Position-sensing technologies for movement analysis in stroke rehabilitation

H. Zheng[1] **N. D. Black**[1] **N. D. Harris**[2]

[1]School of Computing & Mathematics, University of Ulster, Newtownabbey, Northern Ireland
[2]Clinical Measurement, Royal National Hospital for Rheumatic Diseases, Upper Borough Walls, Bath, UK

Abstract—*Research has focused on improvement of the quality of life of stroke patients. Gait detection, kinematics and kinetics analysis, home-based rehabilitation and telerehabilitation are the areas where there has been increasing research interest. The paper reviews position-sensing technologies and their application for human movement tracking and stroke rehabilitation. The review suggests that it is feasible to build a home-based telerehabilitation system for sensing and tracking the motion of stroke patients.*

Keywords—*Position sensing, Motion tracking, Human movement, Rehabilitation, Inertial sensors*

Med. Biol. Eng. Comput., 2005, **43**, 413–420

1 Introduction

DISABILITY STATUS has been traditionally equated with health status (HEALTHYPEOPLE, 2001). According to Healthy People 2010 (HEALTHYPEOPLE, 2010), nearly 20% of the population in the United States currently live with disabilities. In the UK, stroke is the biggest cause of severe disability, and the majority of people who sustain a stroke are elderly. Each year, over 130 000 people in England and Wales have a stroke (Stroke). Stroke has a greater disability impact than any other medical condition. A quarter of a million people are living with long-term disability as a result of stroke in the UK (Stroke) and are not capable of independent living, and their quality of life is significantly affected.

Stroke rehabilitation is primarily concerned with maximising the functional and cognitive abilities of the patient and settling them back into the community (WALKER, 2002). As part of rehabilitation, intensive and repetitive movement training (such as sit-to-stand, step with affected lower limb, reach with affected upper limb and take affected hand to mouth) can be necessary over periods of months or years to modify neural organisation and regain lost function (WALKER, 2002; ROSSINI *et al.*, 2003; MILTNER *et al.*, 1999). However, the approaches currently used in hospital or rehabilitation centre to monitor body position and movement during training either require access to specialised equipment and a dedicated laboratory set-up, or rely on clinician observation and patient recall (MERRYN *et al.*, 2004). Owing to the cost barrier, in-patient rehabilitation length of stay for patients with stroke has been decreased, and out-patient physiotherapy rehabilitation is typically only two or three times per week (REINKENSMEYER *et al.*, 2004).

Correspondence should be addressed to Dr Nigel D. Harris;
email: nigel.harris@rnhrd-tr.swest.nhs.uk

Paper received 31 December 2004 and in final form 29 March 2005

MBEC online number: 20054017

There is a need to develop low-cost systems that are able to provide support for the rehabilitation of post-stroke patients in the home environment to promote/aid functional recovery and enhance their quality of life (REINKENSMEYER *et al.*, 2004). The salient challenge is how to monitor and assess rehabilitation in a domestic environment. In this paper, we review position-sensing technology for human movement, compare different technologies and present analysis issues and current and potential applications to human movement analysis in stroke rehabilitation.

2 Position-sensor technology

There are a range of body-fixed sensors to measure motion and associated changes in limb/body position. These include pedometers, goniometers, electromechanical switches or pressure sensors, magnetometers and inertial sensors. We review these sensors in the following Section.

2.1 *Pedometers*

Pedometers are stepcounters designed to measure steps and estimate distance walked and energy expenditure (kcal). They are typically worn on the belt or waistband and respond to vertical accelerations of the hip during gait cycles. There are three basic mechanisms by which pedometers function (CROUTER *et al.*, 2003). The first uses a spring-suspended horizontal levered arm that moves up and down in response to the hip's vertical accelerations. This movement opens and closes an electrical circuit, the levered arm makes an electrical contact (metal-on-metal contact), and a step is registered. The second incorporates a glass-enclosed magnetic reed proximity switch. With this type, a magnet is attached to the lever arm, the magnetic field triggers the switch, and a step is counted. The third type uses an accelerometer-type mechanism consisting of a horizontal beam and a piezo-electric crystal, and steps are determined from the number of zero-crossings of the instantaneous acceleration against time curve. Pedometers are simple, lightweight and inexpensive devices. The cost is approximately US$10–30 per unit (MELANSON *et al.*, 2004).

Pedometers have been successfully applied in the measurement of physical activity in free-living populations (BALOGH *et al.*, 2004; BASSETT *et al.*, 2000; CROTEAU, 2004; GROVES, 1988; HOODLESS *et al.*, 1994; SAGAWA *et al.*, 2000; SCHNEIDER *et al.*, 2004; SEQUEIRA *et al.*, 1995; STEELE *et al.*, 2003; TALBOT, 2003). However, the limitations of their application have also been investigated:

(*a*) Pedometers are not designed to capture pattern, intensity or type of physical activity.

(*b*) Accuracy: In general, pedometers are most accurate in counting steps, less accurate in calculating distance, and even less accurate in estimating energy expenditure (BASSETT *et al.*, 1996; 2000). Researchers have demonstrated that they detect steps taken with acceptable accuracy (CYARTO *et al.*, 2004; KILANOWSKI *et al.*, 1999; MELANSON *et al.*, 2004; SHEPHERD *et al.*, 1999). CROUTER *et al.* (2003) compared ten electronic pedometers, measuring steps, distance and energy cost, and found that at $80\,m{\cdot}min^{-1}$ and above, most pedometers estimated mean steps within $\pm 1\%$ of actual steps; $\pm 10\%$ for mean distance and $\pm 30\%$ for energy expenditure, and most pedometers underestimated steps at $54\,m{\cdot}min^{-1}$. LE MASURIER and TUDOR-LOCKE (2003) compared the accuracy of pedometer and accelerometer under controlled conditions, and the pedometer detected significantly ($p < 0.05$) fewer steps than actually taken at the speed of $54\ m \cdot min^{-1}$, and fewer steps than the accelerometer at this speed (75.4% against 98.9%, $p < 0.05$). The magnitude of this error may not limit these devices for the assessment of free-living ambulatory populations, but may be a problem when monitoring frail, older adults with slow gait, a major concern in severely functionally impaired patients. A study comparing commercially available pedometers was also carried out by MELANSON *et al.* (2004), who agreed with the above conclusion.

