Chapter 3
A Review of and Taxonomy for Computer Supported Neuro-Motor Rehabilitation Systems

Lucas Stephenson and Anthony Whitehead

Abstract Stroke and other acquired brain injuries leave a staggering number of people worldwide with impaired motor abilities. Repetitive motion exercises can, thanks to brain plasticity, allow a degree of recovery, help adaptation and ultimately improve quality of life for survivors. The motivation for survivors to complete these exercises typically wanes over time as boredom sets in. To ease the effect of boredom for patients, research efforts have tied the rehabilitation exercises to computer games. Review of recent works found through Google scholar and Carleton's summon service which indexes most of Carleton's aggregate collection, using the key terms: *stroke*, *acquired brain injury* and *video/computer games* revealed a number of research efforts aimed primarily at proving the viability of these systems. There were two main results; (1) A classification scheme for computer neurological motor rehabilitation systems (CNMRS) was created based on the researched systems. (2) The systems reviewed all reported some degree of positive results—small sample sizes, large range of neuro-impairments, varied motion recording technology and different game designs make it problematic to formally quantify results, beyond a general net positive trend. The taxonomy presented here can be used to classify further works, to form the basis for meta-studies or larger long term longitudinal study and by neurological rehabilitation practitioners to help select and deploy systems to match client specific needs.

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3.1 Introduction

Stroke and other traumatic brain injuries leave many with residual motor impairment. Stroke is the leading cause of adult disability in the United States [1], and along with other types of acquired brain injuries, results in a variety of neurological impairments, including impaired motor ability. A primary method for aiding recovery are repetitive motion exercises. The goal of these exercises is to utilize the brain's plasticity to (re)build and strengthen neural pathways to affected motor systems which allows a degree of recovery [2]. This type of rehabilitation differs from typical physical rehabilitation, in that the *focus* is on rebuilding neurological control, and not directly on muscle strength and flexibility.

The effectiveness of neurological motor rehabilitation is dependent on the volume of repetitions of prescribed exercises, in other words: a high volume of repetitions is prescribed by clinicians [3]. Patient motivation, especially when away from a clinician's watch, often wanes over time [4]. The primary causes of declining interest and motivation are the declining benefit to exercise ratio and mental fatigue (boredom). The mental boredom of repeatedly performing "tedious" movements can be mitigated by attaching the exercises to additional stimulation, such as interactive games. This connection enables the client to potentially sustain interest and maximise the possible movement-based therapy recovery.

By digitally capturing human movement, computer system processing is possible; passing this information through a computer can provide verification to help ensure that movements comply with prescribed therapeutic exercises. Supporting compliance provides confidence to stakeholders; therapists can verify that their clients are performing required therapeutic movements and clients can be sure that they are optimising their recovery whilst performing their exercises. A system that helps verify that exercises are being executed correctly allows prescribed rehabilitation to be most effective [5]. Further, a system that allows the capture of motion data allows a trained professional to review and enforce proper form without their physical presence during the exercises. Indirect monitoring of clients allows greater coverage of patients at lower cost and allows for remote (outpatient) rehabilitation and facilitates long term tracking by therapists, which has been shown to be instrumental in maximising recovery [6].

The purpose of a computer neurological motor rehabilitation system (CNMRS) is to facilitate the provisioning of effective and long-term rehabilitation services to patients. A typical CNMRS is composed of 4 main logical parts: capture, process, interact and report, illustrated in Fig. 3.1.

A therapist is a primary stakeholder; deciding which CNMRS best fit with a client's current needs, monitoring progress and re-assessing requirements. In practise, a system that makes use of a CNMRS will have at least one software application configured; that users will interact with, the software would provide the user feedback including the cognitive and motivational aspects of the therapy. When choosing applications to be used in conjunction with the CNMRS, the goals of the client must be considered. For example, if the application is to be used as pure motivation/entertainment, then a commercially available game might be

