A study of activity and body posture with the PiiX mobile body-adherent device

Niranjan Chakravarthy, Jonathan M. Engel, *IEEE Member*, Abhi Chavan, *IEEE Senior Member*, Brion Finlay and Grant Nosbush

***Abstract*— Remote monitoring of in-home activity and body posture provides useful physiological parameters for understanding patient status and for making clinical judgment in patients living with heart failure. The Corventis PiiX is a mobile chest-adherent device that provides continuously recorded accelerometer data from patients in an in-home setting. In particular, a 3-axis accelerometer enables quantification of full body activity and body posture changes. In this paper, the prevalence of sedentary activity with subject age, the population-wide distribution of upright body posture and resting body posture, and a diagnostic for reduced activity levels and resting body posture is presented with retrospective analysis on a large nonrandomized dataset.**

I. Introduction

The convergence of high-performance sensing, high-throughput wireless communications, large-scale automated data analysis, miniaturization and low-cost has enabled the development of wearable mobile patient monitoring systems for a wide range of healthcare applications. One such application is the in-home monitoring of subject activity and body posture, which may be useful diagnostic markers for health conditions such as congestive heart failure, syncope and chronotropic incompetence [1], [2], [3].

Corventis has developed non-invasive on-skin adherent devices for mobile cardiac telemetry (MCT) and mobile patient monitoring (MPM) that impose minimal restriction on patient lifestyle, enable high patient compliance and aid in diagnosis [4], [5], [6], [7], [8]. In addition to providing ongoing system feedback, the data generated by these devices are also helpful in understanding patient characteristics across large populations, developing customized diagnostic yield improvements and potentially providing input for health infrastructure decisions and regulations.

Here, a retrospective analysis of Corventis system data for subject activity and body posture monitoring to characterize population-level subject posture and activity, and detect worsening health status is presented.

II. The Corventis PiiX™ Device

Corventis' PiiX device provides timely feedback on cardiac arrhythmias and heart rate. These signals are wirelessly relayed via a mobile-networked gateway, the zLink, to the Corventis monitoring center where data are reviewed and made available to the prescribing physician. In addition to other sensors, the PiiX device also includes an on-board 3-axis accelerometer (XL) that continuously senses and transmits data.

Following the system instructions for use (IFU), the patient, caregiver or medical professional applies the adherent PiiX to the skin in the upper left quadrant of the chest (Figure 1). The wireless system with the water-resistant PiiX and inconspicuous nature of on-body wear allows for high patient compliance. The system is FDA-cleared for up to a 30 day prescription with each adherent PiiX device providing up to 180 hours continuous monitoring.

All authors with Corventis, Inc., Saint Paul, MN 55108 USA. Corresponding author: N. Chakravarthy. Phone 651 925 3677; fax: 651 389 3251; email: Niranjan.Charkavarthy@corventis.com.

III. Data and Methods

De-identified age, gender and PiiX sensor data were collected from 429 subjects (223 female). The analysis presented here was carried out retrospectively on archived data and as such was not and could not be used to modify patient care or device usage during the prescription period. The total device data duration of 9278 days was collected with 1436 PiiXs.

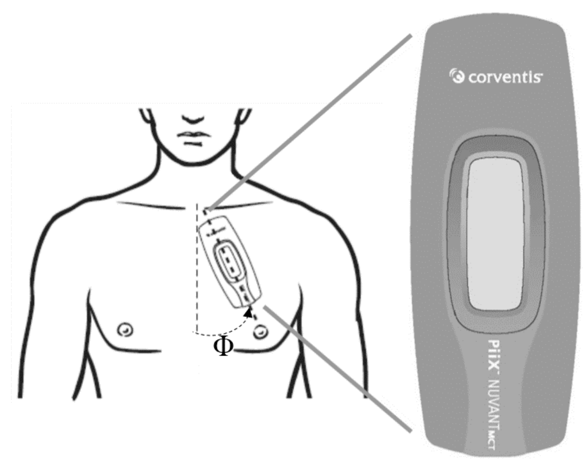

Figure 1. Application site for the Corventis PiiX.
The application angle, Φ, is also shown. See text for details

A. Data pre-processing and computing the activity intensity

The 3-axis XL values (in mG units) were high-pass filtered to remove posture-related offsets. A power signal was calculated from the resulting values and low-pass filtered to yield a smoothed activity intensity signal (in mG units). The subject was deemed to be in a resting state when the activity intensity signal was less than a threshold and in an active state when the activity intensity signal was greater than a threshold; the threshold to discriminate between resting and active states is based on previous analysis of real-world PiiX XL data.

