Comparison of Bed-Sensors for Nocturnal Behaviour Assessment

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***Abstract*— Most older adults wish to age in place. Numerous home-based monitoring technologies are being developed to help provide solutions to the human resource challenge created by the aging population. Bed-based monitoring systems can measure something as simple as frequency of bed exits and as complex as sleep quality. This work compares the abilities of three available consumer bed mats from Best Buy, Withings and Emfit to identify bed exit, sleep time and sleep quality. The results show that the Best Buy Canada Assured Living platform provides the most accurate measurement of bed exit/entry with only a single error over 54 nights of testing. The estimates of sleep quality, based on sleep scores derived using commercial algorithms, did not align well between the Withing and Emfit sensors. However, these mats provide more detailed information on estimated time asleep and sleep state compared to the Best Buy sensor. Analysis of the raw data provided by the sensors may provide a more useful method to assess sleep related outcome measures in the research setting and to eventually guide clinical decision making.**

Keywords- IoT; cloud processing; bed-sensing; pressure sensing; aging-in-place.

I. INTRODUCTION

Aging in place and independence for aging adults is important for their wellbeing and also to avoid the costs and demands that an alternative of communal care [1] places on the healthcare system or the family. For older adults to continue to live independently, they are frequently supported by family care-givers [1] and this represents a burden affecting the care-giver especially when care is provided by an elderly partner.

The potential for sensors, smart homes and Internet of Things (IoT) technologies to provide an alternative source of information to support the aging adult, their care-giver or formal care providers is an emerging area of research including proposals for systems to assist in the ongoing assessment [2]–[5] of the aging adult.

The sensors used within these systems include wearables [6][7] and passive sensing systems for assessment of very specific behaviours such as urination [8]. IoT sensors within a residence can now be easily connected to cloud services [9][10] and the advanced processing of the combined information from many sensors can then lead to insight into behaviours and behavioural changes by the aging adult [11] [12].

Sleep is important to the well-being of older adults, and changes in sleep pattern can be associated with numerous health conditions. For instance, Alzheimer’s disease can lead to disturbances in the circadian rhythm [12]. Nocturia can be associated with a number of clinical conditions and the resulting impact on sleep can be significant. Medical issues as simple as an infection can lead to frequent need urinate. Respiration related illness can also lead to sleep interruption [13] while sleep quality [14], often assessed by time spent in various sleep states, is also important.

Bed sensing in conjunction with smart home technology has been applied and trialed for a supportive smart home system to support care-givers of persons with dementia specifically associated with the challenge of nighttime disorientation to time and/or place that can lead to wandering and elopement [15][16]. These works specifically used a pressure sensitive mat (Ideal Security Pressure Mat SK630) located between the mattress and box spring. This mat was identified as the source of many errors associated with incorrect reporting of bed occupancy, such as detection of status for a specific occupant in a double occupancy bed [16].

This report explores alternative bed mat sensors that have recently entered the consumer market to evaluate their performance to accurately detect overnight bed exits for a specific subject within a double occupancy bed, assess time in bed, and quality of sleep (if provided by the manufacturer). The Ideal Security Pressure Mat was not included in this assessment as two different versions of this mat with different sensitivities were tested in the study bed and they were either closed by the mattress weight alone (indicating someone always in bed) or never closed continuing some of the issues identified in the previous works [15][16].

This paper presents the methodology for the data collection and study in Section II, Section III presents the results from the bed sensors within the study with Section IV discussing the results and potential areas of further exploration.

II. METHOD

A. Research Subjects

The participants in the project are summarized in Table I and included a spousal pair. The research project had research ethics approved by the Bruyère Continuing Care and Carleton University Research Ethics Boards. Both of the participants are adults with post graduate education and no known issues associated with general, physical or cognitive health.

TABLE I. DEMOGRAPHIC INFORMATION FOR THE TWO BED OCCUPANTS. SUBJECT 1 SLEPT ON THE SENSORS WHILE SUBJECT 2 WAS IN THE BED ADJACENT TO THE SENSORS.

Subject	*Gender*	*Age (yr)*	*Height (m)*	*Weight (kg)*
1	M	55	1.85	85
2	F	50	1.65	60

B. Sensors Systems and Set-up

The sensors were placed in the queen sized (North American sizing) bed as shown in Figure 1. Each of the sensors was placed on subject 1's side of the bed in the positions shown in the figure. Each sensor was placed according to the respective installation instructions between the box spring and mattress. The three sensors had differing placement instructions allowing for them to be placed side by side without overlap. The selected sensors included two sensors used by the team in current trials (E) and (W) and a sensor just entering the market (B). There is a practical limit on the number of sensors that can be used by one subject without them overlapping or being installed in an incorrect location.