The two main issues above restrict the application of pedometers for use in the rehabilitation of individuals with moderate to severe motor impairment who may not be ambulant.

2.2 *Goniometers*

A goniometer is an electrical potentiometer that can be attached to a limb to measure a joint angle (WINTER, 1990). Currently, electrogoniometers, either potentiometer-based or flexible ones, have been applied to measure the range of motion (ROM) for wrist and forearm (HANSSON *et al.*, 1996; 2004; JONSSON and JOHNSON, 2001; JOHNSON *et al.*, 2002; MCGORRY *et al.*, 2004), knee (KUIKEN *et al.*, 2004), back (SHIRATSU and COURY, 2003), cervical spine and neck (HAYNES and EDMONDSTON, 2002) and pelvic (SPRIGLE *et al.*, 2003) position, and shoulder strength (BLOMQVIST *et al.*, 2004).

GOODWIN and SUNDERLAND (2003) compared the reliability and interchangeability of three types of goniometer, including a universal goniometer, fluid goniometer and electrogoniometer, from joint measurements on the upper limb. They reported that the use of the electrogoniometer (EGM) reduced the variability between tests, and that different types of goniometer should not be used interchangeably.

Flexible EGMs are presented commercially in different sizes (SHIRATSU and COURY, 2003), as they are anthropometric-dependent. Some types of EGM, e.g. the models for wrist movements, have been used for the study of diverse functional situations (HANSSON *et al.*, 1996) and are recognised as being reliable and accurate in the evaluation of uniplanar movements (Rawes *et al.*, 1996). A major source of error with the most widely used commercially available EGM is cross-talk (HANSSON *et al.*, 1996).

SHIRATSU and COURY (2003) estimated the reliability and accuracy of flexible EGMs with four different twin-axis goniometers attached at the back/spine. All the goniometers had similar working mechanisms, different physical sizes and the specific planes/axis they were designed for. Four goniometers showed good reliability in the flexion–extension and right and left lateral flexion movements with errors of 3–5°. These are equal to or below the 5° mean error limit accepted by the American Medical Association to consider the measurements reliable for the evaluation of movement impairments in a clinical context. However, one type of goniometer presented errors for the right (7°) and left (5°) rotation, and another two types presented different error patterns with an error of 5°, which is above the maximum acceptable error of $\pm 3°$ set by the EGM manufacturer for extreme amplitudes. Studies (HANSSON *et al.*, 1996) measuring wrist postures have shown a mean error of up to $5 \pm 5°$ for flexion/extension and $6 \pm 5°$ for radial/ulnar deviation.

New types of goniometer have been reported in recent research studies. A computer-based goniometer (BARREIRO *et al.*, 2003) has been developed focused on measurement of the angles of arms. A computerised biofeedback knee goniometer (KUIKEN *et al.*, 2004) was introduced for self-monitoring in post-total knee arthroplasty rehabilitation.

In general, goniometers are inexpensive and contain sufficient information for gait event detection. However, they have practical limitations. There is always a problem of attachment and the need for a range of devices to fit different-sized limbs and digits. Joint goniometers are vulnerable to breakage where they cross a joint. Other common issues are difficulties in alignment with, and determination of, joint centres of rotation, restriction of movement by the device, or incomplete decoupling of the measurement of motion in the two planes (cross-talk). The size, weight and physical location of the goniometer can be critical so that it does not interfere with function. Only relative angular data are produced, not absolute angles. Furthermore, it is unlikely that an older person preparing to embark on a period of exercise could successfully attach these devices without external assistance.

2.3 *Electromechanical switches or pressure sensors*

Pressure sensors are used in different types of pressure switch. A simple, single-point switch is similar to a conventional pressure transducer, with the addition of an adjustable control point and relay or transistor output. The more sophisticated pressure sensor incorporates a microprocessor that accepts the digitised signal from the amplifier and provides the keyboard interface and a variety of options, including local readout, digital or analogue output and adjustable switch points. The sensors can measure gauge, absolute or differential pressure. In addition simply to measuring pressure and sending signals to a remote controller, some switches themselves can control many local operations. These include sequences based on minimum, normal, maximum and shut-down system pressures, as well as automatic filling, emptying, pressurising and unloading accumulators. One multifunctional pressure sensor can house a number of switches and supervise multiple pressure points.

Pressure sensors have been applied in the detection of walking posture. The sensors can be installed into a shoe or a measurement pad to obtain foot–floor contact information. During each phase of walking, the pressure under the foot varies considerably. For example, a simple foot switch has been used in the Odstock dropped-foot stimulator to trigger electrical stimulation of the common peroneal nerve (TALOY *et al.*, 1999). The foot switch indicates heel-off and heel-strike. The switch remains pressed when the patient remains standing with the heel on the ground. When the patient continues walking, the pressure is removed from the switch at heel-rise, and stimulation continues. SKELLY and CHIZECK (2001) reported the real-time detection of gait events using force-sensitive resistors, and five phases of gait cycle functions, foot-flat, heel-off, toe-off, max-knee-flexion and heel-strike, were detected. It is possible to use them for lower-limb rehabilitation, i.e. walking, stands, but they are not suitable to use for upper-limb rehabilitation. Pressure sensors under the feet are not satisfactory for use in the domestic environment as they generally require long cables for connection to a portable unit, which is often worn at the waist (VELTINK *et al.* 1996).

2.4 *Inertial sensors*

Micromachined inertial sensors, including accelerometers and gyroscopes, are silicon-based sensors (YAZDI *et al.*, 1998; TUNG, 2004). They are small in size and can be worn on the body. The working principle of these sensors is based on the measurement of inertia and can be applied anywhere without a reference. Owing to these advantages, an extensive amount of research has been carried out to evaluate their use for detecting human movement.

2.4.1 *Accelerometers*

Accelerometers are instruments that measure the applied acceleration acting along a sensitive axis. Conceptually, a single-axis accelerometer consists of a mass, suspended by a spring in housing. The mass is allowed to move in one direction, and the displacement of the mass is a measure of the difference in acceleration and gravity along the sensitive axis given by the unit vector. To track human motion, one is needed for each of the three planes of motion. A triaxial accelerometer (TA) can be constructed by mounting three such single-axis accelerometers together (LUM *et al.*, 2002) or by using a single mass with three translational degrees of freedom (LTTERS *et al.*, 1998).

