A Device for Measuring Potentially Hazardous Forces on Medical Equipment for Patient Transport

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***Abstract*—Transport of critically ill patients has been identified as a risky procedure. Among other factors, it exposes subjects to external forces (not limited to mechanical shocks) that can be detrimental to the physical condition of humans. Intra- or interhospital transfers are associated with a high level of risk, and emergency maneuvers may cause heavy damage to vital functions. Unfortunately, there are no tools that enable measuring the impact of external forces on critically ill patients. Consequently, there is a lack of information on physiological changes and accidents related to transfer, and the deleterious implications of moving an ill patient are mostly unknown.**

In this paper, we present a novel device especially designed to detect potentially harmful agents and forces acting on medical equipment for patient transport. Particularly, the proposed solution can measure the impact of inertial forces on both the subject and the appliances that are on board.

***Index Terms*—Critical care, monitoring, patient transport;**

I. Introduction

Intra- and interhospital transfer of patients is a common and recurrent event. Nonetheless, it is an extremely critical procedure that poses important risks, and its potential impact to patients' safety is an emerging issue [1]. Despite intrahospital transport usually occurs in a controlled environment over pre-defined paths that are relatively short, transferring subjects between different wards within the hospital (e.g., from the radiology suite to operating rooms or to intense care units) involves numerous en route complications. Moreover, in several hospitals, departments are organized in a way that require moving patients over long distances, thus increasing the occurrence of adverse events. Furthermore, interhospital transfer (whether by air or ground) exposes patients to additional risk factors due an increased number of variables (e.g., environmental conditions) and to hazardous procedures (e.g., vehicle load and unload).

Although several studies reported that transport rarely causes fatalities [2], multiple adverse effects may occur during and after transfers. Significant changes in patients' physiological conditions are documented in the literature [3]. Mishaps during subjects transportation are not negligible, and they often lead to severe physiological reactions that can be harmful for humans [4]. Moreover, critically ill patients are particularly frail, as they are characterized by acute symptoms. Thus, adverse events can result in severe consequences for their vital functions.

Potential complications of transfers represent a multifaceted problem. Apart from human mishaps, there is a high chance of adverse events directly caused by external forces. Factors that characterize the transport itself [4], such as mechanical stress (e.g., vibrations, accelerations, decelerations, shocks), pose important risks. Particularly, in circumstances such as craniocerebral injuries and assisted ventilation, subjects are highly susceptible to mechanical forces. Changes in acceleration can be caused by environmental conditions (e.g., temperature, humidity, sterility), that result in excessive humidity of the floor. Problems related to the equipment constitute 50% of the risk of transport operations [5], and the majority of adverse events involve standard monitoring devices or life-sustaining appliances [4]. According to guidelines [6], measurements such as ECG, blood pressure, temperature, arterial oxygen saturation, are mandatory during patient transport. The following are the most frequently reported incidents:

- displacement or loss of venous and arterial lines, peripheral or central, with consequent haemorrhage;
- extubation of endotracheal tubes;
- dislocation of fracture restraints;
- detachment of the patient from the automatic ventilator;
- disconnection of drainage pipes (particularly the chest drain);
- dislodgement of ECG electrodes.

Also, hospitals' logistics have a crucial influence: obstacles and bumps on the ground, disconnections of the floor in correspondence of doors and elevators, and cramped pathways that amplify vibrations and shocks during emergency manoeuvres, may contribute to physiological changes that are extremely difficult to predict.

According to [7], many incidents are preventable. In the recent years, several guidelines for the inter- and intrahospital transport of critically ill patients have been published [5] [6] [4]. Currently, international objectives in the context of Patient Safety aim to minimize the impact of transport on patients' conditions [6]. However, there is a lack of studies on the physiological responses of subjects during transport [8], and the hazardous potential of external forces on patients remains largely unknown [9].

In this paper, we describe a novel solution that enables monitoring potentially dangerous forces and external agents during transport. Specifically, we will focus on inertial forces such as vibrations, acceleration and shocks. Signals are ac-

PERVASIVEHEALTH 2010, March 22-25, Munchen, Germany
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DOI 10.4108/ICST.PERVASIVEHEALTH2010.8810

quired by a number of sensors, and they are analyzed by a central processing unit. This, in turn, simultaneously triggers an alert to medical and nursing staff whenever measurements are above a defined threshold (i.e., in case they may lead to complications).

