Literature Review on Wearable Systems in Upper Extremity Rehabilitation

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Abstract—This paper reports a structured literature survey of research in wearable technology for upper-extremity rehabilitation, e.g., after stroke, spinal cord injury, for multiple sclerosis patients or even children with cerebral palsy. A keyword based search returned 61 papers relating to this topic. Examination of the abstracts of these papers identified 19 articles describing distinct wearable systems aimed at upper extremity rehabilitation. These are classified in three categories depending on their functionality: movement and posture monitoring; monitoring and feedback systems that support rehabilitation exercises, serious games for rehabilitation training. We characterize the state of the art considering respectively the reported performance of these technologies, availability of clinical evidence, or known clinical applications.

I. INTRODUCTION

Rehabilitation technology is often seen as a means to increase the amount of training and the quality of training that can be offered to patients with obvious health and economic benefits. For a long time research in rehabilitation technology for upper extremity rehabilitation has focused on robotic technologies [1]. However, the miniaturization of devices, the evolution of sensing and body area network technologies has triggered a wave of interest in wearable rehabilitation technologies [2-5]. A large number of experimental systems and even some commercial products have been developed for upper extremity training, supporting rehabilitation for several patient groups: stroke, spinal cord injury, multiple sclerosis, cerebral palsy patients, etc. [11-27] reflecting the large need for effective upper extremity rehabilitation technologies.

Rehabilitation training is aimed at developing compensatory strategies as well as inducing neural plasticity and recovery [6]. Wearable systems with this purpose may encompass a wide variety of components: for sensing (sensors, wearable materials, smart textiles, power supplies,) for actuating (actuators, wireless communication modules and links, control and processing units), and for providing feedback and for interacting with the user (user interface software, and advanced algorithms for data extraction and decision making) see [4,7].

This article reviews the literature on wearable technologies supporting upper extremity rehabilitation aiming to provide an overview of the state of the art regarding their technical characteristics, their known effectiveness, available clinical evidence, and open challenges for this research area. As there is a large variety of such technologies we summarize and group related systems in terms of their functionality and compare them.

II. RELATED WORK

Paralleling the advances in rehabilitation technology applications, a number of reviews of relevant literature have been published. For example, [8] reviews exoskeletons for upper extremity to assist or rehabilitate patient. They classify them based on degrees of freedom, technology used & purpose, and engineering challenges. Improvements are needed with regard to comfort, portability, aesthetic and the naturalness of their form. We consider exoskeletons outside the scope of the current review. A recent innovation in upper extremity rehabilitation is virtual reality (VR) environments for retraining movement; Amy Henderson et al studied the effectiveness of such a system [9]. Their results suggest that utilizing VR on rehabilitation is valuable and highlight the advantages. Shyamal Patel [10] surveyed wearable sensors and systems with applications for monitoring health and wellness. They note that the first decade of research in this field has focused on enabling technology while currently there is a shift from developing sensors to designing systems, integrating sensors with wearable technologies and communication systems. Their scope is much broader than the present review, which focuses on technologies supporting upper extremity rehabilitation, including sleep monitoring, assisted living scenarios, and emergency response systems.

III. METHODOLOGY

A structured literature review is presented. Since the purpose of this paper is to review the wearable systems research for upper extremity rehabilitation, we will not review all areas for upper-extremity rehabilitation. A search on Google Scholar issued in Nov. 2013, using the following key terms: “upper extremity”, “arm hand”, “rehabilitation”, and “wearable systems”. This search returned 61 results, on which we carried out ancestor and descendent search trying to identify related papers introducing technologies for upper extremity rehabilitation. Based on the abstracts we selected papers discussing rehabilitation technologies (at home or the clinic) and excluded papers discussing prevention, prosthetics, coaching and information/educational applications for smartphones that do not have a direct use during rehabilitation, as well as robotic system.

Eventually 19 papers were selected [11-22,24-31]. They are categorized as follows: a) Wearable posture & movement training systems that have potential in rehabilitation applications by monitoring posture and movements;
b) Wearable rehabilitation systems providing movement feedback; c) Wearable rehabilitation systems integrated interactive games.