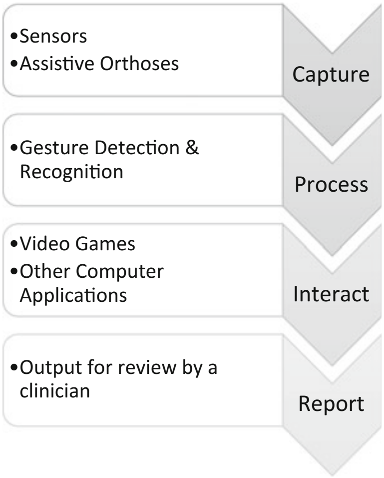

Fig. 3.1 Logical structure of a CNMRS

applicable by mapping gestures and movement input from the CNMRS to in-game controls. Alternatively, if specific learning objectives are desired, custom or specialized software could be provided, optimally a mix of these two ends of the spectrum could be used to meet a specific client's needs.

3.2 Taxonomy Overview

Identifying and classifying the characteristics of computer systems intended to provide support for neurological motor-rehabilitation enables clarification of the available systems and technologies, through categorization. This categorization allows efficient evaluation of current systems based on case specific need. Further, it allows a simple path to develop goals for new and evolving systems.

The cognitive aspect of these systems is either motivation based or client-specific-goal based, which are considered aspects of application design. It is assumed that a CNMRS provides the user with control of computer applications; ranging from commercially available games to custom designed software for cognitive rehabilitation and development. The software user interface, or game design aspect of these systems is related, but distinct and separable from the sensor systems that support these systems. This taxonomy is a classification system for CNMR hardware and software systems used to acquire and process raw input and provide directly usable data, for use as input into a computer system. It does not include terms to describe games or other software used with these systems.

To develop a taxonomy for CNMRSs an existing related taxonomy [7] was used as a starting point. The proposed taxonomy in [7] was deemed insufficient primarily because it couples application design and control aspects, a coupling that is felt artificially limits the applicability of the control apparatus. Further, the classification scheme assumed systems were pre-configured; we wanted to include basic setup and deployment information, in order to give stakeholders an idea of the costs involved with providing a system to the end users.

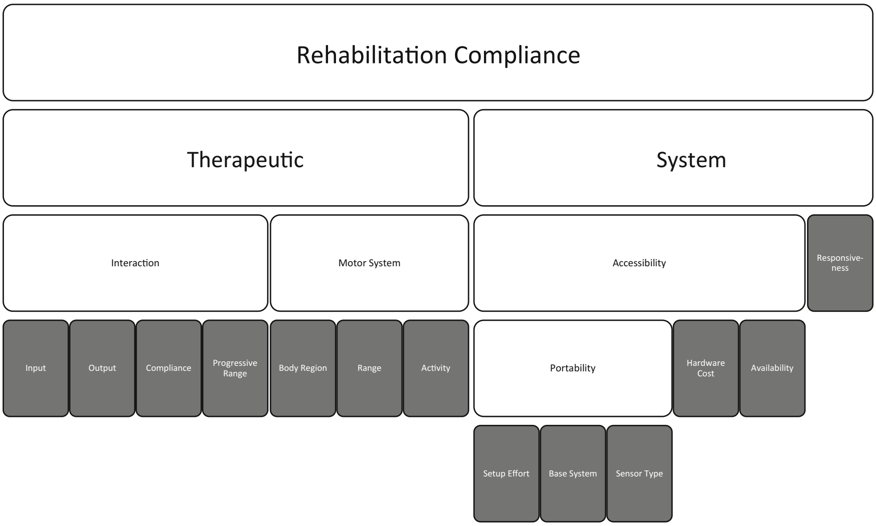

Fig. 3.2 Classification hierarchy for CNMRS

A review of the available literature was performed to identify key features of these systems. After features were identified, terms that allow classifying a system's implementation details were added so that review of the potential barriers to acquisition, setup and use of a particular CNMRS is possible.

The resultant taxonomy presented in Fig. 3.2, is presented as a hierarchy, intended to categorize the taxonomy terms, and thus classified systems into digestible chunks. The classification terms themselves are presented in a darker shade.

