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Review of Sensing and Robot Solutions to Stroke Rehabilitation, Focusing on Upper Limbs

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Abstract—**The abstract goes here.**

Index Terms—**Stroke rehabilitation, robot, sensors, body position.**

I. Introduction

THIS review is intended as a resource for people wishing to do further research into robot or sensor systems for rehabilitation of stroke victims with upper limb hemiplegia. Systems based on functional electrical stimulation (FES) will not be covered in this review.

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A. Effects of a Stroke

1) Right or Left Hemispherical Stroke: A stroke in the right or left hemispheres of the brain can cause partial or full paralysis down the opposite side of the body (hemiplegia). It can also cause problems with short term memory [1].

Right-hemispherical strokes can also cause the victim to suffer a loss of spatial awareness and an impairment of judgment that manifests as impulsiveness [1].

Left-hemispherical strokes can cause the victim to develop problems with language (aphasia) and may effect their judgment in the opposite way to right-hemispherical victims, with them becoming ponderous and unsure [1].

2) Cerebellar Stroke: A cerebellar stroke affects balance and co-ordination and can cause dizziness and nausea [1], [2].

3) Brain Stem Stroke: Brain stem strokes are the most dangerous as this is the part of the brain that controls essential functions such as your heart, breathing and swallowing [1], [2].

A stroke in the brain stem can also cause full or partial paralysis in either or both sides of the body [1].

B. Traditional Rehabilitation of Stroke Patients

Rehabilitation is possible after a stroke due to the ‘plasticity’ of the brain, which is its ability to adapt to damage and reconfigure to allow continued function [2].

The most basic aim of stroke victim rehabilitation is to allow the victim to regain their independence. The management of stroke patients is broken down into three areas: acute care, rehabilitation care and community care [3].

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1) Acute Care: This is the stage of care that covers preventing further strokes and making sure the patient is breathing and their heart is beating. The patient’s bladder and bowel function should be checked at this stage along with their ability to perform the actions associated with such. The patient should also be brought to a point whereby they can move, albeit with impairments. The last element of care at this stage is emotional support to the patient and their family [3].

2) Rehabilitation Care: This stage of care is all about improvement, it’s about setting goals, developing a plan and then monitoring the patient’s progress against these. It is about getting the patient back on their way towards normality or at least towards ‘functional independence’. It is also about getting the patient to a stage were they’re ready to go home [3].

There are several tests through which the patient’s motor and sense function can be evaluated, a popular one is the fugl-meyer test which scores the patient out of 100 for the whole body (66 for upper limbs, 34 for legs). This score can then be used to measure improvement over the course of treatment [4].

3) Community Care: This stage of care is all about reintegrating the patient, into the community and potentially into work as well if they had a job. It is also about providing support to the patient and to their family and any carers they might have. The patient should also continue with their rehabilitation plan as it is likely that further improvement can still be achieved [3].

C. How Sensing / Robots can Help

Sensor systems for upper limb rehabilitation as they exist at the moment are systems for monitoring position of all or part of the arm, often linked to a game or simulation in a virtual environment [16]. Robotic systems are similar but are able to actively move the patient’s limb through some or all of the degrees of freedom available to it [16].

These robots are helpful to rehabilitation because they can provide detailed feedback which provides useful information to the physiotherapist and potentially a sense of achievement to the patient, allowing them to monitor their own progress. Linking the system to a game or simulated environment also helps to improve the patient’s motivation [16].

There is evidence that use of robots in rehabilitation leads to functional improvements in the patient but there is some question as to whether this is much of an improvement over traditional methods (i.e. not involving a robot) [16].

1) What they need to be able to do: At the most basic level the system needs to be able to accurately measure and report the position of the limb (or section of limb) that it is to be used to aid in the rehabilitation of.

The system also needs to be safe to use, for sensor systems this means not being sharp or too heavy and for robotic systems this also means that the range of movement it can be driven over needs to be the same as that of the human arm and there should be controls in place to stop the system if it is likely to become dangerous [18].

In order for the system to be more effective as a rehabilitation tool it should also be able to support the limb in order to help reduce the likelihood of injury to the patient and it should be comfortable to use for extended periods [16].

It has also been shown to be helpful for the system to incorporate some form of interactive virtual environment, such as a game, in order to increase patient motivation and maintain their cooperation [16].

II. Sensor Systems

THERE are a wide range of sensors available which can prove useful in mapping the position and other qualities of a limb. For this study will will consider sensors as the individual components and sensor systems as a collection of such that can be used to gain a more complete picture of the position and activity of a limb.

A. Position/Movement Sensors

1) The sensors: The most common sensor type used for this purpose is the accelerometer. Accelerometers measure the effect of acceleration on a mass in free-fall. A standard construction method for accelerometers for use at the correct range and frequency of human motion is to have a test mass on a damped spring and have the deflection of this mass move one plate of a capacitor thus changing its capacitance [17].