The Withings Sleep (sensor W) [17], is a 62 x 18.8 x 0.5 cm sensor that is placed under the chest area of the subject. The sensor consists of a single air bladder that occupies the full sensor which is then connected to a pneumatic sensor. The sensor inflates and when placed under the mattress, assesses the variations in the pressure in air chamber associated with the movements of the subject.

The Emfit QS (sensor E) [18], is a 56 x 6 x 0.5 cm sensor that uses a proprietary plastic technology to create a pressure sensitive capacitor and from this assesses the subjects motion through ballistocardiography. This sensor is placed at the upper chest region.

The bed sensor mat from Best Buy Canada's Assured Living solution (sensor B) is a 76cm x 28cm x 1cm sensor from Telehealth Sensors [19] that is provided as a component of the Assured Living platform and the sensor is located near the hip region. This sensor is also based on a pressure sensitive capacitor but the unit includes post processing to determine an adaptive threshold leading to a binary output of occupied or not for the bed. The Assured Living platform also includes other sensors such as motion sensors that were placed throughout the house. For this work, the motion sensors located in the bathroom and a flight of stairs are reported as these represent the two potential directions for an overnight bed exit.

The sensors were each placed in the bed per their respective installation instructions and each was connected through the residential Wi-Fi network to the Internet. Sensor B, uses the Z-Wave wireless protocol to connect to a base station that then connects to cloud based Internet services within the Assured Living portal for data logging and review. The W and E sensors directly connect to the residential Wi-Fi network and through that to cloud based services and portals provided by each of the vendors.

The B sensor system was not available at the start of the study and was introduced 21 days into the study leading to 75 consecutive nights of study for the E and W sensors and 54 nights for the B sensor. The data presented represents a sample of convenience consisting of all nights that had all data available including API portal data allowing for direct comparison between the sensors.

C. Data Collection and Analysis

This work reports on the first 75 consecutive nights within a longitudinal study. During the study, the research subject (Subject 1 – author BW) maintained a paper log for their bed entry and exit times and also the times associated with any overnight exits from the bed. The subject also made note of additional details associated with each night such as the perceived sleep quality based on a simple rating of poor, average or above average.

Each of the sensors independently captured their information within respective cloud-based services provided by each of the sensor vendors. The data for each sensor is stored within the respective vendor's cloud and the sleep summary is available each morning. The E sensor includes a real-time monitoring tool within its portal. The cloud systems for each of the sensors presents that sensor information to the research subject. An end-user, such as the aging adult, their family or a health care provider, would access the data in this manner. The systems had options for the download of raw data that were not readily available to a typical end user. This data was accessed to determine if there were any differences between the raw data and the Web browser presented summary.

The comparison of the times recorded for each of the sensors to the recorded times within the logs was assessed such that if the log time and sensor reported time was within two minutes of each other, they were accepted as the same time to account for any drift or error in the reference time sources for each of the sensors and the log. The actual results indicated that sensor logs were very similar to the paper log reported time and there were no cases of sensor events that were just outside of the two-minute window.

Time asleep, sleep state and sleep quality were assessed by comparing the results reported by the sensors that assessed these attributes and through comparison to the user log notes regarding subjective assessment of sleep quality. As this was a longitudinal study, it was not practical to use physiological sensors to directly assess sleep state and time.