Steele *et al.* summarised issues related to monitoring activity in the rehabilitation setting for people with chronic pulmonary disease (STEELE *et al.*, 2003). They reviewed motion-sensor technology and compared motion-sensing devices, including accelerometers, and MATHIE *et al.* reviewed accelerometry for long-term, ambulatory monitoring of human movements (MATHIE *et al.*, 2004*a*).

There is a range of different types of accelerometer, including piezo-electric crystals, piezorestive sensors, servo force balance transducers, electronic piezo-electric sensors and variable capacitance accelerometers. Most human movement applications use piezoresistive accelerometers or variable capacitance accelerometers, both of which respond to gravitational acceleration as well as to acceleration due to movement (BOUTEN *et al.*, 1997; FAHRENBERG *et al.*, 1997; FOERSTER *et al.*, 1999; MATHIE *et al.*, 2004*a*; VELTINK *et al.*, 1996). Both of these types are based on micro-electromechanical-system (MEMS) technology, and, hence, are small in size and can be easily mounted on the skin. Both types require an external power supply, and the accelerometer responds to static gravitational acceleration.

The accelerometer is normally placed on the part of the body the movement of which is being studied. For example, accelerometers are attached to the thigh or ankle to study leg movement during walking; to the wrist to measure Parkinsonian bradyinesia; to both arms and legs for the study of Parkinsonian tremor; to the chest to study coughing, and to the pelvis or cross body to study 'whole body' movements (MATHIE *et al.*, 2004*a*).

Given that most human movements occur between 0.3 and 3.5 Hz, a filter with a cutoff frequency between 0.1 and 0.5 Hz has been used to separate static orientation due to gravity from body movement. The major energy band for daily activities is 0.3–3.5 Hz, whereas slightly higher frequencies occur during running. Most acceleration is below 18 Hz at the ankle. The maximum frequencies decrease from the ankle to the head and are greater in the vertical direction than in the transverse plane. During running, 8.1–12.0 g can be measured vertically at the ankle. To assess daily activities, accelerometers must be able to measure accelerations up to $\pm 12\ g$ in the limbs and up to $\pm 6\ g$ at waist level and cover frequencies up to 20 Hz.

Measurement of human movement can be summarised into three types: inclination(angle to the vertical), orientation(relative angle of limbs or body) and ambulatory measurement (e.g. activity monitoring, training of motor skills during daily life); the latter requires measurement of both inclination and orientation. Accelerometers measure the gravity vector and the acceleration. When the acceleration is sufficiently small compared with the gravity, they can be used as inclinometers to measure inclination. Accelerometers have been used in all the above three types of measurement to assess metabolic energy expenditure (EE), physical activity, postural sway, gain, fall detection, postural orientation and activity classification (MATHIE *et al.*, 2004*a*).

Studies have been performed to validate both uniaxial and multiaxial accelerometers as a measure of EE and showed the significant correlations between the two (STEELE *et al.*, 2003). Accelerometry systems typically use a model in which the area under the curve traced by the time course of body movement acceleration is linearly related to EE, and the actual energy expenditure is calculated by regression (BOUTEN *et al.*, 1997). The major issue is that the measurement unit is not standardised, and no direct translation into EE exists. Differences in the accuracy of the calibration equations, rather than differences in the monitors themselves, have been shown to contribute to differences in recorded energy expenditure (WELK *et al.*, 2000). It is therefore recommended that the motion data be analysed as counts (FREEDSON and MILLER, 2000; STEELE *et al.*, 2003; MATHIE *et al.*, 2004*a*).

Because uniaxial sensors track motion in the vertical plane only, they are not accurate for activities with static trunk movement, such as cycling and rowing (FREEDSON and MILLER, 2000). The specific activities being performed also affect the accuracy of accelerometery for measuring energy expenditure. For example, the Tritrac accelerometer has been shown to overestimate the energy expenditure of walking and jogging and to underestimate the energy expenditure of stair climbing, stationary cycling and arm ergometry (CAMPBELL *et al.*, 2002). Similarly, another study comparing three accelerometers and a pedometer for the prediction of energy expenditure during moderate-intensity activity suggested that all four motion-sensing devices overpredicted energy expenditure during walking, but underpredicted energy expenditure in activities that included arm movement and static work (BASSETT *et al.*, 2000).

BOUTEN *et al.* (1997) described the development of a triaxial accelerometer (TA) and a portable data processing unit for the assessment of daily physical activity. The TA is composed of three orthogonally mounted uniaxial piezoresistive accelerometers and can be used to register accelerations covering the amplitude and frequency ranges of human body acceleration. A major advantage of a triaxial sensor over a uniaxial sensor is that the instrument is more sensitive to light activities, such as slow walking. A disadvantage, however, related to this greater sensitivity, is that the device is also sensitive to vibrational artifact.

Several studies have compared the relative accuracy and validity of accelerometers and pedometers (LEEDERS *et al.*, 2001; TUDOR-LOCKE *et al.*, 2002) and the absolute and relative validity of different accelerometers (WELK *et al.*, 2000; KOCHERSBERGER *et al.*, 1996) and found that they were highly correlated, and that accelerometers had higher accuracy in slow movement than pedometers. This suggested that accelerometers were comparable for assessing the amount and intensity of activity.

Accelerometers have been reported to be a reliable method for measuring balance and postural sway (FOERSTER *et al.*, 1999; KAMEN *et al.*, 1998; MOE-NILSSEN, 1998). KAMEN *et al.* (1998) described an inexpensive, efficient system for the clinical assessment of static and dynamic balance and postural sway using accelerometry-based measurements for both young and elderly individuals.

The information that accelerometers provide can also be used for the classification of postures and activities, such as sitting, lying, standing, walking, stair climbing and cycling (BUSSMANN *et al.*, 1998; FAHRENBERG *et al.*, 1997; MATHIE *et al.*, 2004*b*; UITERWAAL *et al.*, 1998; VELTINK *et al.*, 1996; WILLIAMSON and ANDREWS, 2000). Sit-to-stand and stand-to-sit transitions can be classified by identifying the preceding and succeeding postures as sitting and standing (AMINIAN *et al.*, 1999; FAHRENBERG *et al.*, 1997; MATHIE *et al.*, 2003). However, little work has been reported using accelerometers for quantification of the biomechanics of the sit-stand-sit movement, and this area remains to be investigated.

