A Broad Range of New Clinical Applications for a Magnetic Sensor Measuring Distance on the Human Body

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Abstract—**This paper describes the features of a magnetic distance meter initially intended to detect sleep-related breathing efforts through the recording and analysis of jaw movements. The design of the device made it a very sensitive, non-invasive, wearable and easy-to-use motion detector. As such, it rapidly became an interesting equipment in wholly different clinical domains like radiotherapy and biomechanics. The new prospects offered by this magnetic motion-sensing solution in various clinical applications are presented and discussed here.**

I. Introduction

ORIGINALLY, motivation for the development of a sensor measuring distance on the human body comes from direct observation of patients experiencing sleep-disordered breathing (SDB) [1]. It was noticed that movements of the mandible were concomitant with breathing efforts. Therefore, tracking and recording jaw movement during sleep with a simple, non-invasive, distance-measuring sensor could be a powerful solution to overcome the limitations of commonly used methods of respiratory effort measurement, which are either invasive (e.g., oesophageal pressure measurement) or require some skill for correct placement and interpretation (For example, frequent loss of signal is observed in ambulatory applications due to displacement of thoraco-abdominal bands.). Thanks to the new sensor, it was later shown that characteristic jaw movement patterns were indeed associated with different types of sleep respiratory disorders including obstructive, central and mixed apneas, hypopneas, upper airway resistance syndrome, and mouth breathing [2], [3], [4].

Shortly after this solution was turned into a line of commercial products – JawSens, Somnolter, and Somnolter BriZZy – for the screening of SDB, other clinical applications for the sensor emerged: In radiotherapy, the sensor helps to track respiratory motion with high sensitivity during tumor treatment whereas its usefulness as a tool for gait analysis in neurology, rehabilitation, and orthopedics was recently established. Technical solutions dedicated to these applications are currently under development and testing.

After briefly describing the sensor and the associated acquisition system, this paper focuses on the potentialities of such a solution in the different clinical settings and discusses future work.

Manuscript received June 7, 2006. JawSens, Somnolter, Somnolter BriZZy, RespiSens, and Kinesolter are trademarks of Nomics s.a.

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II. System Description

A detailed description of a prototype of the SDB-screening device is given in [2]. Therefore, only a short overview of the system is presented here.

The sensor is composed of two circuits having matching resonant frequencies. As pulses of excitation energy are delivered to the transmitter, the voltage induced in the receiver depends, all other conditions being equal, on the distance between them (Fig. 1).

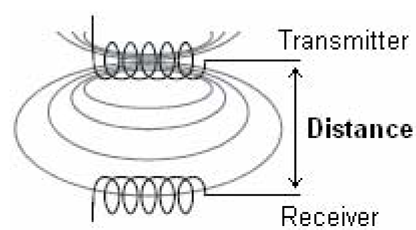

Fig. 1. Principle of the magnetic sensor

A direct measure of distance between the two elements is obtained after analog-to-digital conversion, patented specific processing, and linearization of the signal. Note that in order for the circuit to give an accurate measure of the distance between the sensor elements the two coils must be parallel and on the same axis.

As it is, the system measures distances ranging from 7cm to 23.5cm at a frequency of 10Hz or 20Hz depending on the application and with a sensitivity on the order of 0.1mm on most of the measurement range.

III. Clinical Applications

A. Sleep Studies

Sleep-disordered breathing may have severe consequences like hypertension, heart disease, and accidents due to hypersomnolence. However it is still widely underdiagnosed among adults and children. Although polysomnograms (PSGs) at the sleep clinic give the most detailed evaluation of sleep disturbances, the need for at-home preliminary screening with ambulatory devices is well recognized by clinicians.

Respiratory effort is an essential parameter to measure in order to differentiate subsets of sleep related breathing disorders and select appropriate treatment [5]. However, common methods for direct respiratory effort measurement are impractical for at-home monitoring.

The distance-measuring magnetic sensor described above offers an alternative method of respiratory effort measurement and analysis through the recording of mandibular movements. Distance between the two elements of the sensor is recorded while one element is taped on the forehead and the other one on the chin, on the vertical midline of the face (Fig. 2). Measurement of the distance between these two points constitutes an equivalent for maxillo-mandibular distance.