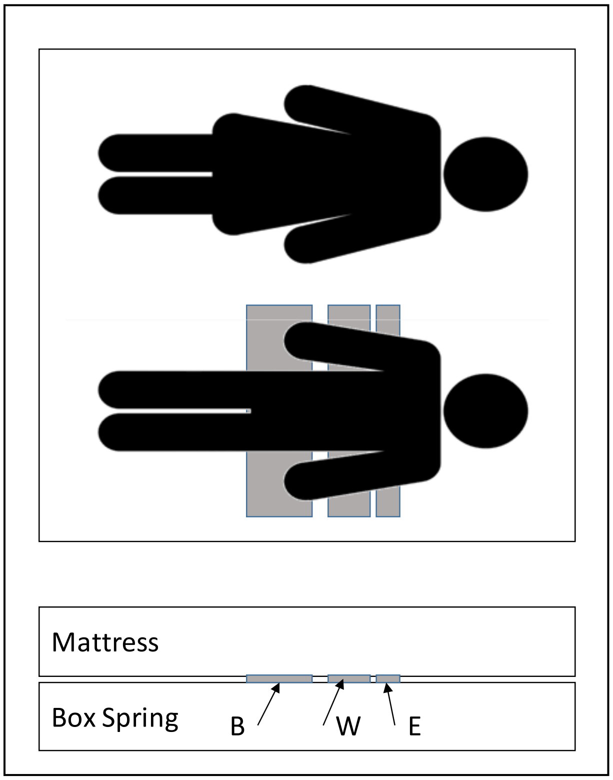

Figure 1. Image showing the placement of the sensors within the bed. Upper portion of the figure shows a top view while the lower portion shows a side view of the bed.

III. RESULTS

The three sensors under evaluation within this longitudinal assessment each provided a measure of presence in bed that would allow assessment of overall time in bed and also for the detection of nocturnal exits during the overnight period. Two of the sensors (W and E) also claim to be able to identify the 4 distinct sleep states (awake, light sleep, deep sleep, REM sleep) purporting to be able to determine time asleep and sleep quality.

A. Measuring Time in-Bed

The performance of the three sensors to assess time in bed is summarized in Table II where the results for the sensors are shown for the 75 consecutive night study period. The W and E sensors were present for the complete study period while the B sensor was added when it arrived and was present for the last 54 days of the study period.

Comparison of the results for the three sensors to the detailed log maintained by the subject show that all three sensors were able to measure the mean Time in Bed with sensor B providing the best performance compared to the research subject logs. Sensor W assessment is lower than the log reference values as this appears to be associated with cropping of the overnight period on some nights where nocturnal exits happened just after the initial entry to bed or just prior to the final bed exit in the morning.

During the study, subject 1 typically went to bed and rose from bed prior to subject 2 and the results for sensor E shown in Table II are higher than the log data for subject 1. The additional time is associated with the sensor reporting a later rise time, which turned out to specifically align with the noted rise time for subject 2.

Table II shows the number of nights that each of the sensors reported the incorrect Start or End time for the night and the errors for each of the W and E sensors are associated with the above described cases. The one error for sensor B (also reflected in sensor E) occurred on one morning where subject 2 was more centered in the bed when subject 1 rose leading to the sensors not detecting this rise. This was the only occurrence of this in the reported period.

TABLE II. PRESENCE IN BED BASED ON TIME OF ENTRY AND TIME OF EXIT COMPARISON OF EVENTS LOGGED BY EACH OF THE SENSORS IN COMPARISON TO A WRITTEN LOG MAINTAINED BY THE RESEARCH SUBJECT

Sensor	***Nights (count)***	***Start Time Error (count)***	***End Time Error (count)***	***Mean Time in Bed (min)***	***St. Dev. Time in Bed (min)***
Log	75	na	na	562.4	39.6
W	75	7	9	550.9	44.2
E	75	4	19	580.2	36.9
B	54	0	1	566.2	39.4

B. Measuring Nocturnal Exits

Each of the sensors detects and reports nocturnal exits for the subject and these are summarized in Table III for all three of the sensors in comparison to a count of exits derived from the log maintained by the research subject. Again, the W and E sensors were used for a 75-day longitudinal period while the B sensors were assessed for the last 54 days of that period. In addition to the B sensor deployed within the bed, motion sensors from the B system were also deployed within the bathroom and flight of stairs. This allowed for a second measure of nocturnal exits as these were either for washroom use or to let a family dog outside during the night.

The results show that B bed sensor detected all of the bed exits during the study period with no errors, the motion sensors from the B system did have two errors that are directly attributable to a failed battery in a motion sensor. Although this issue was identified by the B system for correction by the subject, it was not corrected until the two errors occurred associated within a single overnight period.

The W sensor performed extremely well during the period and it only had 3 missed bed exits (false negatives - FN) while also reporting three exits that did not occur (false positives - FP). The cause of the latter are not known while the cause of the FN appears to also be associated with the cropping of the overnight period noted previously for this sensor.

The results for the E sensor show that this sensor frequently misses bed exits. The bed exits during the study in almost all cases were associated with the bed having double occupancy and so although subject 1 had left the bed, subject 2 remained in the bed.