3.3 Taxonomy Development

There were 3 stages to the survey that informed the development of the taxonomy. Stage 1 included reviewing the works cited in Serious Games for Rehabilitation [7] and focusing on the research that was classified as having a "Motor" Application Area in the presented taxonomy. From these works, we were able to identify a variety of input mechanisms that used a number of sensor input types further described in Sect. 3.3.1.1. We also found that these systems are usually designed specifically for a particular body region/joint(s) [8–11]. While all systems surveyed provided video (and assumed audio ability) output [8–11], Ma and Bechkoum [9] made use of a haptic glove to provide an additional output modality, namely, haptic. Also noted was the granularity of movements supported. For example, Burke et al. [10] required explicit positions be held by the user, while others [8, 9, 11] proposed systems with a dynamic movement range that could be adjusted in software. This enabled us to craft a draft intermediary CNMRS taxonomy.

The 2nd stage of the review involved querying research databases, primarily Google scholar to seek out recent (since 2011) projects that involved stroke or acquired brain injury (ABI) computer aided motor rehabilitation. Those works found were filtered for relevance (many of the terms are common or have homonyms) and the references in found works were inspected for additional projects. Subsequently, works were classified using the intermediary taxonomy, and minimal refinement and expansion of terms occurred. The individual terms of the taxonomy are discussed in Sect. 3.3.1 along with the projects that effected their inclusion within the final proposed taxonomy.

Stage 3 was a validation stage, a thought exercise, cognitively inspecting novel input and output mechanisms such as Google Soli [12] and Microsoft HoloLens [13], verifying that these could be represented within the proposed taxonomy. This stage resulted in no changes to the taxonomy.

3.3.1 Taxonomy Details

To provide clarity, subgroups of related terms were implemented. There are two main groups that delineate the therapeutic and system classifiers. The therapeutic side includes all the portions of a system that would be relevant to treatment and the therapy capabilities of the system. The system stem includes classifiers related to the setup, cost and mobility and hardware of the system.

3.3.1.1 Therapeutic

The therapeutic aspect of the systems reviewed was further divided into 2 subgroups: (1) Interaction: to identify a system's input and output modalities and how and if the system can support progressive range, and (2) Motor System: provides terms for the granularity (fine vs. gross) and type(s) of motor system that is intended to be supported by a system.

Interaction

The interaction group holds classifiers that identify the ways in which the client interacts with the rehabilitation system; how movement data is provided to the system, any output mechanisms inherent in the system and whether the system provides progressive range adjustment (e.g. range of motion can increase over time).

Input
The *Input* classifier indicates the type of input the system tracks. This can be motion or tangible. A tangible system tracks the user through their interaction with explicit objects, potentially providing an augmentation path for existing therapeutic techniques, such as in [14] where a box and blocks therapeutic game was augmented with sensors. A motion system uses sensors that track the client's movements directly, capturing motion, confirming the client's compliance with the prescribed gestures

and poses, either from external sensors, sensors attached to the body or explicit actions. The majority of the reviewed works included: basic video camera setups that do *blob detection* [10, 15, 16], systems that provide inverse kinematic skeletal reconstruction simulations using external (unattached sensors) [17–19], systems that use inertial measurement units (IMU) that are attached to the limbs [11], EMG sensors that measure muscle flexion [20], and pressure sensor arrays that can be used to measure weight distribution [8, 11]. Additionally there were a few examples of systems that used more direct interaction, such as touch [21], or provided classical options for input such as mouse and keyboard to record motion data [9].

Output
Output indicates the methods the client receives live feedback from the system. Most of the reviewed systems output standard video, and sometimes audio. There was an example of specialized video; a head mounted display, allowing for a 3D-immersive environment [9]. An additional form of output that was recorded were haptic gloves that can provide some tactile based feedback to clients when worn [9, 22].

Compliance
The Compliance term is used to indicate if the system helps the client complete the required rehabilitative motions correctly, either through software analyzed feedback or (inclusively) physical orthosis. Initial construction of the taxonomy did not include *compliance,* primarily because it was seen as something purely provided by analyzing sensor input and providing feedback through the software interface. There was, however a number of works that included physical feedback by way of orthosis [23], control of objects (tangible) [14] or haptic feedback [9] and the term was added.