IV. WEARABLE SYSTEMS TO MONITOR MOVEMENT AND TRACK POSTURE

Papers in this category report on the development and evaluation of sub-systems for monitoring posture and movement of upper extremities. These sub-systems are developed with the explicit aim to support upper extremity rehabilitation but the surveyed articles stop short of their focus on different sensing technologies to track and monitor upper-extremity movement. For arm-hand rehabilitation, wearable systems involve various types of sensors, either embedded in garments or sensor networks. Sensors range from accelerometers goniometers, gyroscopes, Plastic optical fiber (POF), optical linear encoder (OLE), magnetic sensor, inertial measurement units (IMU) etc. Most systems in this category (see Table I) are based on different combinations of multiple sensors and technologies.

The sensing system developed by Kim Doang Nguyen et al [11] is the first system integrated optical linear encoder (OLE) and accelerometer, consisting of three sensing modules placing on shoulder joint, elbow joint and wrist joint based on its biomechanics and bone structure, Fig.7 shows the sensor package design for elbow part. With this system, the OLE measures the angle of the joint the sensing module wraps around. Both comparison tests and statistical tests are reported. The results from a comparison test with a rotary Power Cube show the system’s accuracy. The device was used to control a virtual arm in order to reach a virtual ball in a simulation environment during the statistical tests, based on the average DOF values, the average error range is 2.819, its repeatability and reliability of the measurements were found satisfactory, showing the potential for rehabilitation applications.

Guo Xiong Lee et al [12] designed a monitor system (Fig.2) based on wireless wearable sensor network that is ambulatory and unrestrained. Experiments showed an accuracy value of 0.52° is achievable and the comparison of goniometer measurements show similar results.

Daponte et al developed another wireless and IMU-based system [13] for monitoring movements by real-time 3D reconstruction of patient motion. Consisting of 3 parts, body area sensor network (BASN), posture reconstruction server and ROM analysis software, the system towards tracking motion for home rehabilitation and bringing movements and posture of patient on the therapist’s desk. The system is also a IMU-based technology supports 3D animation based on joint angle computation, in this way merging visual inspection of body posture with objective ROM measurements.

In [14], a motion tracking system using two inertial sensors located near the wrist and elbow joints to determine localizing wrist and elbow joints and for measuring translation and rotation of the shoulder. Experimental evaluation found an RMS position error less than 0.01m and an RMS angle error 2.5°-4.8°. This system has not yet been integrated into a complete rehabilitation system to report the upper limb movements of a patient.

In order to capture motion in home based stroke rehabilitation sessions a mobile and wireless inertial platform is proposed [15], called Institute of Microelectronic Systems Inertial Measurement Unit (IM2)SU. The sensor fusion on an 8-bit MCU is enabled by algorithmic modifications of the utilized Kalman filter. The platform consists of hardware part and software part, which provide high orientation, estimation accuracy, low costs, a platform independent, wireless connection and extensibility. Its performance was compared to Xsens MTx system using an optical tracker, achieved an orientation estimation accuracy of 1.3°RMS.

A smartphone based monitoring system [16] serves as the platform for integrating an accelerometer-based sensor network. One sensor and smartphone is placed on the affected shoulder, and the other sensor is placed on the chest. Five monitoring exercise are conducted and the records can be used as reference of patients’ activity. From the evaluation approach, the testing results Classification Model ranges from 92.6% to 99.1%. The system provides three benefits: visibility, portability, and extensibility.

Compared to other systems, the system Dunne et al [17] presented focus on the field of monitoring seated posture for computer users. Integrated the plastic optical fiber sensor (POF) a garment was developed and tested, the experiment data and analysis show its greater accuracy than expert visual. In addition, the study described the initial system interface design, while the garment design can be improved to maximize the wearable and comfort.