A subject's absolute daily average activity intensity level in mG is not intuitively interpretable; e.g., an absolute daily average activity intensity of 100mG is not easily interpretable as "high" or "low". Hence, the absolute daily activity intensity was mapped to a categorical activity scale with 5 levels: "Basal Metabolic Rate" (BMR), "Sedentary", "Light", "Moderate" and "High". These activity levels are analogous to the "Basal Metabolic Rate", "Sedentary with little or no exercise", "Lightly active with light exercise/work", "Moderately active with moderate exercise/work" and "Very active with hard exercise" in the Harris-Benedict principle [9], [10]. The scaling factor to transform daily average activity intensity to the categorical daily activity levels is proprietary and customized for the PiiX based on sample testing and analysis of real-world PiiX XL data.

B. Subject-specific application and upright body angle offsets and resting body posture

The PiiX is intended to be adhered on the chest at an angle, as shown in Figure 1, to record Lead II ECG. The PiiX application angle, Φ, is the offset angle from the body midline to the long axis of the PiiX (the PiiX adherence offset; see Figure 1). The upright body angle, ϴ, is the angle from the horizon to the subject body midline (see Figure 2); per this convention, the upright angle is 90^o if the PiiX were applied to a perfectly flat surface and the long axis of the PiiX was parallel to the gravity vector. Body posture and chest geometry differences cause a subject-specific upright angle offset from 90^o.

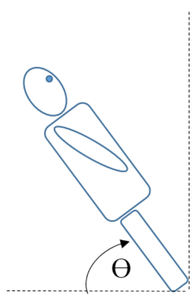

Figure 2. Schematic representation of upright body angle, ϴ, from horizon.

Assuming that subjects were upright when active, the median of the first day's 3-axis XL measurements when the subject was deemed active per the activity intensity signal were used to estimate the subject-specific application and upright body angle offsets by essentially solving for the rotation matrices from an initial orientation where the PiiX long axis is perfectly parallel to the gravity vector. The PiiX application angle offset Φ was computed once for each PiiX patch since the application angle can vary from one patch application to another. Assuming that the subject's upright body posture and physiological offset do not change through the monitoring duration, the upright body angle offset ϴ was computed once for each subject from the first applied PiiX. The subjects' body posture was then continuously estimated for the monitoring duration after compensating for the subject-specific application and upright body angle offsets. Based on this compensated body posture estimate, the subject was deemed to be upright when $ϴ > 60^o$.

As a measure of resting body posture, we derived the proportion of time a subject was upright at rest by combining the compensated body posture estimate and resting state indicator. These proportions were computed every day for day and night time; day time was considered to be from 10 AM to 6 PM local time, and night time was considered to be from midnight to 5 AM local time.

C. Detecting worsening resting body posture and activity level changes

Elongated rest durations with little activity and spending longer rest durations in an upright body posture can be useful in ascertaining worsening disease states such as orthopnea and congestive heart failure [11]. Days with elongated rest durations were identified when the subject's daily activity level was less than sedentary and the day's rest duration increased by more than 50% relative to the previous day or if the absolute daily rest duration exceeded 12 hours. Days with worsening resting body posture were identified when the subject's daily activity level was less than sedentary with a relative increase >50% in the daily upright rest duration compared to the previous day and the daily upright rest duration > 1 hour.

IV. Results

In this section we present the population-level distribution of daily activity levels vs. age (Section IV A), the population-level distribution of subject-specific upright body angle offsets and differences by gender (Section IV B), population-level observations on resting body posture (Section IV C) and the detection of worsening resting body posture and activity level changes (Section IV D).

A. Distribution of daily activity level vs. age

The population-level distribution of the daily activity levels vs. age is shown in Figure 3. Notice that with increasing age, subjects typically spend a larger percentage of days in a sedentary and BMR state. The daily activity levels were statistically different across the age bins.

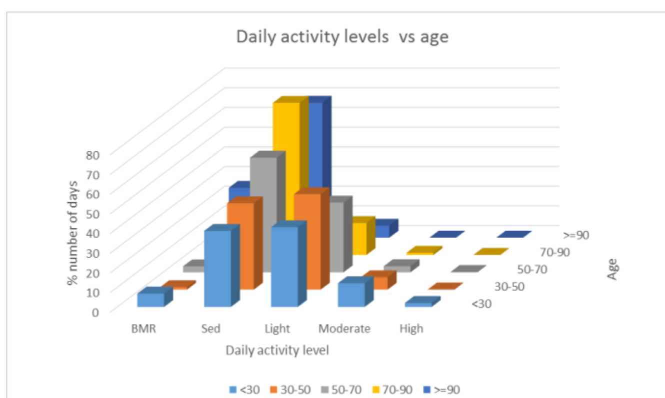

Figure 3. PiiX XL-derived daily activity levels vs. age.

Similar to our previously presented distribution of maximum absolute PiiX-derived activity intensity (in mG) vs. age [3], we observed an inverse correlation between the maximum activity intensity vs. age with this subject population as well.