Progressive range
Progressive range indicates that the system provides the ability for incremental changes to required motions, for example to extend (or contract), the required range of motion. This can be therapeutically beneficial allowing the client to progress over time with the use of the system [24]. The reviewed works were implicitly able to support progressive range, and this data would be interpreted by the target game or application, however, in most configurations there is a logical maximum range. For example, a camera-based motion capture sensor would be restricted to the camera's viewable area.

There is a variety of options for how progressive range is implemented:

1. The CNMRS provides the progressive range classification, providing the underlying system with the corresponding executed movement input only when the range is sufficient to overcome the current target extent.
2. The CNMRS passes sufficient motion data for applications to interpret range along with recognized motions, allowing in-game feedback.

The CNMRS could be developed to be flexible enough to provide both. Option 1 would be ideal for existing software (where the CNMRS emulates standard input mechanisms) while 2 is potentially more interactive, as it allows the target software to provide a varying experience and direct feedback.

Motor System

The motor system subgroup holds terms to classify a system's target body region, and target motor range maximum and minimum, which can be used to determine what range of the fine/gross motor spectrum a system can analyze.

Body Region
The term *Body Region* is used to specify what regions of the body can be tracked and in what dimensional order (1D, 2D, 3D). This is important for therapists selecting a CNMRS so that they can provide targeted rehabilitation. It was described in every work surveyed; explicitly classifying supported body region(s) allows clinicians to select relevant systems more efficiently. Appropriate values would include; whole body/balance, major limb (arm/leg/head), minor joints (hands/feet/fingers/toes).

Range
Range is used to specify where on the gross versus fine motor spectrum the system lies. It specifies the minimum and maximum recordable movements in terms of distance and speed. Underlying sensor systems generally have limitations—a touch panel has specific dimensions, a video capture system can only record in a well-defined area, and IMU systems have maximum speeds.

Activity
The *Activity* classifier allows a brief description of the typical rehabilitative motions supported by the system; that is, the motions the researchers designed the system to support. This classifier, in combination with the body region classifier, enables more comprehensive coverage of the system's designed rehabilitation. Researchers looking to perform further work in supporting a specific motion type can use this term to focus their efforts on similar projects.

3.3.1.2 System

The system group includes classifiers for how accessible and responsive the system is. Table 3.2 shows the system subgroup classification results for the reviewed works.

Accessibility

The accessibility subtree was included to provide classification of the system within potential time, monetary and mobility restrictions. It is used to identify *where, when and at what cost can a CNMRS be used?*

Portability
The portability group explicitly states if a system is movable during use (base system). The amount and type of setup were also viewed to be relevant to clinicians (setup effort). All the systems reviewed were attached to stationary systems, and thus were classified as having a fixed range system value for portability. Subsequently, an additional term (sensor type) was added, to allow identification of sensor mobility. The intention of this field is to allow researchers looking to extend and create mobile rehabilitation frameworks to be able to identify and leverage existing works.

Hardware Cost
Hardware cost directly affects the level of access a client will have to the system. However, none of the systems reviewed specified this information, in addition, the price of these systems is constantly in flux. Therefore, an estimation is provided with a relative rating of *Low*, *Medium* or *High* based on estimates of hardware cost.

Availability
The *Availability* term is used to indicate the availability of the hardware involved, the values *Off the Shelf (OTS), Specialized* and *Multiple* can be specified. *OTS* indicates the sensors are generally available commercially, and easy to access, service and replace. *Specialized* means it is not mainstream hardware, and is likely more difficult to acquire, and repair/replace. *Multiple* is intended to represent systems that require more than one piece of sensor hardware, with at least one being *OTS* and another *Specialized.*

Responsiveness
In order to be considered valid for use in a game, a sensor system, must be able to provide an interactive experience for clients. However, real and perceived system reaction time is a factor in a system's appropriateness for use. For example, if the system requires that a pose be held, or has a client-noticeable delay in recognizing a movement, then the system is unlikely suitable for use with many real-time applications. For this reason, the responsiveness term was added. Systems that indicated perceptively real-time responsiveness were indicated as "real-time", systems that required a position be held for any length time for technical reasons were indicated as "delayed".