2.4.2 *Gyroscopes*

Orientation is an essential quantity to be estimated in human movement. Accelerometer signals do not contain information about the rotation around the vertical and therefore do not give a complete description of orientation. Gyroscopes measure angular velocity and can be combined with accelerometers to estimate orientation (KEMP *et al.*, 1998). The construction of angular rate sensors, gyroscopes, is based on different designs: spinning rotor gyroscopes, laser gyroscopes and vibrating mass gyroscopes (SDERKVIST, 1994). Conventional spinning rotor gyroscopes and laser gyroscopes are expensive and big. They are not suitable for human motion analysis. Vibrating mass gyroscopes are small, inexpensive and have low power requirements, making them ideal for human movement analysis. A 3D gyroscope can be assembled using three single-axis gyroscopes, and the gain, offset and sensitive axis of each of these gyroscopes with respect to the sensor housing can be obtained (KEMP *et al.*, 1998).

A three-axial gyroscope and a three-axial accelerometer can be mounted to one point to form an inertial measurement unit (IMU). It is used to measure 3D angular velocity and 3D acceleration and gravity with respect to the sensor housing, so that full kinematic information can be derived.

VELTINK *et al.* (1996) reported a three-dimensional inertial sensing system, consisting of two-axial accelerometers and three perpendicularly oriented rate gyroscopes, for measuring foot movements during gait.

Typically, angular orientation of a body segment is determined by integrating the output from the angular rate sensors strapped onto the segment. A relatively small offset error on the gyroscope signal will introduce large integration errors. In most situations of human movement sensing, the gravitational acceleration is dominant, thus providing inclination information that can be used to correct the drifted orientation estimate from the gyroscopes. The principles for measuring orientation of a moving body segment fusing gyroscopes and accelerometers in a Kalman filter have been described by LUINGE (2002).

The magnetometer is an instrument for measuring the direction and/or intensity of magnetic fields. It is sensitive to the earth's magnetic field. It gives information about the heading direction to correct drift of the gyroscope about the vertical axis. BACHMANN *et al.* (2001) used inertial and magnetic sensors, the nine-axis magnetic field, angular rate and gravity (MAGRG) sensor unit, to track the three degrees of orientation of human body limb segments, and it demonstrated the practicality of inertial and magnetic orientation tracking in real-time. However, ferromagnetic materials in the neighbourhood of the sensor will disturb the local magnetic field and will therefore distort the orientation measurement. This interference impedes applications such as ambulatory motion tracking.

3 Motion-tracking systems

Human motion-tracking systems generate real-time data that represent human movement (MULDER, 1994). Sensors or markers are placed on the body to measure the distance to, or orientation or position of, an external source. Alternatively, sensors or markers can be attached to anatomical landmarks on the body and used to calculate their relative positions in space.

Motion-tracking systems can be classified according to the position of the sensors and sources (KALAWSKY, 1993), or according to the motion-tracking techniques, e.g. electromagnetic position and orientation trackers, acoustic position and orientation trackers, mechanical position and orientation trackers, electrostatic position and orientation trackers, and video and electro-optical tracking systems. The following classification (ZHOU and HU, 2004) is suggested: non-vision based systems (e.g. MT9, G-link, MotionStar, InterSense, Polhemus, HASDMS-1 and glove-based devices), vision-based tracking systems with markers (e.g. Qualisys, VICON, PeakMotus, CODA, ReActor2, ELITE bitomech and APAS), vision-based tracking systems without markers and robotic-guided tracking systems (e.g. Cozens, MANUS, MIME, ARM Guide and robotic arms etc.). These systems are reviewed in detail by ZHOU and HU (2004).

All of the above systems need specialist equipment and are expensive. They also restrict body movement to some degree. For example, robotic-guided tracking systems are limited in the range of human motion and, in particular, walking or other transitional motion; glove-based systems are disadvantaged by wires attached to each sensor. Of these systems, 3D optical tracking systems such as Vicon or CODA are being used for rehabilitation work in clinical environments. Entry-level systems comprise one or more video cameras or sensor arrays, a PC with interface cards and active or passive markers. The CODA system is pre-calibrated and uses active (light-emitting) sensors that can be set up at a new location without recalibration. The system can use up to six sensor units altogether and can track 360° movements. The VICON system uses multiple video cameras with passive markers and must be calibrated each time it is relocated. With both systems, the calculation of the 3D co-ordinates of each of the markers is in real time, which opens up many applications that require real-time feedback. However, the operation of the systems, mounting of markers and interpretation of the kinematic data require bio-engineering expertise. Because of the complexity and cost of the systems, they are limited to a laboratory-type environment and are not suitable for use in the home.

An alteration to the above systems involves the design of a tracking system using inertial sensor devices as these are relatively low cost and small in size, which makes them suitable for a home environment.

The Xsens MT9 (MT9) is a digital measurement unit that measures 3D rate-of-turn, acceleration and earth-magnetic field. It provides real-time 3D orientation data in the form of Euler angles and quaternions, at frequencies up to 512 Hz and with an accuracy better than 1° RMS. An MT9 miniature inertial orientation sensor, with $2\,g$ acceleration range and $900\,\mathrm{deg\,s^{-1}}$ rate-of-turn range costs about 1690 Euro.

The G-Link or MicroStrain is a triaxial accelerometer-based device, designed to operate as part of an integrated wireless sensor network system (glink). The G-Link can be wirelessly commanded to transmit data continually, at 1 KHz sweep rates, for a pre-programmed time period. The G-link has two acceleration ranges: $\pm 2\,g$ and $\pm 10\,g$, and its battery lifespan can be 273 h. This is suitable for long-term monitoring. The transceiver size is $25 \times 25 \times 5\,mm^2$. A G-Link starter kit, including two G-Link data-logging transceivers ($\pm 10\,g$ full-scale range), one base station and all necessary software and cables, costs about US$2000. It can be operated over the full 360° of angular motion on all three axes with $\pm 300\,\mathrm{deg\,s^{-1}}$ angular velocity range, 0.1° repeatability and $\pm 5^\circ$ accuracy.