Another accelerometer-based system is developed by Patel et al [18], the data recorded during performance of a subset of the motor tasks pertaining to the Functional Ability Scale that

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Function</th>
<th>Sensor</th>
<th>Accuracy</th>
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<tbody>
<tr>
<td>11</td>
<td>Shoulder, elbow &amp; wrist joint angles</td>
<td>Accmeter, OLE</td>
<td>RMS of 1.2, 3.8 &amp; 3.1 compared to PowerCube, Goniometer and ShapeWrap</td>
</tr>
<tr>
<td>12</td>
<td>Elbow joint angle</td>
<td>Acc/meter</td>
<td>RMS 0.52°</td>
</tr>
<tr>
<td>13</td>
<td>Elbow joint angle</td>
<td>IMU</td>
<td>No data available</td>
</tr>
<tr>
<td>14</td>
<td>Wrist, elbow &amp; shoulder joint</td>
<td>Inertial sensor</td>
<td>RMS position error less than 0.01m, RMS angle error of 2.5°-4.8°</td>
</tr>
<tr>
<td>15</td>
<td>Elbow joint</td>
<td>Acc/meters, mag/meters gyroscopes</td>
<td>RMS of 1.3°</td>
</tr>
<tr>
<td>16</td>
<td>Execution of recognize &amp; a set of 5 exercises</td>
<td>Acc/meter</td>
<td>Accuracy of Classification Model between 92.6% and 99.1%</td>
</tr>
<tr>
<td>17</td>
<td>Seated spinal posture of computer users</td>
<td>Plastic optical fiber</td>
<td>RMS 0.64° and a mean time error of 0.53 seconds</td>
</tr>
<tr>
<td>18</td>
<td>Hand, forearm, upper arm, index finger, thumb and sternum of affected arm</td>
<td>Acc/meter</td>
<td>Scale score marked by a bias of 0.04 points, std 2.43 points</td>
</tr>
</tbody>
</table>
is one of the clinical scales to assess levels of impairment and functional limitation in individuals after stroke.

Table 1 summarizes wearable systems reviewed in this section that are aimed at monitoring movement or posture with respect to the body parts they refer to, the technology used, and results regarding their accuracy. The state of the art in wearable sensing of motion and posture appears to have exceeded that of human observers; for example, [15] argue that the angular resolution of human perception ranges between 2°-6°, which suggests its potential in the context of rehabilitation where still most monitoring and feedback relies on therapists. Developments are very fast, and there are as yet no direct comparison studies regarding the performance of these systems. Where comparisons are reported they do not use a standard benchmark to compare against which would make results comparable. Finally, reported evaluations focus on accuracy while but many of the papers illustrate a growing awareness of the importance of comfort and ease of wearability.

V. WEARABLE TRAINING SYSTEMS WITH MONITORING AND FEEDBACK

Sensing technologies like those reviewed in section A, can be seen as enabling of more complete applications that will guide rehabilitation training. A great deal work has been done toward integrating sensing technologies in complete wearable rehabilitation solutions. In comparing these systems, it is important to consider the feedback part and the interface for the user. Normally the systems consist of at least two main parts: 1) wearable sensing and central controller subsystem, 2) data communication and feedback subsystem.

Wearable sensor technology is used neuro- rehabilitation for stroke patients, combined with a vibratory stimulus [19]. The study evaluates the tolerability and feasibility of the system, with an assortment of vibratory stimuli, delivered at the ankle joint. The device was developed for long-term ambulatory use and the stimuli can be programmed in intensity, duration, and interval of actuation. It has not yet been evaluated empirically. Markopoulos et al have presented a system Us'em [20], aiming that training could be task-oriented, relevant to daily life tasks and preserve their complexity. The system (Fig.3) consists of a wristband device with accelerometer and communication modules and a watch-like device equipped with a graphical display as well. System usability and treatment credibility/expectancy were evaluated and rated to be good by both sub acute and chronic stroke patients.

Another application of these systems is a personalized exercise trainer system [21] based on wearable sensor network that enables capturing user motion. Fig.1 shows the sensor jacket and the interface during training instructions. The exercise evaluation comprises a teach-in mode and a trainer mode, focus on home-based training, personalization and usability for elderly.