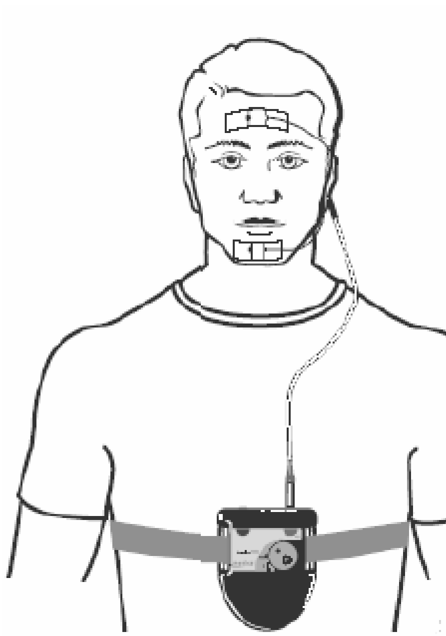

Fig. 2. Jaw movement sensor plugged into an ambulatory SDB-screening device (Somnolter BriZZy)

An automatic analysis algorithm was created in order to diagnose obstructive sleep apnea and hypopnea syndrome (OSAHS) from the recording of mandibular movements during night [6]. A comparative study showed that the Apnea/Hypopnea Index (AHI) computed from mandibular movements by this automatic method was accurate, reliable and in correlation with the AHI computed from the oesophageal pressure measurement, which is the gold standard of respiratory effort measurement [7].

Thus, jaw movement recording constitutes a non-invasive and user-friendly method for the screening of OSAHS. Thanks to its ease of use and sensitivity to fine movements, the sensor is also thought to be a useful tool for the study and quantification of other sleep related disorders like bruxism (tooth grinding) and Restless Legs Syndrom. Some of these applications are already under investigation.

B. Radiotherapy

In radiation therapy, accurate knowledge of localization and shape of a tumor is essential in order to destroy it while sparing healthy surrounding tissue. As a number of organs (e.g., lung, liver, pancreas, and prostate) are subject to respiratory motion, tumors located in these areas move too. Compensating for tumor motion due to breathing during the course of treatment is a major challenge in radiotherapy nowadays.

A variety of techniques are used for this purpose [8]. Turning the beam on only while the patient holds its breath is one approach to the problem. Another approach is respiratory gating, in which the radiation beam is turned on and off in synchronization with the patient's breathing cycle. In dynamic treatment delivery, the beam is continuously adjusted to follow the trajectory of the tumor during the entire breathing cycle.

All of these options require some equipment in order to either directly monitor the tumor's position during beam delivery or indirectly localize the tumor by correlating tumor motion with that of a surrogate marker. Common surrogates are respiratory volume measured by spirometry, optical tracking of chest and abdominal displacement, and electromagnetic motion tracking systems [8], [9]. The sensor described in this paper falls into this third category.

In one study [10], several options for the placement of the sensor elements were tested in order to obtain a valid breathing curve. Fig. 3 shows the breathing signal obtained when the two elements were both taped, aligned and parallel to each other, on a healthy volunteer's chest. Respiration-induced chest motion was bringing these elements closer to and away from each other. The sensitivity of the system is such that even tiny – on the order of 0.1mm – variations of distance due to heart beats are detected. The most meaningful breathing curve was obtained when one element was taped on the treatment table and the other one on the thorax, approximately 10cm away. In this configuration, variations of 3 to 4mm during quiet free breathing and of 1 to 1.5cm during deep inspiration breath hold could be observed. This study led to the conclusion that tracking thoracic wall motion with this simple magnetic distance sensor was a valid technique to study and to monitor the breathing curve during radiotherapy. Moreover, this solution is cheap compared to sophisticated optical tracking systems, it does not alter normal breathing pattern as spirometry does, and it is amazingly sensitive and easy to use. Several studies are underway to evaluate the performance of the system – named RespiSens – as an external surrogate indicator of respiratory-induced tumor motion. In particular, the device already demonstrated its potential as an additional security tool in the treatment of breast cancer in deep inspiration breath hold, a technique which ensures that the tumor is away from the heart during irradiation.