4 Telerehabilitation and home-based rehabilitation

According to new research (WALLING, 2004), home-based therapy after a stroke can improve a patient's ability to perform everyday activities. The advantages of rehabilitation in a domestic environment are

(i) the evaluation of activities of daily living can provide a good assessment of the outcome of the treatment
(ii) home-based rehabilitation can provide patients with more frequent treatment than the limited resources of the current health care system
(iii) patients can stay at home, which can reduce the cost to the health care system
(iv) patients with chronic conditions can receive treatment that is required to prevent deterioration in their condition.

The other emerging term in rehabilitation is telerehabilitation or teletherapy, which is defined as 'the use of communication and information technologies to deliver rehabilitation services and exchange information over geographical distances' (TURNER, 2001).

Telerehabilitation has been integrated with home-based rehabilitation and opens up a new opportunity for stroke patients. Pilot programs have shown that telerehabilitation can be effective in providing services to underserved regions (CLARK *et al.*, 2002; SELLERS *et al.*, 1998). Researchers from the University of Glasgow (CLARK *et al.*, 2002) in the United Kingdom analysed 14 clinical trials to evaluate home-based therapy for stroke patients. The study included 1600 stroke patients who were living at home, within one year after having a stroke. The study found that rehabilitation at home reduced the odds of deteriorating in ability to undertake personal activities of daily living such as walking and dressing by 28%. In addition, rehabilitation increased the ability of patients to undertake daily activities by 14%. The EU FP5 project, MEDICATE (MEDICATE), developed a telecare system for the delivery and dispensing of drugs. A device is connected to a dedicated control centre to which doctors, pharmacists and other registered professionals have access, by a communications network. The project has been successfully completed, and some of the telemedicine techniques can be applied in telerehabilitation.

The measurement/monitoring of home-based rehabilitation has very different requirements from monitoring in the laboratory. Measurements should not be limited to a small measurement space and can be performed for very variable periods of time. The measurement system should be portable. Sensors should be small and light and packaged so they can be easily mounted on the body. For the data analysis and processing, both kinematics and kinetics information is necessary (MATHIE *et al.*, 2004*a*). This should be carried out automatically, with a summary of measurements (such as number of repetitions) presented to the user/carer.

Inertial sensors have been reported as being used for remote monitoring. TAO and HU (2003) built a visual tracking system for home-based rehabilitation using both marker-based and marker-free methods. The system is low-cost, though computationally expensive. A small body-mounted instrument utilising accelerometers and gyroscopes was used to investigate the kinematics and dynamics of locomotion without any limitation of laboratory conditions (OHTAKI *et al.*, 2001). Temporal gait parameters were determined by classification of accelerations and angular velocities. Joint angles, joint moments and energy consumption (calculated as mechanical work) were estimated assuming rigid-body dynamics in the sagittal plane. The method was verified by comparison of the results with data from a video-based motion capture system and force plates. They evaluated accuracy for normal level walking at four cadences. No significant differences were observed between the results of the new method and those from the conventional method.

MATHIE *et al.* (2004*c*) used a waist-mounted, wireless TA to monitor human movements in an unsupervised home setting to detect changes in functional status. The pilot study was carried out with six healthy subjects aged 80–86 years. The subjects wore a TA unit every day for two–three months. Their study found that the TA system is practical for long-term, unsupervised home monitoring.

5 Discussion and conclusions

The technologies discussed in the paper show that inertial sensors have many advantages compared with other sensing technologies. The feasibility of assessing individual movements for ambulatory monitoring using inertial sensors, especially accelerometers, has been demonstrated by a number of workers. Preliminary research suggests that a home-based rehabilitation system for telerehabilitation can be developed using these technologies.

The sit–stand–sit movement is a useful indicator for rehabilitation. The ability to rise from a chair and to sit down in a controlled manner is of fundamental importance for functional independence. Sit–stand–sit training does not require much space and is suitable for repeated practice in the home environment for rehabilitation. Whereas pedometers, goniometers or pressure sensors are not suitable for the assessment of this movement, accelerometers may provide useful clinical information to assess performance, although, so far, little research has been carried out in this area. This is a novel area open for investigation.

In conclusion, the key to successful implementation of a home-based rehabilitation system is making technology reliable and invisible to the user, so that it is simple to attach and use. The MT9 and G-Link wireless tracking devices are two practical devices available on the market. Because they are small in size, relatively low-cost and easy to interface with computers, they are good candidates on which to base a tracking system for use by stroke patients at home.

The SMART EQUAL project (SMART) funded by EPSRC aims to examine the appropriateness and effectiveness of this technology to support hospital or home-based rehabilitation programmes for older people who have sustained a stroke. The project proposes to develop a real-time tracking system utilising a customised three-axis accelerometer that will provide both therapeutic instruction and support information. Information on a patient's movement (e.g. sit–to–stand) at home will be collected and sent to a central station for analysis in real time, and the feedback will be provided to the person in an appropriate format (audio/visual) and, where appropriate, to their carers or health care professionals. The techniques involved in the system are mature; however, work needs to be done to develop detection/analysis software, calibration algorithms and 2/3D kinematic models. Other important issues that need to be addressed are the development of clinical protocols, integration into clinical practice and assessment of the benefits of such systems to the patient. These will be addressed in the later stages of the project.

Acknowledgments—This research was supported by the UK EPSRC under Grant GR/S29089/01. The authors would like to thank all partners from the University of Bath, University of Essex, Sheffield Hallam University, University of Ulster and the Stroke Organisation.

References

AMINIAN, K., ROBERT, P., BUCHSER, E. E., RUTSCHMANN, B., HAYOZ, D., and DEPAIRON, M. (1999): 'Physical activity monitoring based on accelerometry: validation and comparison with video observation', *Med. Biol. Eng. Comput.*, **37**, pp. 304–308

BACHMANN, E. R., MCGHEE, R. B., YUN, X., and ZYDA, M. J. (2001): 'Inertial and magenetic posture tracking for inserting humans into networked virtual environments'. *Proc. ACM Symposium on Virtual Reality Software & Technology*

BALOGH, I., ORBAEK, P., OHLSSON, K., NORDANDER, C., UNGE, J., WINKEL, J., and HANSSON, G. A. (2004): 'Self-assessed and directly measured occupational physical activities – influence of musculoskeletal complaints, age and gender', *Appl. Ergon.*, **35**, pp. 49–56