The Stroke Rehabilitation Exerciser [22] can support patients and therapists in the implementation and execution of a personalized neurological motor exercise plan at home. It provides “therapist station”, used by therapists to exchange data with patients, also select exercises and compile a training plan. The system has been evaluated in a clinical trial which demonstrated significant and clinically relevant improvements in skilled arm-hand performance of stroke patients in the chronic phase.

This system (Fig. 5) is used for training skilled arm-hand performance of the participants in the study, aiming to assess system usability, patient motivation, and treatment outcome. The clinical trial follows the technology-supported task-oriented arm training (T-TOAT) method and the performance shows the training improved arm-hand performance significantly on Fugl Meyer, Action Research Arm Test, and Motor Activity Log.

The development of smart phone platforms promises to make available to result into suitable solutions for an effective integration of smart phones into wearable systems [23]. Goodney et al proposed a novel system Dr. Droid [24] using mobile phones for assisting stroke rehabilitation. The system collects a motion trace by sampling the built in 3-axis accelerometer on the phone, an application is developed giving audio and visual instructions to administer the test. To generate the scores of patients movements, the study present a novel path based reorientation algorithm that improves the performance of the DTW (dynamic time warping) and HMM (hidden Markov models) algorithms.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Purpose</th>
<th>Technology</th>
<th>Nature of Validation Studies</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>Wrist joint and ankle joint</td>
<td>Vibratory motor</td>
<td>No quantitative results</td>
</tr>
<tr>
<td>20</td>
<td>Motivating stroke patients to use their impaired arm-hand in daily life activities</td>
<td>Acc/Sec/meter</td>
<td>Pre-clinical &amp; Usability evaluation (n=9)</td>
</tr>
<tr>
<td>21</td>
<td>Home-based exercise trainer for elderly people</td>
<td>Inertial measurement units</td>
<td>Pre-clinical &amp; Usability evaluation (n=4) Planned clinical assessment (n = 30)</td>
</tr>
<tr>
<td>22</td>
<td>Home rehabilitation</td>
<td>Inertial sensors and Wireless</td>
<td>Small scale clinical trial (n =9)</td>
</tr>
<tr>
<td>24</td>
<td>Stroke rehabilitation</td>
<td>Acc/Sec (built in phone)</td>
<td>Correctness of algorithms</td>
</tr>
<tr>
<td>25</td>
<td>Telerehabilitation for stroke</td>
<td>Inertial sensors (acc/meter, mag/inert &amp; gyroscope)</td>
<td>Pre-clinical &amp; Usability evaluation (n=8)</td>
</tr>
</tbody>
</table>
TABLE III. Rehabilitation systems integrated interactive games

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Application</th>
<th>Sensor</th>
<th>Feature</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>Track arm and finger motion</td>
<td>OLE, IMU</td>
<td>Arm-hand rehabilitation</td>
<td>No evaluation</td>
</tr>
<tr>
<td>28</td>
<td>Stroke rehabilitation</td>
<td>Acc/meter (built in Wii controller)</td>
<td>Customizable games design and guidelines description</td>
<td>Small scale pre-clinical trial (N=4)</td>
</tr>
<tr>
<td>29</td>
<td>Stroke rehabilitation</td>
<td>Acc/meter</td>
<td>Tabletop game applied</td>
<td>Preclinical evaluation (N=10)</td>
</tr>
<tr>
<td>30</td>
<td>Stroke rehabilitation</td>
<td>Acc/meter</td>
<td>Display monitor combined with Kinect Sensor</td>
<td>Preclinical evaluation (N=10)</td>
</tr>
<tr>
<td>31</td>
<td>Upper limb home rehabilitation</td>
<td>OLE, Acc/meter</td>
<td>Real-time</td>
<td>Compared to commercial system</td>
</tr>
</tbody>
</table>

Mountain et al [25] developed a telerehabilitation system which enables stroke survivors to undertake rehabilitation exercises at home. The system consists of a prototype worn on the upper arm and forearm and a decision support interface which enable recording and feedback. Four volunteers participated in the home testing and home-based testing for the first and second integrated prototypes separately. While the results and end-user experiences showed that technology improvements from clinical perspective may also compromise usability.