These devices are usually MEMs devices constructed in silicone but it is also possible to manufacture larger devices (mm scale) using PCB techniques at potentially lower cost [17].

It is also interesting to note that an accelerometer at rest will show an acceleration of 1 g upwards as the acceleration it measures is relative to the free-falling mass, and from the reference point of said mass the casing of the accelerometer appears to be accelerating upwards at a rate of 1g.

2) How they're used: Most usually accelerometers are used to measure the acceleration of whatever they're attached to. If the initial position and velocity are known then it should be possible to calculate the position and velocity from the acceleration via integration although the errors accrued in this process may make using accelerometers this way to estimate body position may not be feasible [8].

One system that uses accelerometers to recognise the action being performed by the patient is described in [10]. This system uses two 3-axis accelerometers one attached at the wrist and one above the bicep [10]. Both these sensors transmit their values via wireless modules to a computer where these values are analysed [10]. This system doesn't map limb position into 3D space but instead uses the output of the sensors whilst the patient is performing an action from their rehabilitation routine and uses this to classify the action [10].

B. Angle Sensors

1) The sensors: The most usual method for measuring angle is with a potentiometer as their resistance changes as they are rotated which is simplicity itself to measure. In order to accurately measure the angle of a joint by this method the potentiometer has to be properly aligned with the joint. Misalignment is one of the main causes of error in systems that use such angle sensors and has to be carefully compensated for [16].

It is possible to use accelerometers as angle sensors relative to gravity, this could also be described as a tilt sensor. Angle of a joint can be measured by putting a sensor either side, both aligned, and calculating the difference [7].

A more novel sensor for measuring angle via measuring flexible displacement is described in [6], it is a type of potentiometer based on nylon string coated in carbon to allow it to be flexible. It is also shown as being able to measure the angle of the elbow joint of a human arm by measuring the flexing of the bicep [6].

2) How they're used: Angle sensors are most commonly used to measure the angle at which a joint in the arm is bent or rotated, if you have such a sensor or each degree of freedom that the arm can move through then a picture of the position of the arm can be constructed. This is usually the position mapping scheme used in exoskeletal systems [16].

C. Force Sensors

1) The sensors: Some examples of force sensors are the force sensitive resistor (FSR) developed by interlink electronics [11], [13], quantum tunneling composites (QTCs) developed by Peratech [12] and piezoelectric force/vibration sensors.

FSRs have contacts on either side of a slightly conductive layer, as force is applied more of the contacts are shorted together and thus the resistance across them is reduced. FSRs are not very accurate for measuring force, they are more suited to detecting its presence [11].

QTCs work by quantum tunneling, they are made of metal particles suspended in an insulator (rubber). When no force is applied the material is an insulator but when force is applied the material deforms and the metal particles are brought closer together allowing the material to conduct via quantum tunneling of electrons [12]. The resistance of a QTC varies exponentially with applied force and can be used for force measurement [12].

Piezoelectric sensors work by the piezoelectric effect; which is that a deformation of the material causes a voltage to appear across it. These types of sensors are only suitable for measuring dynamic force as they only give an output when the applied force is changing, this combined with the fact that they have a very fast response, is why they are often used for monitoring vibration.

2) How they're used: Force sensors in upper limb rehabilitation robots and sensor systems are almost exclusively used to measure the strength of the patient's grip. Force sensors are also used in lower limb rehabilitation to the forces on the feet and help measure gait.

One system that uses force sensors to measure grip strength is the PLEMO system [19]. This system adds grip strength and wrist angle sensors to an existing end-effector type robotic rehabilitation device [19]. The system was tested with a group of healthy subjects and a group of stroke victims so that any differences in the way they performed a task (as described by the information from the sensors) could be identified, from the results the stroke patients were clearly identifiable [19].

III. Robotic Systems

Robotic systems are systems that are able to not only measure the position of the limb but also to actively move it. This allows such systems to physically guide a patient's arm through the required movement. It also allows the system to provide varying amounts of support to the patient as they perform an action [16].

A. End-effector

An end-effector system is a system that is anchored at one end and measures the position of the other end relative to this [16]. The end that is free to move is usually attached to the patient's wrist and thus its position in 3D space can be tracked and controlled (via actuation) which allows the system to monitor the performance of an action and show variations [16].