BARREIRO, M. S., FRERE, A. F., THEODORIO, N. E. M., and AMATE, F. C. (2003): 'Goniometer based to computer'. *Proc. 25th Ann. Int. Conf. IEEE Eng. in Med. Biol. Soc., 17–21 Sept. 2003*, Cancun, Mexico, pp. 3290–3293

BASSETT, D. R., AINSWORTH, B. E., and LEGGETT, S. R. (1996): 'Accuracy of five electronic pedometers for measuring distance walked', *Med. Sci. Sports Exerc.*, **28**, pp. 1071–1077

BASSETT, D. R., CURETON, A. L., and AINSWORTH, B. E. (2000): 'Measurement of daily walking distance-questionnaire versus pedometer', *Med. Sci. Sports Exerc.*, **32**, pp. 1018–1023

BLOMQVIST, L., STARK, B., ENGLER, N., and MALM, M. (2004): 'Evaluation of arm and shoulder mobility and strength after modified radical mastectomy and radiotherapy', *Acta Oncol.*, **43**, pp. 280–283

BOUTEN, C. V. C., KOEKKOEK, K. T. M., VERDUIM, M., KODDE, R., and JANSSEN, J. D. (1997): 'A triaxial accelerometer and portable processing unit for the assessment daily physical activity', *IEEE Trans. Biomed. Eng.*, **44**, pp. 136–147

BUSSMANN, H. B. J., REUVEKAMP, P. J., and VELTINK, P. H. (1998): 'Validity and reliability of measurements obtained with an "activity monitor" in people with and without a transtibial amputation', *Phys. Therapy*, **78**, pp. 989–998

CAMPBELL, K. L., CROCKER, P. R., and MCKENIE, D. C. (2002): 'Field evaluation of energy expenditure in women using tritrac accelerometer', *Med. Sci. Sports Exerc.*, **34**, pp. 1667–1674

CLARK, P. G., DAWSON, S. J., SHEIDEMAN-MILLER, C., and POST, M. L. (2002): 'Telerehab: Stroke teletherapy and management using two-way interactive video', *Neurol. Rep.*, **26**, pp. 86–92

CROTEAU, K. A. (2004): 'A preliminary study on the impact of a pedometer-based intervention on daily steps', *Am. J. Health Prom.*, **18**, pp. 217–220

CROUTER, S. E., SCHNEIDER, P. L., KARABULUT, M., and BASSETT, D. R. (2003): 'Validity of 10 electronic pedometers for measuring steps, distance, and engergy cost', *Med. Sci. Sports Exerc.*, **35**, pp. 1455–1460

CYARTO, E. V., MYERS, A. M., and TUDOR-LOCKE, C. (2004): 'Pedometer accuracy in nursing home and community-dwelling older adults', *Med. Sci. Sports Exerc.*, **36**, pp. 205–209

FAHRENBERG, J., FOERSTER, F., SMEJA, M., and MULLER, W. (1997): 'Assessment of posture and motion by multichannel piezoresistive accelerometer recordings', *Psychophysiology*, **34**, pp. 607–612

FOERSTER, F., SMEJA, M., and FAHRENBERG, J. (1999): 'Detection of posture and motion by accelerometry: a validation study in ambulatory monitoring', *Comput. Human Behav.*, **15**, pp. 571–583

FREEDSON, P. S., and MILLER, K. (2000): 'Objective monitoring of phsical activity using motion sensors and heart rate'. *Res. Q. Exerc. Sport*, **71**, pp. S21–29

GLink: *http://www.microstrain.com/*

GOODWIN, N., and SUNDERLAND, A. (2003): 'Intensive, time-series measurement of upper limb recovery in the subacute phase following stroke', *Clin. Rehab.*, **17**, pp. 69–82

GROVES, D. (1988): 'Beyond the pedometer – new tools for – monitoring activity', *Phys. Sports Med.*, **16**, pp. 160–164

HANSSON, G. A., BALOGH, I., OHLSSON, K., and SKERFVING, S. (1996): 'Goniometer measurement and computer analysis of wrist angles and movements applied to occupational repetitive work', *J. Electromyogr. Kinesiol.*, **6**, pp. 23–35

HANSSON, G. A., BALOGH, I., OHLSSON, K., and SKERFVING, S. (2004): 'Measurements of wrist and forearm positions and movements: effect of, and compensation for, goniometer crosstalk', *J. Electromyogr. Kinesiol.*, **14**, 355–367

HAYNES, M. J., and EDMONDSTON, S. (2002): 'Accuracy and reliability of a new, protractor-based neck goniometer', *J. Manip. Physiol. Therap.*, **25**, pp. 579–586

HEALTHYPEOPLE (2001): *http://www.healthypeople.gov/document/html/volume1/06disability.htm*

HOODLESS, D. J., STAINER, K., SAVIC, N., BATIN, P., HAWKINS, M., and COWLEY, A. J. (1994): 'Reduced customary activity in chronic heart-failure – assessment with a new shoe-mounted pedometer', *Int. J. Cardiol.*, **43**, pp. 39–42

JOHNSON, P. W., JONSSON, P., and HAGBERG, M. (2002): 'Comparison of measurement accuracy between two wrist goniometer systems during pronation and supination', *J. Electromyogr. Kinesiol.*, **12**, pp. 413–420

JONSSON, P., and JOHNSON, P. W. (2001): 'Comparison of measurement accuracy between two types of wrist goniometer systems', *Appl. Ergonom.*, **32**, pp. 599–607

KALAWSKY, R. S. (1993): '*The science of virtual reality and virtual environments*' (Addison-Wesley, Wokingham, England, 1993)

KAMEN, G., PATTERN, C., DU, C. D., and SISON, S. (1998): 'An accelerometry-based system for the assessment of balance and postural sway', *Gerontology*, **44**, pp. 40–45

KEMP, B., JANSSEN, A. J. M. W., and VAN DER KAMP, B. (1998): 'Body position can be monitored in 3d using miniature accelerometers and earth-magnetic field sensors', *Electro-encephalogr. Clin. Neuro-physiol./Electromyogr. Motor Control*, **109**, pp. 484–488

KILANOWSKI, C. K., CONSALVI, A. R., and EPSTEIN, L. H. (1999): 'Validation of an electronic pedometer for measurement of physical activity in children', *Ped. Exer. Sci.*, **11**, pp. 63–68