A number of systems to support rehabilitation training exercises using wearable motion and posture monitoring have been reviewed in this section. They combine wearable technology with some on screen feedback and most implement a pre-programmed set of exercises. The effectiveness of executing these exercise with the help of these technologies has been demonstrated with small scale clinical trials only or in some cases has not been evaluated at all. No randomized clinical trials have yet been reported to validate the use of these technologies.

VI. REHABILITATION SYSTEM INTEGRATED WITH INTERACTIVE GAMES

A great deal of technology and devices can be utilized to create interactive rehabilitation environment. Recent advances in Virtual Reality, tangible games led their integration with sensor-based wearable device, facilitate the implementation of rehabilitation and improve the patients’ motivation [26,10]. Applications gradually shifted their focus toward medical problems compared with systems designed for better user experience in the context of implementing home rehabilitation.

An example of such system is an interactive therapy system developed by Luo et al [27]. By using the combination of the OLEs with IMUs, the system consists of one arm suit and one SmartGlove, tracking the arm motion and five fingers’ motion separately. Fig.6 shows two VR interactive game scenarios (piano playing, ball catching) designed for motivating users to perform functional motor recovery tasks.

Focusing on supporting game use in different levels of recovery, Alankus et al [28] proposed a low cost, innovative and unobtrusive system. Commercial devices, the Nintendo Wii remote (with built-in accelerometer) and the webcam are chosen as hardware part of the system, attaching the remotes to bands worn on patients’ arms. Supporting game use throughout the rehabilitation process, nine relevant games are presented. The authors present lessons regarding the design of games for how to elicit motions that are useful in a therapeutic context. The results are tentative as only a small number of participants participated in the tests and the evaluation was qualitative.

Expect VR (Virtual Reality) games, tangible tabletop games also applied as promising tools in the rehabilitation systems. The Playful Arm Hand Training Rehabilitation System [29] by Beursgens et al is an example of integration of tabletop game and wearable sensing technology designed for stroke survivors (Fig.2). The patients wearing the jacket can use fork to catch a virtual bug displayed on the screen, the registered compensation movement should be smaller than the setting range, and game provide stimulus and feedback. During the second iteration of the system [30], both the accuracy and applicability are improved, the game content is extended and a display monitor combined with a Kinect sensor for multi-touch interaction replaced the touch screen.

Kian Lim et al [31] developed a low cost, innovative and unobtrusive wearable system. Real time experimental data are collected from a subject using a hand exerciser and compared with a commercial motion capture system, showing good accuracy and atability. The sensor module consists of an Optical Linear Encoder (OLE) and an accelerometer. A VR game “Virtual Teacher” (Fig.8) is proposed to guide the patient to perform the same movement and tasks at home as in clinic, it will not change the pose unless the patient attains the same pose required at that moment.

In summary, wearable systems are successfully used to support the gamification of rehabilitation training. A few such systems have been developed and there is already some positive evidence from clinical trials of limited scale. Still no randomized clinical trial has been reported, showing the need for expanding the empirical evidence regarding the effectiveness of this category of systems.
VII. CONCLUSION

We report on a structured literature survey on existing rehabilitation technologies. Current systems are still in the research phase and have been classified according to the supposed system function and achievement. The survey reveals that major technical advances have been made in the last years since the emergence of wearable rehabilitation technology as a credible option. Current developments aim to improve the accuracy of monitoring and sensing technologies, but with the lack of standard benchmarks, it is difficult to compare technologies based on published reports. Gradually increasing attention needs to be paid to comfort and wearability. A few systems have shown the potential of integrating wearable technologies in rehabilitation technologies and even the gamification of technology supported training. Clinical studies show positive results but no randomized clinical trials have been reported that will demonstrate convincingly the effectiveness of these technologies. Several systems aim to support tele-rehabilitation or gamification of training, but such a scenario has not been realized yet.

REFERENCES