3.4 Classifying CNMRS Systems

The crafted taxonomy detailed in Sects. 3.2 and 3.3 was applied to 55 published research papers. The *System* and *Therapeutic* areas, as seen in Fig. 3.2, were classified independently, and are presented below in Tables 3.1 and 3.2.

Table 3.1 Therapeutic terms: classification of reviewed CNMRSs

Research	Input	Output	Compliance	Progressive range	Body region	Range	Activity
Betker et al. [8, 27]	Motion	Video/audio	Virtual	Software	Sitting balance	Gross	Leaning
Ma and Bechkoum [9]	Motion	3D Video/audio/haptic	Virtual/physical	Software	Hand	Fine	Pointing and grasping
Burke et al. [10], Crosbie et al. [28]	Motion	Video/audio	Virtual	Manual	Arms	Gross	Arm pointing and simple gestures
Ryan et al. [11]	Motion	Video/audio	Virtual	Software	Balance	Gross	Standing balance/in place navigation
Zhao et al. [14]	Tangible	Video/audio	Virtual/physical	Manual	Arms/hands	Fine	Grasping
Adamovich et al. [22]	Motion	Video/audio/haptic	Virtual/physical	Software	Hand	Fine	Pointing/hand dexterity
Chang et al. [17]	Motion	Video/audio	Virtual	Software	Arms and legs	Gross	Shoulder flextion and rotation
Fraiwan et al. [18]	Motion	Video/audio	Virtual	Software	Arms and legs	Gross	Various: gross full body
Cameirão et al. [15, 29, 30]	Motion	Video/audio	Virtual	Software	Arms	Gross	Pointing/grasping
Harley et al. [31]	Motion	Video/audio	Virtual	Software	Arms	Gross	Arm tilt
Okošanovi et al. [21]	Motion	Video/audio	Virtual	Software	Arms	Gross	Mouse gestures
Rahman et al. [19, 32, 33]	Motion	Video/audio	Virtual	Software	Arms, legs and hands	Gross and Fine	Various: full body
Tan et al. [16]	Motion	Video/audio	Virtual	Software	Hand	Fine	Hand gestures
Fukamoto [20]	Motion	Video/audio	Virtual	Manual	Foot/lower leg	Gross	Foot tilt
De et al. [23]	Motion	Video/audio	Virtual/physical	Manual	Arm	Gross	Assisted elbow flexion
Bhattacharya et al. [34]	Explicit	Video/audio	Virtual	None	Arm	Gross	Tilting arm/jostiq
Brokaw and Brewer [35]	Motion	Video/audio	Virtual	Software	Arms/shoulders	Gross	Arm gestures

(continued)

Table 3.1 (continued)

Research	Input	Output	Compliance	Progressive range	Body region	Range	Activity
Crocher et al. [36]	Motion	Video/audio	Virtual	Software	Hand	Fine	Hand movement/grasping/selecting
Dukes et al. [37]	Motion	Video/audio	Virtual	Software	Upper arm	Gross	Hand movement/grasping/selecting, arm movement
Erazo et al. [38]	Motion	Video/audio	Virtual	Software	Arm	Gross	Arm gestures
Gil-Gómez et al. [39]	Motion/speech	Video/audio	Virtual	Software	Upper arm	Gross	Arm gestures
Gonçalves et al. [40]	Motion	Video/audio	Virtual	Software	Standing balance	Gross	Standing or sitting balance
Kafri et al. [41]	Motion	Video/audio	Virtual/physical	Software	Ankle/leg	Gross	Ankle rotation
Kim et al. [42]	Motion	Video/audio	Virtual	Software	Arm/balance	Gross	Tilting/jogging in place/boxing
Kizony et al. [43]	Motion	Video/audio	Virtual	Software	Arm	Gross	Various
Labruyère et al. [44]	Motion	Video/audio	Virtual	Software	Arm	Gross	Arm gestures
Maier et al. [45]	Motion	Video/audio	Virtual	Software	Gait/balance	Gross	Gait/ambulating
Mainetti et al. [46]	Motion	Video/audio	Virtual	Software	Upper body	Gross	Arm gestures
Parafita et al. [47]	BCI*	Video/audio	Virtual	Software	General	Gross	Navigation/w BCI
Siqueira et al. [48]	Motion	Video/audio	Virtual/physical	Software	Ankle/leg	Gross	Ankle rotation
Saposniket al. [49]	Motion	Video/audio	Virtual	Software	Upper body	Gross	Arm gestures
Sucar et al. [50]	Motion/explicit	Video/audio	Virtual	Software	Arm	Gross	Hand grip and arm pointing
Vandermaesen et al. [51]	Tangible	Physical/audio	Physical	Manual	Arms	Gross	Griping and placing object
Méndez [52]	Motion	Video/audio	Virtual	Software	Balance	Gross	Balance activities
Vourvopoulos et al. [53]	Motion/explicit/BCI	Video/audio	Virtual/physical	Software	Sensor dependent	Sensor Dependant	Various, sensor dependant
Yavuzer [54]	Motion	Video/audio	Virtual	Software	Upper body	Gross	Arm gestures
Caglio et al. [55, 56]	Motion	Video/audio	Virtual	Software	Upper body	Gross	Driving/steering wheel

