elbow – extension	0	0	-10 flex
Wrist – extension.	60	40	0

SILCK clinic has analysed each set of observations in relation to potential goals which would be plausible for patients exhibiting these abnormalities; in the case of the moderate pattern, two goals, of differing difficulty, have been considered. For each combination of observations and goal, Table IV lists five main problems which the software identified as needing to be addressed.

V. DISCUSSION

We suggest that the main problems listed in Table VI are broadly appropriate for their combinations of goal and clinical observations, although the use of subjective expert reference data at this stage of SILCK development inevitably leaves scope for debate about the details.

For the bimanual eating goal, the difference in problem lists for observation sets #1 and #2 shows SILCK identifying the impact of reduced wrist extension range (#2) on grip of a fork; although wrist extension range is observed to be 40 degrees in set #2, the assessment confidence profile for this observation reflects the uncertainty surrounding goniometer measurements [7]. Observation set #2 also demonstrates switching of priorities if the patient's goal is changed: weakness of finger flexion would impede grasp of cutlery for bimanual feeding, whereas finger extension is more important to lay the hand in an extended posture on the table; shoulder abduction/external rotation are required to place the arm therapeutically, away from the trunk. Even though observation set #3 indicates dense weakness, SILCK clinic has not included this as a problem, because voluntary power is not required to passively position the arm. However, elbow flexor tone would make it difficult to place the forearm on the armrest; wrist flexor tone would impede laying the hand in an extended, pronated posture.

VI. CONCLUSION

It has been demonstrated that the SILCK framework can be used as a template for software to capture clinical observations of patients and their rehabilitation goals, and analyse these to identify the main problems to be addressed during rehabilitation. In conjunction with framework extensions for specific device modalities, such as robotically-assisted exercise, SILCK can aid development of clinically-oriented devices which meet the requirements for adoption by rehabilitation services.

TABLE VI. MAIN PROBLEMS IDENTIFIED BY SILCK CLINIC SOFTWARE FOR OBSERVATION SETS #1 TO #3 AND POTENTIAL GOALS

	Observation set #1	**Observation set #2**		**Observation set #3**
Main problems identified by SILCK clinic software (relevance index sum)	***Goal: Independently feed bimanually – cutting food with knife and fork***	***Goal: Independently feed bimanually – cutting food with knife and fork***	***Goal: Actively place left upper limb on table in a therapeutic position, then feed by right hand***	***Goal: Use right hand to passively position left upper limb on wheelchair arm support***
Most relevant problem	Left elbow extensor weakness (2.5)	Left elbow extensor weakness (5.2)	Left elbow extensor weakness (5.2)	High tone in left elbow flexors (6.3)
2nd problem	Left wrist extensor weakness (1.4)	Left wrist extensor weakness (4.0)	Passive ext. rotatn. range of left shoulder (4.2)	Passive ext. rotatn. range of left shoulder (6.1)
3rd problem	Left elbow flexor weakness (1.3)	Left elbow flexor weakness (3.5)	Left shoulder abductor weakness (3.7)	Passive extension range of left wrist (5.8)
4th problem	Left digit flexor weakness (1.2)	Left digit flexor weakness (3.4)	Left elbow flexion weakness (3.5)	High adductor tone in left shoulder (5.0)
5th problem	High flexor tone in left elbow (0.6)	Passive extension range of left wrist (1.3)	Left digit extensor weakness (3.1)	High flexor tone in left wrist (2.4)

The framework should now be populated with further assessment methods, using confidence profiles built through formal analyses of their measurement properties. A broader range of goals should be assembled, with objective task analysis of the performance components which underpin each sub-schema. The rules for suggesting treatment strategies need to be defined.

Once this work is complete, SILCK will be ready to be formally validated. There is no established benchmark, so we anticipate criterion validation against a panel of clinical experts, examining a representative sample of patients with neurological conditions.

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