TABLE III. NOCTURNAL EXIT DETECTION BY THE SYSTEMS OVER THE STUDY PERIOD IN COMPARISON TO THE LOG MAINTAINED BY SUBJECT 1.

Sensor	*Actual Exits (n)*	*Exits Detected (TP)*	*Exits Missed (FN)*	*Extra Exits Reported (FP)*
W	92	89	3	3
E	92	30	62	0
B bed	73	73	0	0
B motion	73	71	2	0

C. Assessment of Sleep State and Quality

In addition to being able to assess time in bed and nocturnal bed exits, two of the sensors (W and E) provide information regarding sleep state and time asleep with the results summarized in Table IV. These results show a large difference between the values reported for the two sensors. For instance, sensor W suggested mean time asleep was 7 hours and 17 minutes, while sensor E provided a number of 8 hours and 41 minutes. Causes of this difference include the inclusion of sleep within the score for sensor E from participant 2, such as in example night 1 in Figure 3 vs 4, showing participant 1 as asleep during and around missed overnight exits and lastly missed bed exits resulting in the inclusion of sleep from participant 2 after participant 1 had risen.

Further analysis of these data from the two sensors was performed by downloading the raw data for each sensor and doing subsequent analysis on the raw data in comparison to the known data within the sleep log. Two example nights are reported and for the first night, the results presented within the Web portal for the W and E sensors is shown in Figure 2 while the raw data for the W sensor is shown in Figure 3 and the E sensor is shown in Figure 4. This particular night, subject 1 reported poor sleep and specifically was unable to get to sleep at the start of the night leading to a number of hours of wakefulness, including two bed exits around 1 hour and 2 hours after entry to bed before the initial occurrence of sleep. There was a noted additional overnight bed exit around 6 hours after entry within the sleep period.

TABLE IV. TOTAL SLEEP TIME AND SLEEP STATE TIMES AS REPORTED BY THE W AND E SENSORS.

Sensor	*Nights (n)*	*Mean Time Asleep (min)*	*St. Dev. Time Asleep (min)*	*Mean Light Sleep (min)*	*Mean Deep Sleep (min)*	*Mean REM Sleep (min)*
W	75	437.1	50.5	350.7	64.8	21.5
E	75	520.8	47.3	291.4	92.9	136.6

The results for the W sensor shown in Figure 2, suggest that it incorrectly identified a reentry after one of the bed exits (the one about 2 hours after initial entry to bed) during the wakeful period as the first entry to bed and start on the night. The W sensor does correctly report the subsequent overnight bed exit. The raw data for the W sensor in Figure 4 provides a more accurate portrayal of the night as it does show the correct entry time and the first two bed exits. The documentation for the W sensor notes that it determines and reports the overnight period automatically and this is an example of the effect of this algorithm leading to the portal not including two bed exits and the period of wakefulness not being reported.

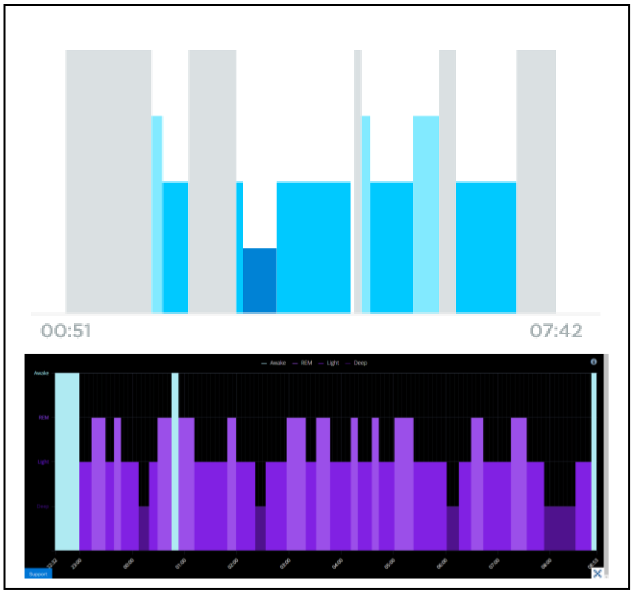

Figure 2. Sleep State information as presented through the user Web portal for the W(upper) and E(lower) sensor example night 1. Legend Upper: grey - awake; cyan - REM, light blue - light sleep, dark blue - deep sleep, white gap – out of bed
Lower: cyan - awake, light purple - REM, medium purple - light sleep, dark purple - deep sleep

The portal results for the E sensor are shown in Figure 2 while Figure 4 shows presents the raw data. The raw data does not differ from the portal presented data and in both cases show the correct entry to bed time. The E sensor appears to show the onset of sleep much earlier in the night than shown by the W sensor and during the actual prolonged wakeful period reported by the subject. This onset of sleep appears to be associated with subject 2 that was adjacent to the sensor while subject 1 was directly on the sensor.