KOCHERSBERGER, C. E., MCCONNEL, E., KUCHIBHATLA, M. N., and PIEOER, C. (1996): 'The reliability, validity, and stability of a measure of physical activity in the elderly', *Arch. Phys. Med. Rehabil.*, **77**, pp. 793–795

KUIKEN, T. A., AMIR, H., and SCHEIDT, R. A. (2004): 'Computerized biofeedback knee goniometer: acceptance and effect on exercise behavior in post-total knee arthroplasty rehabilitation', *Arch. Phys. Med. Rehab.*, **85**, pp. 1026–1030

LE MASURIER, G. C., and TUDOR-LOCKE, C. (2003): 'Comparison of pedometer and accelerometer accuracy under controlled conditions', *Med. Sci. Sports Exerc.*, **35**, pp. 867–871

LEEDERS, N. Y., SHERMAN, W. M., NAGARAJA, H. N., and KIEN, C. L. (2001): 'Evaluation of methods to assess physical activity in free-living conditions', *Med. Sci. Sports Exerc.*, **33**, pp. 1233–1240

LTTERS, J., *et al.* (1998): 'Design, fabrication and characterization of a highly symmetrical capacitive triaxial accelerometer', *Sensors Actuators A: Phys.*, **66**, pp. 205–212

LUINGE, H. J. (2002): 'Inertial sensing of human movement'. PhD thesis, University of Twente

LUM, P., REINKENSMEYER, D., MAHONEY, R., RYMER, W. Z., and BURGAR, C. (2002): 'Robotic devices for movement therapy after stroke: current status and challenges to clinical acceptance', *Top Stroke Rehabil*, **8**, pp. 40–53

MATHIE, M. J., COSTER, A. C., LOVELL, N. H., and CELLER, B. G. (2003): 'Detection of daily physical activities using a triaxial accelerometer', *Med. Biol. Eng. Comput.*, **41**, pp. 296–301

MATHIE, M. J., COSTER, A. C., LOVELL, N. H., and CELLER, B. G. (2004*a*): 'Accelerometry: providing an integrated, practical method for long-term, ambulatory monitoring of human movement', *Physiol. Meas.*, **25**, pp. R1–R20

MATHIE, M. J., CELLER, B. G., LOVELL, N. H., and COSTER, A. C. (2004*b*): 'Classification of basic daily movements using a triaxial accelerometer', *Med. Biol. Eng. Comput.*, **42**, pp. 679–87

MATHIE, M. J., COSTER, A. C., LOVELL, N. H., CELLER, B. G., LORD, S. R., and TIEDEMANN, A. (2004*c*): 'A pilot study of long-term monitoring of human movements in the home using accelerometry', *J. Telemed. Telecare*, **10**, pp. 144–51

MCGORRY, R. W., CHANG, C., and DEMPSEY, P. (2004): 'A technique for estimation of wrist angular displacement in radial/ulnar deviation and flexion/extension', *Int. J. Indust. Ergonom.*, **34**, pp. 21–29

MEDICATE: *http://www.medicate online.org/*

MELANSON, E. L., KNOLL, J. R., MELANIE, L. B., *et al.* (2004): 'Commercially available pedometers: considerations for accurate step counting', *Prevent. Med.*, **39**, pp. 361–368

MERRYN, J. M., COSTER, A. C. F., LOVELL, N. H., and CELLER, B. G. (2004): 'Accelerometry: providing an integrated, practical method for long-term, ambulatory monitoring of human movement', *Physiol. Meas.*, **25**, pp. R1–R20

MILTNER, H. R. W., BAUDER, H., *et al.* (1999): 'Effects of constraint-induced movement therapy on patients with chronic motor deficits after stroke', *Stroke*, **30**, pp. 586–592

MOE-NILSSEN, R. (1998): 'A new method for evaluating motor control in gait under reallife environmental conditions part 1: The instrument', *Clin. Biomech.*, **13**, pp. 320–327

MT9: *http://www.xsens.com/*

MULDER, A. G. E. (1994): 'Human movement tracking technology'. *Technical Report 94–1*, Simon Fraser University

OHTAKI, Y., SAGAWA, K., and INOOKA, H. (2001): 'A method for gait analysis in a daily living environment by body-mounted instruments', *JSME Int. J. C, Mech. Syst. Mach. Elem. Manuf.*, **44**, pp. 1125–1132

RAWES, M. L., RICHARDSON, J. B., and DIAS, J. J. (1996): 'A new technique for the assesof wrist movement using biaxial fleaxible electrogoniometer', *J. Hand Surg.*, **21**, pp. 600–603

REINKENSMEYER, D., LUM, P. and Winters, J. (2004): 'Emerging technologies for improving access to movement therapy following neurologic injury'. *http://www.eng.uci.edu/dreinken/publications/djr%20resna%20chapter.pdf*

ROSSINI, P. M., CALAUTTI, C., PAURI, F., and BARON, J. C. (2003): 'Post-stroke plastic reorganisation in the adult brain', *Lancet Neurol.*, **2**, pp. 493–502

SAGAWA, K., INOOKA, H., and SATOH, Y. (2000): 'Non-restricted measurement of walking distance'. *Proc. IEEE Int. Conf. On Systems, Man, and Cybernetics*, 8–11 Oct. 2000, **3**, Nashville, TN, USA, pp. 1847–1852

SCHNEIDER, P. L., CROUTER, S. E., and BASSETT, D. R. (2004): 'Pedometer measures of free-living physical activity: Comparison of 13 models', *Med. Sci. Sports Exerc.*, **36**, pp. 331–335

SELLERS, W. I., VARLEY, J., and WATERS, S. (1998): 'Remote locomotor monitoring using accelerometers: a pilot study', *Folia Primatologia*, **69**, pp. 82–85

SEQUEIRA, M. M., RICKENBACH, M., WIETLISBACH, V., TULLEN, B., and SCHUTZM, Y. (1995): 'Physical-activity assessment using a pedometer and its comparison with a questionnaire in a large population survey', *Am. J. Epidem.*, **142**, pp. 989–999

SHEPHERD, E. F., TOLOZA, E., MCCLUNG, C. D., and SCHMALZRIED, T. P. (1999): 'Step activity monitor: Increased accuracy in quantifying ambulatory activity', *J. Orthop. Res.*, **17**, pp. 703–708