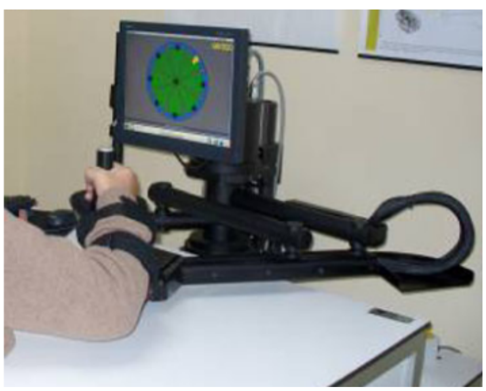

Fig. 1. InMotion2, showing the virtual environment the patient interacts with [21]

The InMotion2 robotic rehabilitation system is an example of and end-effector system [21]. This system attaches to the patient at the forearm and wrist and allows for the motion of these points to be monitored in a 2D plane while the patient completes tasks shown to him on a screen [21]. Data collected from this system at the beginning and end of a course of rehabilitation using the system are able to show that the patient has improved at the tasks set by the system [21].

Another end-effector system is described in [5], this system is designed for hand and finger rehabilitation. This system is interacted with via a finger and allows you to navigate a point about a 3d environment on a computer, in which the patient is to complete tasks [**?**]. This system is also able to show patient improvement at the tasks after rehabilitation using the system [5].

End-effector systems with a single attachment point give no information on the position and alignment of the rest of the limb. Some systems exist with two contact points (e.g. the wrist and the upper arm) in order to get more information but this is still limited [16].

B. Exoskeleton

Exoskeletal systems are systems that are built around shape and degrees of freedom of the limb [16]. They allow much more information to be gathered about the limb as they allow for more sensors to be placed and more degrees of freedom to be monitored and controlled [16]. It is, however, harder to provide support to the limb through a pure exoskeletal system, for this reason the systems are often hybrids; with one end of the exoskeleton attached to and end-effector system [16].

One such hybrid system is the ARMin rehabilitation robot which has an end-effector system for the shoulder attached to an exoskeleton for the elbow and the forearm [9], [18]. The system has 4 active degrees of freedom and 2 passive with which to measure and guide the position and movement of the patient's arm [18]. The ARMin system is also highly adjustable at many points in its structure so that it can be changed to fit patients of different sizes [18].

The ARMin system is also and example of a system that uses interactive games in order to increase patient's motivation and compliance [9], [18]. The ARMin system was piloted on healthy subjects and the results of a questionnaire following this provide evidence for incorporating games increasing motivation [18].

Another exoskeletal system for the arm is the CADEN-7 [20]. The CADEN-7 system was built as a general exoskeleton not specifically aimed at rehabilitation but suitable for use as such or as either an assistive device, a haptic interface or a master device for teleoperation of another robot system [20]. CADEN-7 is a 7 degree of freedom system; 3 at the shoulder, 1 at the elbow and 3 at the wrist to match the human arm [20].

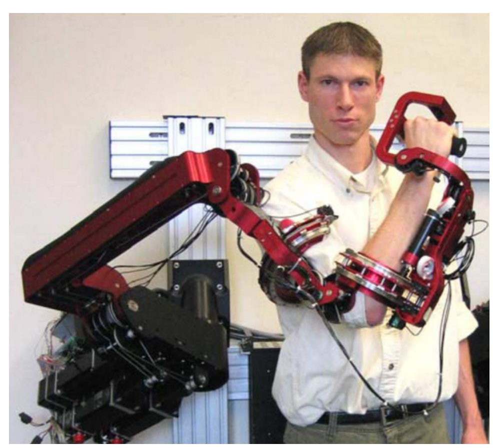

Fig. 2. CADEN-7 exoskeleton system [20]

The name CADEN-7 comes from "cable-actuated dexterous exoskeleton for neurorehabilitation", cable actuation means the torque is transferred from motors to the part of the system to be driven via cables [20]. The advantage of this method is that they can transmit the torque over long distances relatively simply and without much backlash [20].

Exoskeletons are possible for just the hand as well as for the entire arm. An example of such a system is the HEXOSYS-II [14]. This system has a full set of exoskeletal fingers and thumb and each of these can be driven to grasp and unfurl, the system also allows for the fingers to be spread out but this cannot be driven [14].

The HEXOSYS-II has magnetic sensors by the motors in order to sense the finger position (via the motor position) and it also has strain gauges on the linkages between the motor and the fingers in order to sense the forces on the fingers [14].

IV. Vision Based Systems

CAMERAS and computing power is getting cheaper all the time and are therefore more available. This increase in available computing power allows complex image processing to be performed which can be used to track a body in 2d and 3D space.

Motion capture systems such as those used for video games and film are impractical for use in rehabilitation as they involve a large number of high quality cameras, a clean background and the subject has to have markers placed on their body.

A. 2D Tracking Systems

Systems based around a single video camera can only work with 2D images but can still often track bodies in the image and recognise gestures.

One system that tracks the motion of a hand for stroke rehabilitation purposes is described in [22]. This system uses a video camera and a thermal camera in order to facilitate the segmentation of the hand from the image against uncontrolled backgrounds [22]. The system is capable of recognising hand position in a 2D plane and also of distinguishing certain gestures of the hand [22]. The recognition of hand position and gesture is then used as the control for a pair of games designed to be appropriate to stroke rehabilitation [22].