Further analysis for the results for the end of night bed exit time show that the exit time reported for the E sensor matches the time in the subject log while the results for the W sensor match the bed exit time for subject 2. This is the night where it was noted that subject 2 was centered in the bed in the morning leading to the potential for this subject to "seen" by both sensors.

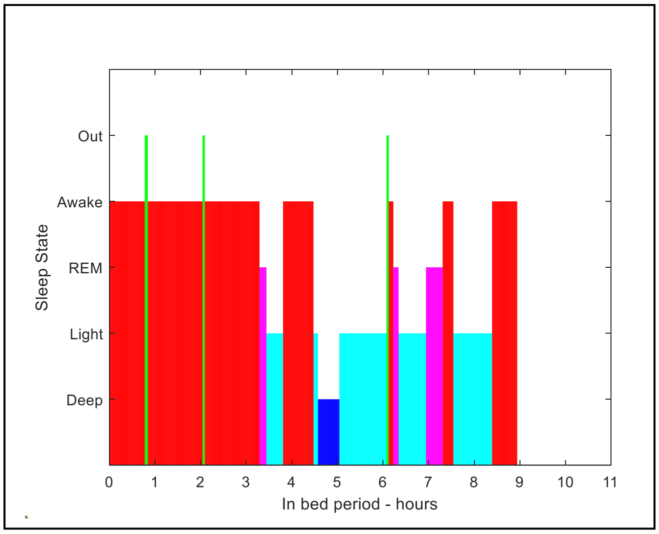

Figure 3. Sleep State reports for an example night per the information available only through detailed raw data download from the portal for the W sensor for example night 1.

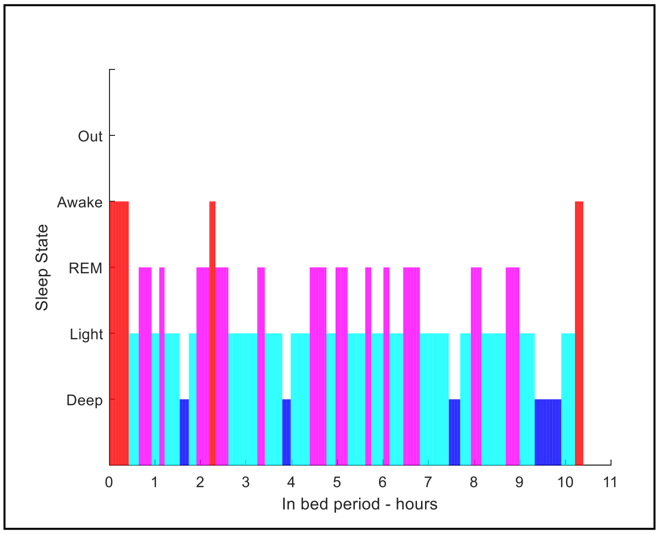

Figure 4. Sleep State reports for an example night per the information available only through detailed raw data download from the portal for the E sensor for example night 1.

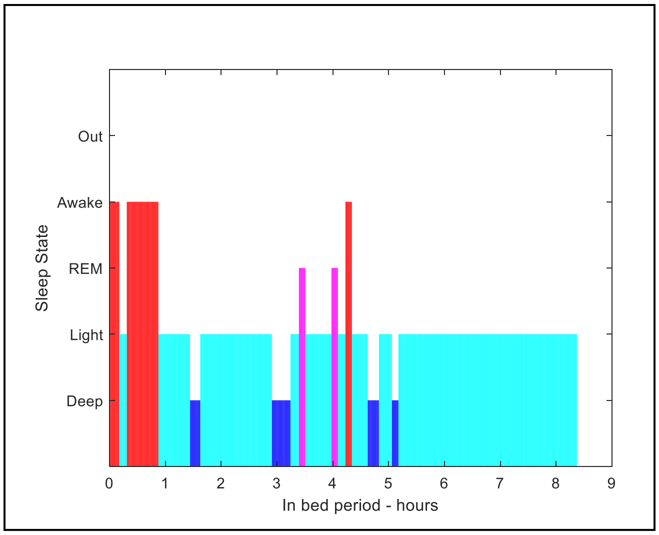

Figure 5. Sleep State reports for an example night per the information available only through detailed raw data download from the portal for the W sensor for example night 2.