II. Related work

In the last decade, different intervention strategies have been adopted to reduce complications during and after patient transport. Assessment methods such as the Risk Score for Transport Patients (RSTP) scale can be used as a triage tool for evaluating patient severity [3]. Incident monitoring provides a means to better understand adverse events [5]. In [10], the authors present a review of the technological systems for monitoring the transport of critically ill patients. Several types of clinical equipment are available. Usually, a standard set of appliances is required to monitor patient's vital signs during transfer. However, detected parameters do not include hazardous forces and external agents. Inertial sensors are implemented in a patented ambulance cot system [11] to control the bed of a stretcher using an hydraulic system. Accelerometers and gyroscopes are employed to evaluate the inclination of the bed with respect to the floor and to manage the movement of the stretcher when it is loaded. Indeed, several solutions for pervasive healthcare have been developed in the recent years. Apart from infrastructures for asset tracking, the majority of current systems regard personal devices for monitoring patients' activities [12] and parameters to prevent various types of problems (e.g., falls, heart attacks).

In conclusion, nowadays there is a lack of technological aids that enable to measure and classify the causes of the most common incidents during transfer.

III. System Design

The proposed solution is designed to detect, analyze and report potentially dangerous forces and other types of external agents impacting on medical equipment for patient transport, and thus both on the human and on the appliances on board. The objectives of our system are two-fold. First, the device is conceived to monitor and signal adverse events to the personnel accompanying the patient. This enables realizing corrective actions when incidents occur (reactively). Secondly, transport monitoring might allow the system to operate proactively, and it may help improve the quality of transport by preventing situations that may lead to complications. Also, understanding the cause of adverse events can increase the staff's awareness of factors and circumstances that contribute to increase risk during transfers.

The system's architecture (see Figure 1) is organized in three components: the acquisition, the control, and the alert layers. During operation, the former continuously measures external forces (e.g., acceleration) by means of different sensing units, and it sends acquired data to the control layer. This in turn, aggregates and analyzes the received signals. A central unit triggers an alarm whenever their amplitudes (or frequencies) exceed a predefined threshold, that is, if measured external forces represent a hazard for the person or for the equipment being transported. Then, the alert layer signals the event with a multimodal alarm conveyed to the transport team. Also, remote operators can be alerted. Simultaneously, the control layer is capable of storing collected data and alarms, and to transmit them to external electronic devices.

Figure 2 shows the device applied to a stretcher (see label 5). Nonetheless, the proposed system can be applied to various types of equipment (with or without wheels) such as wheelchairs, chairs, beds, mattresses. To this end, an anchoring device (see label 4) enables attaching the central unit (see label 1) to the structure of different tools for patient transport. It consists in a detachable apparatus (e.g. a removable arm) that realizes the optimal anchorage with the equipment, minimizing system's intrusiveness during operations. The proposed system is designed to be robust, waterproof, washable, and lightweight. It operates at a low voltage, and it is powered by a replaceable battery integrated in the central unit. In addition, this hosts a plug for connecting the system to the mains. As a result, it is possible to replenish the battery with an external supply, even during its functioning. The device works can operate both during patient transport and when the equipment is parked, and it can work in the presence of medical personnel, or autonomously.

A. Acquisition layer

The acquisition layer consists of a number of homogeneous or heterogeneous sensing units (e.g., pressure or humidity sensors, gyroscopes, microphones) capable of detecting different types of signals produced by forces insisting on the subject and on the appliances. They can comprise natural agents related to transport (such as shocks, vibrations, acceleration, inclination), or signals produced by external sources, such as radio waves and electromagnetic fields. As the system is designed to be modular, different types of sensing units (e.g. electromechanical, optical, or magnetic) can be integrated in the central unit. Alternatively, they can be implemented as satellite systems (see Figure 2, labels 2a and 2b) to be attached (individually or in clusters) to the transport equipment, to subject's body parts, or to the appliances monitoring patient's vital functions. Metal strips, adhesive tape or elastic bands can be utilized to minimize artifacts caused by movement. Figure 2 shows the possible application of a satellite acquisition device attached to the structure of a stretcher using a metallic strip (label 2a). Sensing units can be powered either by independent batteries or by the central unit. They can send data to the control layer using a cable, or through a wireless connection to minimize the presence of wires that can interfere with transport operations.