B. Stereo 3D Systems

With two cameras it is possible to capture 3D information about a scene through proper processing of the images. This is done by first properly aligning and calibrating the cameras and then looking at the differences between the two images, objects closer to the cameras will cause a greater disparity.

A system for calculating body position from the feeds of two cameras is described in [15]. This system takes the 'disparity map' (the differences between the two images) and uses this to first find the centre of gravity of this map [15]. This image is then filtered to remove both noise and the background [15]. With this done the system makes a decision as to whether you subject is self-occluded, if not then pose is calculated directly, if so then pose is calculated based on comparing the image to standard human body shape [15].

C. Structured Light Systems

The Microsoft Kinect Sensor is a relatively cheap and readily available system that uses a structured light sensor in order to generate a depth map of a scene [24]. This structured light sensor works by projecting a grid of IR dots onto the scene and an image of these is then captured by the on board IR sensor, depths are then generated based on the deformation of this grid [24].

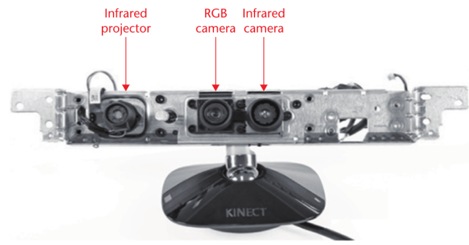

Fig. 3. Kinect with sensors exposed [24]

The Kinect Sensor comes with software for the extraction of the position of people from a scene and the fitting of a skeleton to them as well as gesture recognition built on top of this [23], [24]. This serves as an excellent starting point for use of the Kinect as a rehabilitation tool and it was investigated as a low cost alternative to a conventional motion capture system in [23] and was shown to be able to recognise movements with a similar level of accuracy. Another system exists that improves upon the gesture recognition of the Kinect allowing pose and gesture to be recognised simultaneously [25].

V. Discussion

THERE are a wide range of approaches to the problem of stroke rehabilitation systems, each has its benefits and drawbacks and it may be the case that more than one could be used in a patient's care.

Purely passive sensor based systems provide information on the limb they're monitoring but are unable to support or assist it. They are much lighter and less complex than actuated systems and this might give them an advantage in certain areas of the patient's care; for instance it might be that the system is compact enough that it is something that a physiotherapist could take with them for use in house calls.

Accelerometers are versatile sensors that can be used for inferred position and angle measurements depending on their arrangement. Passive sensing of angle is best done by potentiometer but for measuring the position of a driven joint a magnetometer can be used next to the motor. FSRs and QTCs are the most useful way to sense force for this sort of system and these are used usually in hand/ grip rehabilitation systems.

End-effector type systems are useful and fairly simple but limited, whereas exoskeletons are more complex systems but give more information. The main challenge of an exoskeleton system is to match the degrees of freedom and range of movement of the human arm and, in the interests of safety, not be able to exceed these.

End-effector and Exoskeleton systems for the whole arm tend to be very large, usually wall mounted, systems. This allows them to properly actuate and drive the complete arm throughout its range of motion. There are also end-effector and exoskeleton systems for the hand and fingers which are also important to include in the rehabilitation scheme.

Visual systems are potentially the cheapest candidate for rehabilitation systems. Single camera based systems are limited in the movements they can recognise as they can't extract 3D information whereas multiple camera systems can meaning that they can potentially recognise more complex movements.

The Kinect sensor enables low-cost motion tracking and provides an environment for further experimentation providing a huge amount of potential for rehabilitation systems

VI. Conclusion

A STROKE can affect a person in a multitude of ways including fully or partially paralysing them down one or both sides. The damage caused can however be mitigated by rehabilitation due to the brain's plasticity.

Robotic sensor systems are shown to have potential as useful tools to the physiotherapist and for engaging the patient with their rehabilitation.

There are two main areas where robotic/sensor rehabilitation systems are appropriate; in the hospital for the acute and rehabilitation stages of care, these can big bulky systems, and in the home for the rehabilitation and community stages of care, these have to be smaller and much cheaper systems.

The big end-effector and full arm exoskeleton systems are more suited to the hospital where they can be used as advanced tools for the physiotherapist, providing detailed feedback on the patient's movements.

Systems based around a few sensors placed on the arm or on visual sensors are more suitable for home use, particularly when used as a haptic interface and linked to a game designed to encourage the patient to do appropriate actions for their rehabilitation.

Linking the system to a game is a popular way to increase the patient's motivation and thereby increase the effectiveness of the rehabilitation program due to increased repetition. Almost all the systems developed with rehabilitation in mind linked their system to some form of game or simulation of activities of daily life.

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