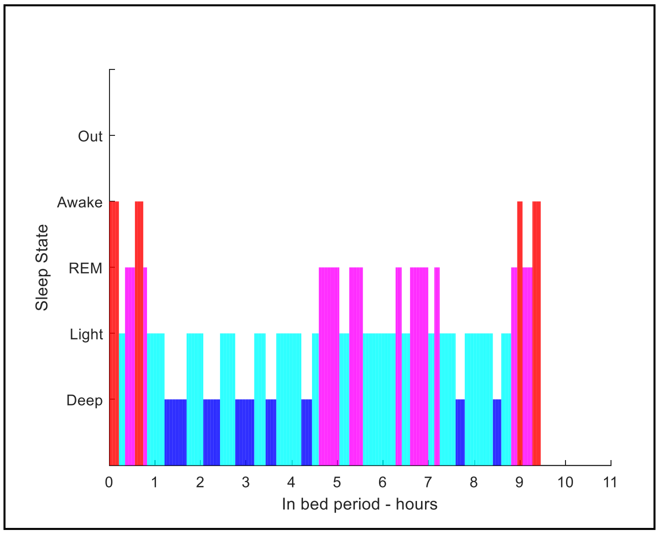

Figure 6. Sleep State reports for an example night per the information available only through detailed raw data download from the portal for the E sensor for example night 2.

Figures 5 and 6 show the raw data for another example night for the two sensors. In this case there is a lot of similarity in the periods reported for the subject being asleep although there is variation in the actual sleep state being reported. In both cases, the sensors correctly reported the start of the night, but the data for the W sensor extends longer than the E sensor. This end of night reporting for the E sensor is correct while again the W sensor results match those for subject 2 that was in a normal position in the bed and not on top of the W sensor in any way, as noted for example night 1.

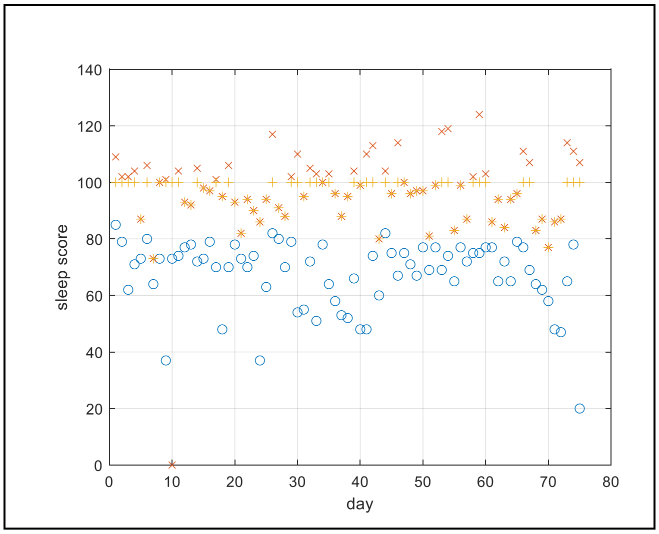

Figure 7. Overnight sleep score are reported by the sensors over the duration of the study. Legend: Blue o – W, Red x – E through API, Orange + – E through Web portal.

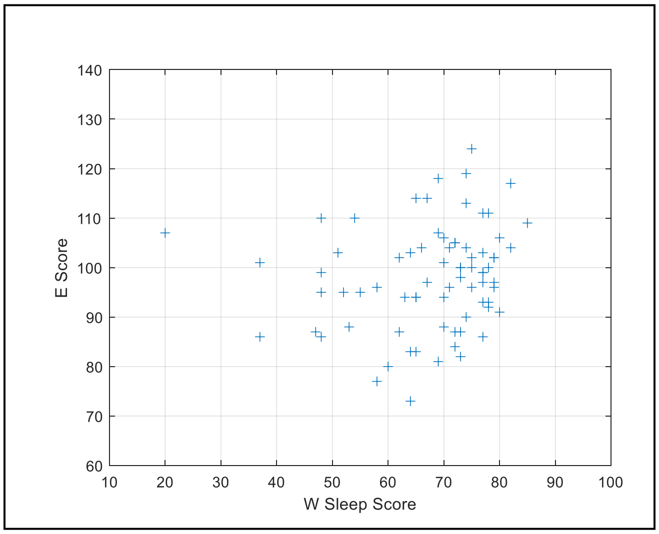

Figure 8. Comparison of the Sleep Score reports for Sensor W in comparison to Sensor E as reported through API for each of the nights within the study.