In our prototype, transport monitoring is realized using microelectromechanical systems (MEMS)-based acceleration sensors. A number of sensing units embedding low-g triaxial digital inertial sensors are employed. They already implement amplification, signal conditioning, low-pass filter and temperature compensation. Their high sensitivity allows accurate

Digital Object Identifier: 10.4108/ICST.PERVASIVEHEALTH2010.8810
http://dx.doi.org/10.4108/ICST.PERVASIVEHEALTH2010.8810

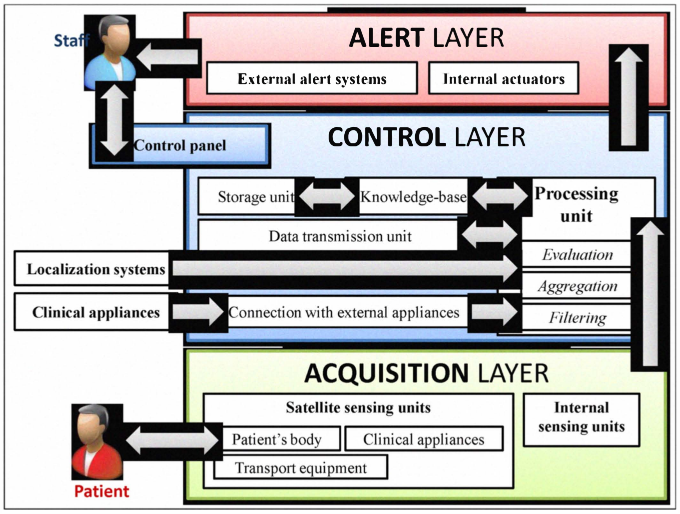

Fig. 1. Architecture of the system.

detection of vibrations, as well as shocks. Moreover, they have small size and low-power consumption.

B. *Control layer*

The control layer realizes real-time analysis of signals. Also, it stores data acquired from the sensing units, and it exchanges data with other electronic devices.

The implements algorithms for digital signal processing that analyze detected forces and agents to evaluate the occurrence of features that are associated with incidents. To this end, the processing unit filters data measured from the acquisition layer. Input signals can be processed individually, or they can be aggregated. It Alert thresholds can be set in relation to the criticality of the conditions of the patient being transported. Methods based on magnitude detection allow triggering an alarm upon the occurrence of excessive forces. Acquired data are associated with reports about incidents, and they are stored in a knowledge-base to enforce the system's capability of classifying adverse events. Transport monitoring offers the possibility to calculate the risk associated with the transfer, and to estimate the probability of adverse events from previously recorded information. Advanced algorithms for pattern analysis can be employed to infer the most common adverse events (e.g., extubation, disconnection of drains) from acquired signals. The control layer is based on an open source rapid prototyping platform. The central unit includes a 16 MHz processing unit. It inherently supports an arbitrary number of input channels for individual sensing units based on digital or analog sensors.

The central unit is equipped with a control panel that allows the medical staff to setup the system. A set of buttons enable changing the operating mode and configuring the details of the transport. Several options such as the sensors being connected, the type of forces to be detected, the intensity of the alarm, or the ability to alert an external system, can be saved as transport settings for further reuse. The control panel includes a graphic display that shows the current functional state of the device. In our prototype, we employed the Active Matrix OLED (AMOLED) technology for its large viewing angle, and we implemented touch screen features.

The control layer includes a data storage unit. This is utilized to store signals acquired from sensors, critical events identified, and statistics of external forces during transport. Also, a complete record of patient status, monitored values, treatment given and other clinically relevant details can be associated with particulars about the transfer (e.g. date, place and time of transfer, information about the equipment and the staff). Moreover, the central unit is equipped with a USB connection to directly exchange data with a PC. An external pen drive can be plugged for loading or dumping data. Additionally, the central unit embeds an onboard Secure Digital (SD) memory card adapter.

Acquired signals, alerts and alarms can be sent to different types of electronic appliances through the data transmission unit using a protocol compliant with IEEE standards. The device is designed to realize bidirectional wireless communication between the control layer and external systems units through the band of industrial, scientific and medical (ISM) frequencies (2.4 GHz). The data transmission unit is designed to be modular, and to support alternative settings to achieve a trade-off between scalability and cost of infrastructure. Expansions allow the device to exchange information with localization systems, so that geographic data can be utilized to proactively raise an alert in proximity of areas identified at higher risk. Localization can be realized with short-range communication technology, such as Radio Frequency Identification (RFId), or by exploiting state of the art technology in the context of asset tracking and indoor localization. Also, the system may include a Global Positioning System (GPS) receiver.