(continued)

Table 3.1 (continued)

Research	Input	Output	Compliance	Progressive range	Body region	Range	Activity
Rábago al. [57]	Motion	Video/audio	Physical/virtual	Software	Gait/balance/upper body	Gross	Gait/balance/game dependent
Holden [58]	Motion	Video/audio	Virtual	Software	Arms	Gross	Pouring
Mumford et al. [59, 60]	Tangible	Video/audio	Physical/virtual	Software	Upper body	Gross	Grasping/griping/moving objects
Ustinova et al. [61, 62]	Motion	Video/audio	Virtual	Software	Upper body	Gross	Arm gestures/extensions
Grealy et al. [63]	Motion	Video/audio	Physical/virtual	Software	Lower body	Gross	Cycling
Housman et al. [64]	Motion	Video/audio	Physical/virtual	Software	Arm	Gross	Orthosis supported arm movements
Subramanian et al. [65]	Motion	Video/audio	Virtual	Manual	Upper body	Gross	Pointing
Jinhwa et al. [66]	Motion	Video/audio	Physical	Manual	Gait/balance	Gross	Gait/ambulation
Yang et al. [67]	Motion	Video/audio	Physical	Manual	Gait/balance	Gross	Ambulation
Broeren, et al. [68]	Tangible	3D video/audio	Virtual/physical	Software	Upper extremities	Fine	Tangible hand/grasping light force feedback
Kim et al. [69]	Motion	Video/audio	Physical	Manual	Gait/balance	Gross	Ambulation
Jo et al. [70]	Motion	Video/audio	Virtual	Software	General	Gross	Various standing upper body
Kwon et al. [71]	Motion	Video/audio	Virtual	Software	General	Gross	Various standing upper body
Cikajlo et al. [72]	Motion	Video/audio	Virtual	Software	Balance	Gross	Supported standing and leaning
Kiper et al. [73–75]	Motion	Video/audio	Virtual	Software	Upper extremities	Gross and Fine	Grasping objects
Mirelman et al. [76, 77]	Motion	Video/audio	Virtual/physical	Software	Ankle/leg	Gross	Foot tilt
You et al. [78]	Motion	Video/audio	Virtual	Software	General	Gross	Various standing upper body
Agmon et al. [79]	Motion	Video/audio	Virtual	Software	Balance	Gross	Leaning/stepping