B. *Distribution of subject-specific upright body angle offset*

For the population, the upright body angle offset was 63.1 ± 13.8 degrees. The upright body angle offset in female subjects was 61.6±14.3 degrees and 64.8±13 degrees in male subjects; the difference was statistically significant. The upright body angle offset was not correlated to subject age. However, we noticed an interesting trend for this subject population wherein the maximum activity intensity (in mG, defined as the 95th percentile of all PiiX-derived activity intensity values for a given subject) increased monotonically with the upright body angle offset; see Figure 4. One hypothesis for this relation is the inverse correlation between subject body mass index (BMI) and the upright body angle offset, and the inverse correlation between subject BMI and maximum activity intensity.

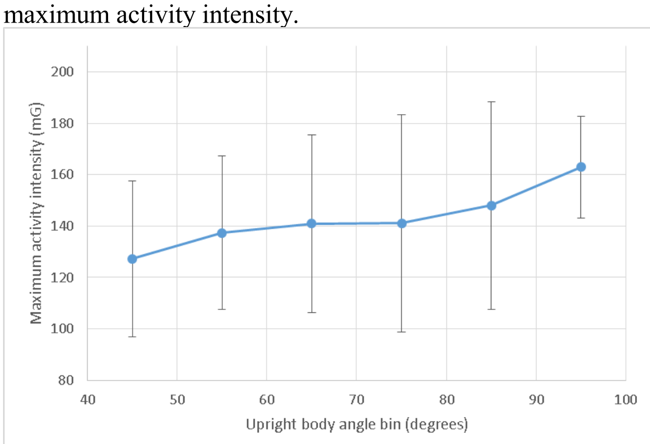

Figure 4. Upright body angle offset vs. PiiX XL-derived maximum activity intensity. The mean and standard deviation of maximum activity intensities of all patients within an upright body angle bin are presented with errorbars.

C. *Resting body posture*

As expected, the subjects were in an upright body posture during rest much more during the day time vs. night time. In particular, this population of subjects spent on average 3.6% of their resting time during night in an upright body posture and 46.1% of their resting time during the day in an upright body posture. There was no significant difference between male and female subjects, and no significant correlation with subject age.

D. *Worsening resting body posture and activity level changes*

For this population of subjects, worsening activity level changes occurred in 30.8% of the subjects, worsening resting body posture changes occurred in 34% of the subjects, and worsening activity and resting body posture changes occurred in 13% of the subjects. In terms of the number of days these detections occurred, worsening activity levels occurred on 9.4% of the monitored days, worsening resting body posture changes occurred on 6.6% of the monitored days, and worsening activity and resting body posture changes occurred on 2.3% of the monitored days. An example of detecting worsening resting body posture and activity level changes is shown in Figure 5 for a 72 year-old female subject. The subject had worsening activity levels on Jan 2 and Jan 4 and worsening resting body posture on Jan 4. The daily activity level (green line), total rest duration (blue) and upright rest duration (orange) are shown along with days (thick black outline) when the subject was not as active as the previous day (Jan 2 and Jan 4) and the subject spent a longer proportion of the rest duration in an upright body posture (Jan 4).

V. Discussion and Conclusion

Continuous activity levels, rest and active durations and body postures were derived with 3-axis XL data from the multi-sensor PiiX device for a large pool of real-life subjects. With increasing age, subjects spent more days in a sedentary state. The subjects spent on average 3.6% of their resting time during night in an upright body posture and 46.1% of their resting time during the day in an upright body posture. Worsening activity and resting body posture was identified in 13% of the subjects.

Study limitations include the study population of primarily cardiac arrhythmia patients which limits possible applicability to other subject groups, and analysis of only the XL sensor from a wide sensor suite. Several extensions are underway to address these, including the analysis of other patient populations such as heart failure patients, multiple sensor information fusion such as XL and arrhythmias, bioimpedance, and respiration, and investigation of the relation between BMI, upright body angle offset and maximum activity intensity.

Despite being retrospective, the above analyses show the value of 1) unobtrusive, continuous, mobile patient monitoring with the wearable PiiX device to obtain continuous in-home data 2) the chest-adherent PiiX device to identify full body movement and body posture, and 3) post-analysis of the large data pool to learn about in-home activity and body posture at a population level and derive subject-centric diagnostic features. With increasing market adoption, low-cost and seamless data availability, such analyses enable the following possibilities: correlation of multiple physiological vital signs monitored by the system for improved diagnostic yield and better understanding of disease etiology, reduced need for manual diagnostic procedures, and expedient guidance on potential therapies.

Creating long-term health trends with continuous easily interpretable data obtained with low-cost, high performance technologies such as the Corventis PiiX can enable the preventive medicine paradigm and may help identify changes across patient populations as new healthcare management strategies take effect.