C. *Alert layer*

The alert layer consists of components that enable the system to raise an alarm to the staff. To this end, a number of heterogeneous actuators for conveying multimodal output through the visual, the auditory and the tactile channels, can be employed (see Figure 2, labels 3a and 3b). In our prototype, we implemented two arrays of ultra-bright triple color light emitting diodes (LEDs). Visual actuators (label 3a) are located one on the top and on the bottom of the central unit, so that the mounting position can be reversed to fit the transport equipment. As LEDs are arranged in matrices, they can represent different risk levels. Moreover, potential adverse events can be associated with specific colors. Also, we included an auditory actuator (label 3b) consisting in two small size speakers having compact dimensions, and adequate output power to alert transport operators. They can reproduce alarm tones or pre-recorded sounds and audio messages. Also, details about the adverse event are available on the graphic display of the central unit. In addition, alarms can be transmitted to external devices that can signal the alert using different methods (e.g., messages to pagers and phones).

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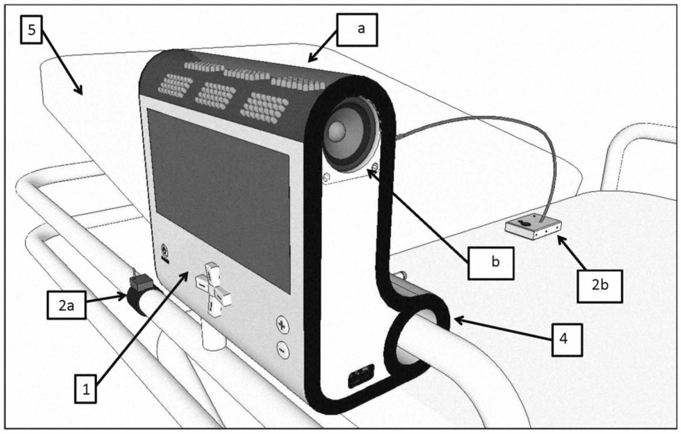

Fig. 2. Design of the prototype (label 1) and example of use on a stretcher (label 5). The system can be attached to any structure by means of an anchoring system (label 4). Sensors (labels 2a and 2b) can be mounted both on the equipment and on patient's body. Multimodal alarm is conveyed through different types of actuators (labels 3a and 3b).

IV. Conclusion

International standards in the context of Patient Safety state that care and monitoring during transport should be at least as good as that at the referring hospital or base unit [4]. In the past decade, considerable advances have been made in the development of best practices for the intra- and interhospital transport of patients, and especially of critically ill subjects. Nonetheless, relationships between factors and accidents related to transfer are still unknown. Thus, it is essential for care institutions to plan and realize interventions that allow to detect and identify potential risks that may arise during patient trasport, both within the hospital and during interhospital transfer, in order to activate preventive measures that allow minimizing the occurrence of complications.

In this paper, we discussed a novel device for acquiring and measuring inertial forces and agents that are detrimental to human conditions. In addition, the system is able to raise an alarm to the staff upon the detection of signals that exceed a defined risk threshold. Moreover, recorded data can provide useful information for the Root Cause Analyses (RCA) of adverse events (reactively), and they can be utilized by the processing unit to infer risky situations from the knowledge-base (proactively). By adding different sensing units, it can measure and analyze several types of potentially dangerous external forces. The system is conceived to be modular and versatile, and it is suitable for different types of equipment. Also, our solution is designed to non-intrusively operate in critical contexts, thanks to its compact size. The device is based on inexpensive hardware, and its cost makes it suitable for a systematic implementation on clinical tools for patient transport.

However, it is difficult to predict the effects of physiologic changes caused by external forces. Therefore, further evaluation in a real deployment context is required to evaluate the methodological application of our system in clinical institutions. In our future work, we will evaluate its potential in reducing adverse events. Furthermore, we will enable the device with the capability of integrating complex sensors, such as motion detectors. Our final objective is to implement roactively. Also, we will focus on the communication with other medical systems, particularly with life-sustaining devices, with appliances for subject monitoring (e.g., electrocardiograph, ventilators), and with different types of infrastructure for asset tracking. The system is patent pending.

V. Acknowledgment

This work is supported by QIRIS (www.QIRIS.org), a non profit organization devoted to research and instruction. This study was realized in the context of the program for Patient Safety.

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Digital Object Identifier: 10.4108/ICST.PERVASIVEHEALTH2010.8810
http://dx.doi.org/10.4108/ICST.PERVASIVEHEALTH2010.8810