Table 3.2 System terms: classification of reviewed CNMRSs

Research	Portability: setup effort	Portability: base system	Portability: sensor	System availability	Hardware cost	Responsiveness
Betker et al. [8, 27]	Initial configuration assist per use	Fixed range	Wheelchair	Specialized	Medium	Real-time
Ma and Bechkoum [9]	Configuration per use	Fixed range	Free range	Specialized	High	Real-time
Burke et al. [10], Crosbie et al. [28]	Configuration per use	Fixed range	Fixed area	Specialized	Low	Delayed
Ryan et al. [11]	Initial configuration	Fixed range	Fixed area	OTS	Low	Real-time
Zhao et al. [14]	Initial configuration	Fixed range	Fixed area	Multiple	Medium	Real-time
Adamovich et al. [22]	Initial configuration	Fixed range	Free range	Multiple	High	Real-time
Chang et al. [17]	Initial configuration	Fixed range	Fixed area	OTS	Low	Real-time
Fraiwan et al. [18]	Initial configuration	Fixed range	Fixed area	OTS	Low	Real-time
Cameirão et al. [15, 29, 30]	Configuration per use	Fixed range	Fixed area	Specialized	Low	Delayed
Harley et al. [31]	Initial configuration	Fixed range	Fixed area	OTS	Low	Real-time
Okošanovi et al. [21]	Monitoring only	Fixed range	Both mobile and fixed area sensor	OTS	Medium	Real-time
Rahman et al. [19, 32, 33]	Initial configuration assist per use	Fixed range	Fixed area	Multiple	Medium	Real-time
Tan et al. [16]	Configuration per use	Fixed range	Fixed area	OTS	Low	Real-time
Fukamoto [20]	Configuration per use	Fixed range	Free range	Specialized	Medium	Real-time
De et al. [23]	Initial configuration	Fixed range	Free range	Specialized	Medium	Real-time
Bhattacharya et al. [34]	Demonstration	Fixed range	Free range	OTS	Low	Real-time
Brokaw and Brewer [35]	Demonstration	Fixed range	Fixed area	OTS	Low	Real-time
Crocher et al. [36]	Demonstration	Fixed range	Free range	OTS	Medium	Real-time

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Table 3.2 (continued)

Research	Portability: setup effort	Portability: base system	Portability: sensor	System availability	Hardware cost	Responsiveness
Dukes et al. [37]	Demonstration	Fixed range	Fixeda	Multiple	Medium	Real-time
Erazo et al. [38]	Initial configuration/calibration per use	Fixed range	Fixed area	OTS	Low	Real-time
Gil-Gómez et al. [39]	Initial Configuration	Fixed range	Fixed area	OTS	Low	Real-time
Gonçalves et al. [40]	Configuration per use	Fixed range	Fixed area	OTS	Low	Real-time
Kafri et al. [41]	Configuration per use	Fixed range	Fixed area	Specialized	Medium	Real-time
Kim et al. [42]	Demonstration	Fixed range	Fixed area	OTS	Low	Real-time
Kizony et al. [43]	Demonstration	Fixed range	Fixed area	OTS	Low	Real-time
Labruyère et al. [44]	Demonstration	Fixed range	Fixed area	OTS	Low	Real-time
Maier et al. [45]	Configuration per use	Fixed range	Free range	Specialized	Medium	Real-time
Mainetti et al. [46]	Configuration per use	Fixed range	Fixed area	Multiple	Low	Real-time
Parafita et al. [47]	Configuration per use	Fixed range	Fixed area	Specialized	Medium	Real-time
Siqueira et al. [48]	Configuration per use	Fixed range	Fixed area	Specialized	Medium	Real-time
Saposnik et al. [49]	Demonstration	Fixed range	Fixed area	OTS	Low	Real-time
Sucar et al. [50]	Demonstration	Fixed range	Fixed area	Specialized	Low	Real-time
Vandermaesen et al. [51]	Configuration per use	Fixed range	Fixed area	Specialized	Medium	Real-time
Méndez [52]	Demonstration	Fixed range	Fixed area	OTS	Low	Real-time
Vourvopoulos et al. [53]	Configuration per use	Fixed range	Fixed area	Multiple	High	Real-time
Yavuzer [54]	Demonstration	Fixed range	Fixed area	OTS	Low	Real-time
Caglio et al. [55, 56]	Demonstration	Fixed range	Fixed area	OTS	Low	Real-time
Rábago et al. [57]	Configuration per use	Fixed range	Fixed area	Specialized	High	Real-time

(continued)

Table 3.2 (continued)