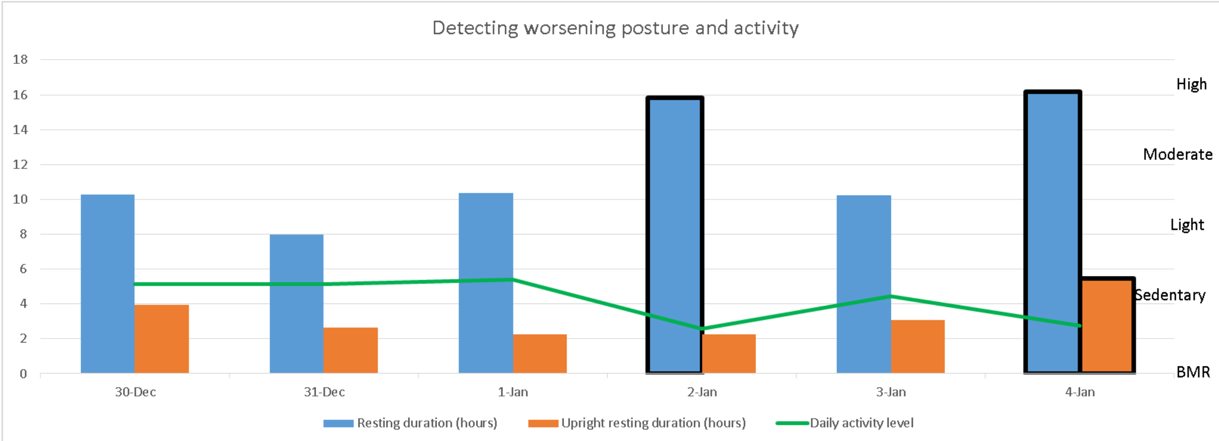

Figure 5. Example of detecting worsening resting posture and activity for a 72 year old female subject. Daily total resting duration and upright resting durations are plotted with blue and orange bars respectively. Daily activity level is plotted in green with a secondary y-axis. Days of worsening activity levels and worsening resting body posture are shown with the thick black outlined bars (Jan 2 and Jan 4).

REFERENCES

[1] I.S. Anand, V.K. Chopra, N. Reddy, I. Libbus, "Chronic monitoring of heart failure patients: Results from the Multi-Sensor Monitoring in Congestive Heart Failure (MUSIC-Asia) study," Journal of Cardiac Failure, vol. 15, no. 6S, pp. S66, 2009.

[2] I. Libbus, "Adherent cardiac monitor with wireless fall detection for patients with unexplained syncope." AMA-IEEE Medical Technology Conference on Individualized Healthcare, 2010.

[3] R.P. Katra, N. Chakravarthy, I. Libbus, "Remote At-Home Detection and Monitoring of Functional Chronotropic Incompetence in Heart Failure Patients," Journal of Cardiovascular Translational Research vol. 4.1, pp. 14-20, 2011.

[4] Corventis, Inc. NUVANT Mobile Cardiac Telemetry [Online]. Available: http://www.corventis.com/products/nuvant-mct/how-it-works/

[5] Corventis, Inc. AVIVO Mobile Patient Management [Online]. Available: http://www.corventis.com/products/avivo-mpm/how-it-works/

[6] I. Libbus, "Arrhythmia detection performance in a wireless multi-sensor patient monitor," Heart Rhythm, vol. 6, no. 5S, pp. S286-287, 2009.

[7] J.M. Engel, N. Chakravarthy, R.P. Katra, S. Mazar, I. Libbus, A. Chavan, "Estimation of patient compliance in application of adherent mobile cardiac telemetry device," IEEE Int. Conf. Engineering in Medicine and Biology Society, pp. 1536-9, 2011.

[8] J.M. Engel, V. Mehta, R. Fogoros, A. Chavan, "Study of Arrhythmia Prevalence in NUVANT Mobile Cardiac Telemetry System Patients," IEEE Int. Conf. Engineering in Medicine and Biology Society, pp. 2440-2443, 2012.

[9] D.C. Frankenfield, E.R.Muth, W.A. Rowe. "The Harris-Benedict studies of human basal metabolism: history and limitations," Journal of the American Dietetic Association, vol. 98.4, pp. 439-445, 1998

[10] S. Jegtvig. (2014, February 14). What's the Harris-Benedict Formula? [Online]. Available: http://nutrition.about.com/od/gettingstarted/f/What-Is-The-Harris-Benedict-Formula.htm

[11] J.C. Kelder, et al. "The diagnostic value of physical examination and additional testing in primary care patients with suspected heart failure," Circulation, vol. 124(25), pp. 2865-2873, 2011.