In addition to measuring sleep state, both the E and W sensors report a sleep score for each night that is shown within the Web portal and available within the raw data. Neither sensor manufacturer provides details on the methodology or algorithm used for this assessment. The sleep score for the E and W sensors is shown in Figure 7. The E sensor data is shown twice as the Web portal presents a sleep score to the user that appears to be capitated at a score of 100 and when the hidden raw data was reviewed through an API, it was found that the scores were no longer capitated at 100, and results up to 124 were found. The minimum reported value was 73, so 100 is now almost the middle of the range and not the maximum.

The comparison of the results between the E and W sensors is shown in Figure 8 where the E sensor data for each night is compared the non-capitated W sensor data. Since these two systems were measuring the sleep quality of the same subject, it should be expected that there would be a high correlation in the results (i.e. a straight line). Figure 7 clearly shows that this is not the case and the correlation coefficient for the best-fit straight line through the data is 0.077, indicating the poor correlation of the values.

The results for the two example nights provide some contrast between the two sensors. The subject reported poor sleep quality on night 1 with above-average sleep quality on night 2. The W sensor correctly scored sleep quality as 20 and 80, respectively. In contrast, sensor E scored sleep quality as 107 and 106, respectively.

IV. DISCUSSION

The challenge of well-being sensing associated with time in bed, nocturnal exits, overall sleep time and quality is of significant interest to care providers that are supporting adults wishing to age in place. As many of these are supported through care partners that are frequently a spouse, the ability to assess the well-being of a specific subject within a shared bed is highly relevant and also presents a significant challenge as passive sensing within the bed has the potential to confuse the two bed occupants.

The results of this work show that the B sensor is able to provide a highly accurate assessment of the time in bed for the specific subject. This sensor greatly improves on the performance of a previous occupancy sensor used by the researchers [15][16]. However, the B sensor by design is limited to only the assessment of bed occupancy.

The E and W sensors provide the potential for significantly more knowledge to be obtained for the overnight periods although each was shown to have limitations. The W sensor was extremely effective at detecting entry and exits from the bed for the research subject with only a few errors but it did report shorter than expected nights on a few occasions. A detailed review of available documentation for this sensor identified that the sensor reports only a single sleep period in each 24 hours and the start and end of the period are not based on first bed entry and last exit. The result is that this sensor will not report on sleep associated with a nap (second sleep period in a day) and can ignore time at the start or end of the night such as removing a period of wakefulness at the start or end of night.

The E sensor performed well for the study and does not include the limitation to a single reporting during any 24-hour period leading it to be better and more appropriate for use within a study where naps or multiple daily sleep periods are expected such as with aging adults. The sensor appears to have had more difficulties associated with confusion between the bed occupants. The differences in sleep stage and sleep scores between the E and W sensors suggests more work needs to be done on these algorithms before assumptions can be made about reliability.

V. CONCLUSION AND FUTURE WORK

The goal of this work was to understand the capability of emerging consumer bed sensing devices to provide accurate assessment of time in bed, bed entry and bed exits. The work also explored the sleep quality assessments provided by some of the sensors. The work has shown the potential for passive bed sensing using consumer bed sensors while also showing the challenges that occur within a double occupancy bed. The results show that studies should consider the use of multiple sensor technologies including wearable sensors and perhaps the use of sensors on both sides of a shared bed.

One area for additional exploration is the effect of mattress structure and size on the performance of mats as this structure could have variable effect on any cross detection by the sensors. Future work could include the creation of a fusion based algorithm that can leverage the more accurate assessment of time in bed provided by the B sensor with the more detailed knowledge of sleep related measures provided by the W, E sensors or other sensors located through-out the home to provide better understanding of behaviour, such as the reasons for bed exit leading to potential for treatment if amenable.

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