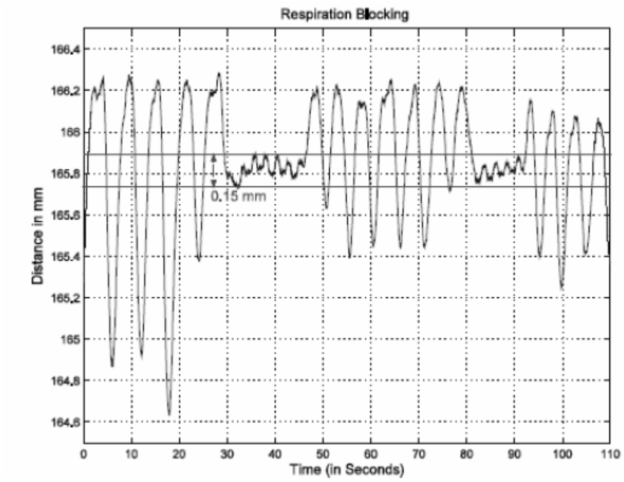

Fig. 3. Respiration signal with two successive breath hold events of 10 seconds. The small movements during the breath hold events come from the aorta.

Due to its ability to detect very fine movements, another possible use of the device is to check that the positioning of a patient is invariant throughout the imaging or treatment session. Indeed, even if the highest sensitivity is obtained when the transmitter and the receiver move parallel and aligned with each other (translation), rotational and shifting movements also impact the signal (Fig. 4). Therefore, any change of position is instantly detected by the sytem. One exception to this rule, although highly unlikely, exists however. If one of the sensing element moves so that it stays exactly on the magnetic field isopotential line (combination of shift and rotation), no movement will be detected. This situation can easily be avoided and the sensitivity of the system to movement in all directions further increased by using two (or more) distance sensors and positioning them judiciously on the patient.

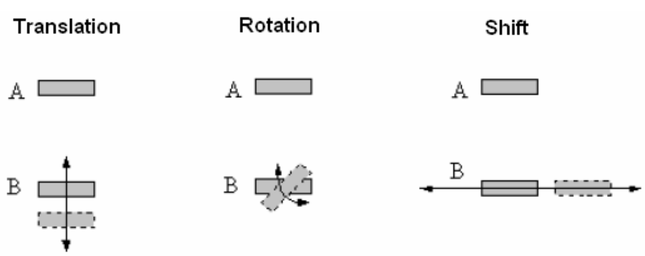

Fig. 4. Different types of movements affecting the signal

A device displaying and recording signals coming from several distance-measuring magnetic sensors is currently under testing at Nomics s.a. (Angleur, Belgium). Such a device is also interesting for the study, for instance, of phase relationships between thoracic and abdominal respiratory movements and for the detection of variations in patient breathing patterns.

Another planned enhancement of the system is the extension of the distance measurement range. This will give clinicians even more freedom for placement of the sensor elements on the patient's body.

C. Biomechanics

Gait analysis has multiple uses in clinical and non-clinical settings. Examples are the study and diagnosis of walking disorders, the monitoring of rehabilitation therapy and orthopedic treatment, and the improvement of athletic performance in sports training. Video acquisition systems, force plates, and electromyography sensors are common tools for analysis and quantification of a set of biomechanical parameters related to gait. Another approach, using magnetic distance sensors, is described here.

Fig. 5 shows a volunteer's leg equipped with markers for video acquisition and analysis and with a magnetic distance sensor connected to a wearable recorder. The two elements of the distance sensor were taped, parallel and vertically aligned, one onto the back of the thigh and the other one onto the calf of the subject whereas the markers were positioned so as to allow knee angle video measurement. Simultaneous recordings of the distance signal and the video signal were performed while the volunteer was walking normally. Examination of the recordings showed that the distance measurement was in perfect agreement with the knee angle obtained from analysis of video data.

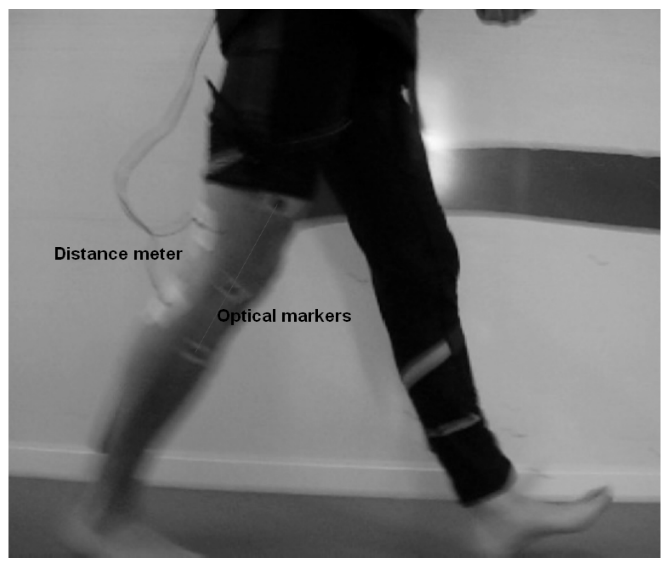

Fig. 5. Picture of a volunteer equipped with a magnetic distance sensor and with markers for video analysis