Research	Portability: setup effort	Portability: base system	Portability: sensor	System availability	Hardware cost	Responsiveness
Holden [58]	Configuration per use	Fixed range	Free range	Specialized	Low	Real-time
Mumford et al. [59, 60]	Demonstration	Fixed range	Fixed area	Specialized	Medium	Real-time
Ustinova et al. [61, 62]	Configuration per use	Fixed range	Fixed area	Specialized	High	Real-time
Grealy et al. [63]	Demonstration	Fixed range	Fixed area	Specialized	Medium	Real-time
Housman et al. [64]	*	Fixed range	Fixed area	Specialized	*	Real-time
Subramanian et al. [65]	Configuration per use	Fixed range	Fixed area	Specialized	*	Real-time
Jinhwa et al. [66]	Configuration per use	Fixed range	Fixed area	Multiple	High	Real-time
Yang et al. [67]	Demonstration	Fixed range	Fixed area	Multiple	Medium	Real-time
Broeren et al. [68]	Demonstration	Fixed range	Fixed area	Specialized	High	Real-time
Kim et al. [69]	Demonstration	Fixed range	Fixed area	Multiple	Medium	Real-time
Jo et al. [70]	Demonstration	Fixed range	Fixed area	Specialized	High	Real-time
Kwon et al. [71]	Demonstration	Fixed range	Fixed area	Specialized	High	Real-time
Cikajlo et al. [72]	Configuration per use	Fixed range	Fixed area	OTS	Low	Real-time
Kiper et al. [73–75]	Assist per use	Fixed range	Fixed area	Specialized	Low	Real-time
Mirelman et al. [76, 77]	Assist per use	Fixed range	Fixed area	Specialized	Medium	Real-time
You et al. [78]	Demonstration	Fixed range	Fixed area	Specialized	High	Real-time
Agmon et al. [79]	Demonstration	Fixed range	Fixed area	OTS	Low	Real-time

3.5 Conclusion

A review of a number of computer based rehabilitation systems revealed that these were created as singletons; novel input mechanisms are used as input to custom designed software. This pattern works well for research efforts and proof of concept prototypes. However, it tightly couples the entire logical system stack (as outlined in Fig. 3.1: Logical Structure of a CNMRS) and limits re-use of both components and software. This artificially limits the availability of such systems, as the time and monetary cost of developing them is higher than a system made primarily of reused components, such as off the shelf hardware and community developed software modules [25].

This taxonomy was created in response to a perceived need—there is significant evidence [8–23] that CNMRSs are effective in boosting patient outcomes, however these systems are not widely available to patients. The primary reason is that the existing solutions are developed and tested for research, not necessarily driven by therapists and thus the cost to deploy such systems widely is prohibitive.

The taxonomy described above, in Sects. 3.2 and 3.3 provides a categorization scheme that can be applied as a tool to identify input apparatus in support of neuro-motor rehabilitation clients. Specifically, systems that can monitor specific motor actions for compliance, record progress, provide feedback and provide digitized input signals. This taxonomy is purposefully external to application design, focusing on the neuro-motor rehabilitation capabilities of the systems. Future work would ideally integrate this taxonomy into a useable interactive database tool that would allow systems to be discovered through taxonomy-based query parameters. This would allow stakeholders to both locate the most appropriate system for a situation, and identify the need for CNMRS with specific parameters.

The collected works used to craft the included taxonomy, feature few works that are built around highly portable mobile systems such as phones or portable tablets. The difficulty in locating work that covered these portable systems might indicate a gap that could be explored further in future works. Further, an analysis of the relative (taxonomy) feature sets could identify over- and underexplored feature sets. To analyze the available research feature sets, an online user contributed, peer-reviewed database of taxonomy classified CNMRS research projects is proposed. This database could be used as a basis for performing multidimensional feature-space analysis.

Some combinations of feature sets could be beneficial to clients. Rehabilitation programs usually indicate to patients that they should make an effort to continue their rehabilitative exercises long term [5, 26]. Providing more accessible feature sets, including portable or mobile options to clients could increase the longevity and compliance with movement therapy programs. With the array of sensors available on consumer mobile phones a project evaluating the long term effectiveness of a mobile phone based CNMRS is needed.

To support the availability of CNMRSs, a tool to process and aggregate movement data, from a variety of sensors is proposed. Such a system would allow the free selection of supported sensors, by the clinician, allowing them to select the most appropriate system for their client's situation. The signals provided as output from the tool would then be mapped to discrete or ranged computer input. Researchers and developers would be able to improve upon the system by developing modules for the system.

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