SHIRATSU, A., and COURY, H. J. C. G. (2003): 'Reliability and accuracy of different sensors of a flexible electrogoniometer', *Clin. Biomech.*, **18**, pp. 682–684

SKELLY, M. M., and CHIZECK, H. J. (2001): 'Real-time gait event detection for paraplegic fes walking', *IEEE Trans. Neural Syst. Rehabil. Eng.*, **9**, pp. 59–68

SMART: *http://hsc.shu.ac.uk/smart/?page=about*

SDERKVIST, J. (1994): 'Micromachined gyroscopes', *Sensors Actuators*, **43**, pp. 65–71

SPRIGLE, S., FLINN, M., WOOTTEN, M., and MCCORRY, S. (2003): 'Development and testing of a pelvic goniometer designed to measure pelvic tilt and hip flexion', *Clin. Biomech.*, **18**, pp. 462–465

STEELE, B. G., BELZA, B., CAIN, K., WARMS, C., COPPERSMITH, J., and HOWARD, J. (2003): 'Bodies in motion: Monitoring daily activity and exercise with motion sensors in people with chronic pulmonary disease', *J. Rehab. Res. Devel.*, **40**, pp. 45–58

STROKE: *http://www.stroke.org.uk/noticeboard/obesity.htm*

TALBOT, L. A., GAINES, J. M., HUYNH, T. N., and METTER, E. J. (2003): 'A home-based pedometer-driven walking program to increase physical activity in older adults with osteoarthritis of the knee: A preliminary study', *J. Am. Geri. Soc.*, **51**, pp. 387–392

TALOY, P., BURRIDGE, J., *et al.* (1999): 'Clinical audit of 5 years provision of the odstock dropped foot stimulator', *Artif. Organs*, **23**, pp. 440–442

TAO, Y., and HU, H. (2003): 'Building a visual tracking system for home-based rehabilitation'. *Proc. 9th Chinese Automation and Computing Society Conf.*, UK

TUDOR-LOCKE, C., AINSWORTH, B. E., THOMPSON, R. W., and MATTHEWS, C. E. (2002): 'Comparison of pedometer and accelerometer measures of free-living physical activity', *Med. Sci. Sports Exerc.*, **34**, pp. 2045–2051

TUNG, S. (2004): 'Position paper: An overview of mems inertial sensors'. *http://www.easasuedu/nsf2000/Table_of_Contents/STpdf*

TURNER, J. W. (2001): 'Telepsychiatry as a case study of presence: Do you know what you are missing?', *J. Comput. Mediat. Commun.* **6**, (4)

UITERWAAL, M., GLERUM, E. B. C., BUSSER, H. J., and VAN Lummel, R. C. (1998): 'Ambulatory monitoring of physical activity in working situations, a validation study', *J. Med. Eng. Technol.*, **22**, pp. 168–172

VELTINK, P. H., BUSSMANN, H. B. J., DE VRIES, W., MARTENS, W. L. J., and VAN Lummel, R. C. (1996): 'Detection of static and dynamic activities using uniaxial accelerometers', *IEEE Trans. Rehabil. Eng.*, **4**, pp. 375–385

WALKER, M. (2002): 'Stroke rehabilitation', *Br. J. Cardiol.*, **9**, pp. 23–30

WALLING, A. D. (2004): 'Home-based rehabilitation improves function after stroke', *Am. Acad. Family Phys.*, **70**

WELK, G. J., DIFFERDING, J. A., THOMPSON, R. W., BLAIR, S. N., DZIURA, J., and HART, P. (2000): 'The utility of the digi-walker step counter to assess daily physical activity patterns', *Med. Sci. Sports Exerc.*, **32S**, pp. S481–488

WILLIAMSON, R., and ANDREWS, B. J. (2000): 'Gait event detection for fes using accelerometers and supervised maching learning', *IEEE Trans. Rehabil. Eng.*, **8**, pp. 312–319

WINTER, D. A. (1990): *'Biomechanics and motor control of human movement*, 2 edn' (Wiley, New York, 1990)

YAZDI, N., AYAZI, F., and NAJA, K. (1998): 'Micromachined inertial sensors (invited paper)', *Proc. IEEE*, **86**, pp. 1640–1659

ZHOU, H., and HU, H. (2004): 'A survey – human movement tracking and a research proposal'. *Smart Equal Project Report*

Author's biographies

HUIRU ZHENG received the BEng degree in biomedical engineering from Zhejiang University, China in 1989, the MSc degree in communication & electronic system from Fuzhou University, China in 1992, and the PhD degree from the University of Ulster, UK in 2003.

She took the post of Assistant Lecturer in the Department of Radio Engineering at Fuzhou University in 1992, becoming a Lecturer in the same department in 1995, and an Associate Professor in 2000. Her research interests include biomedical engineering, medical informatics, bioinformatics and data mining.

She is currently a Postdoctoral Research Fellow in the Faculty of Engineering at the University of Ulster.

NORMAN BLACK received the BSc degree in electrical and electronic engineering and the PhD degree from the Queen's University of Belfast, UK, in 1980 and 1984 respectively.

He joined the University of Ulster, Jordanstown, UK, in 1985 as Lecturer in the Department of Electrical and Electronic Engineering, becoming a Reader in the same department in 1989 and Professor of Digital Communications in 1995. From 1994 to 1999 he was Director of the Northern Ireland Bioengineering Centre (NIBEC), University of Ulster, and in 1999 became the Head of Medical Informatics, University of Ulster. He is also Dean of Informatics at the University of Ulster. His research interests include biomedical engineering, medical informatics, telemedicine, data fusion, and bioengineering education.

Professor Black is currently President of the European Society for Engineering and Medicine (ESEM)

NIGEL HARRIS received the BSc degree Biophysical Science from the NE London Polytechnic in 1980, MSc in Medical Biophysics from the University of Manchester in 1982. He received a PhD from the Department of Medical Physics at the University of Sheffield in 1991 for his work on the Application of Applied Potential Tomography in Respiratory Medicine.

He became Head of the Clinical Measurement and Medical Imaging at the Royal National Hospital for Rheumatic Diseases in 2001 and is a Honorary Senior Lecturer in the School for Health at the University of Bath. He is a Fellow of the Institute of Physics and Engineering in Medicine. Research interests include physiological measurement, medical imaging, biomedical engineering and informatics.