Using two magnetic sensors, distance measurement was applied to both knees. Subjects were asked to walk a certain distance then stop. Results of the tests on a healthy volunteer and on a patient with multiple sclerosis are shown on Fig. 6 and Fig. 7. This demonstrates that a number of problems (desynchronization between legs, disturbed kinetic patterns) can be detected using this simple technique. Tests are underway with a device – named Kinesolter – that simultaneously records distance signals coming from magnetic sensors taped around the left and right hip, knee, and ankle joints.

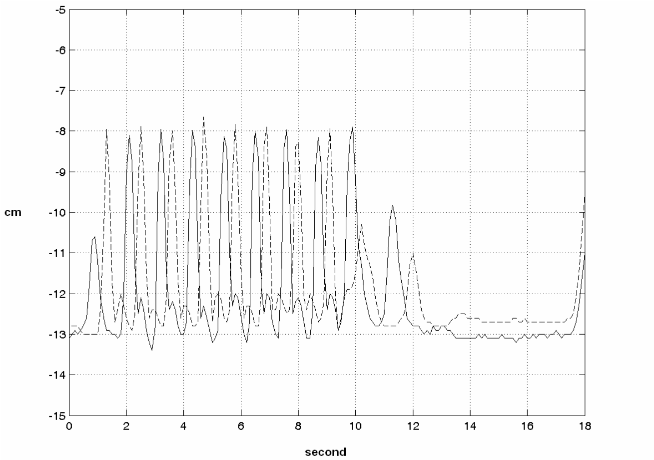

Fig. 6. Distance measurement performed on both knees during walk (healthy volunteer)

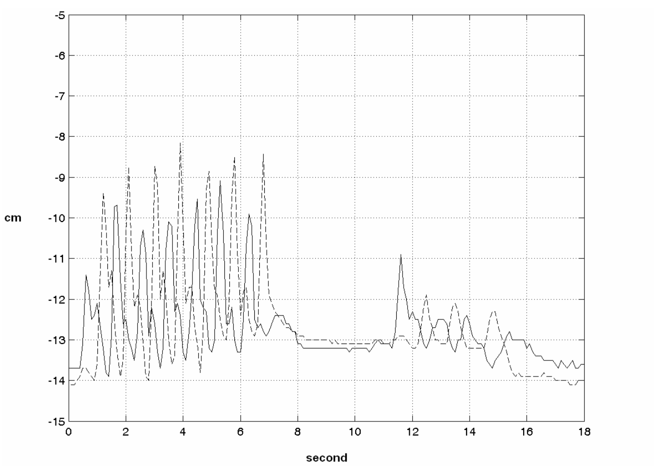

Fig. 7. Distance measurement performed on both knees during walk (patient with multiple sclerosis)

In addition to being simple, non-invasive, easy to set up, and cost-effective, this approach has several other important advantages that offer new prospects in biomechanics. Indeed, since the device can be comfortably fitted around the waist, data can be recorded on long periods of time (several hours), on long distances, and in environments where introducing a video acquisition system is impracticable. This property opens up the prospect of at-home monitoring for example. This also simplifies the study of the effects of fatigue on motor behavior. Another great advantage of the system is its ability to record the movement of both legs simultaneously without the need for a complicated set up.

IV. Conclusion

This paper demonstrated the versatility of a magnetic-based distance-measuring system through a variety of examples of clinical applications. Since the system can be used to measure distances anywhere on the body, there is little doubt that other interesting applications – clinical and non-clinical – will surface in the near future.

Integration of the magnetic sensor(s) into skin-tight garments (e.g., leg tights in gait analysis) and real-time wireless data transfer will improve comfort of the solution in ambulatory applications.

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