Using Wrist-Worn Sensors to Measure and Compare Physical Activity Changes for Patients Undergoing Rehabilitation

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***Abstract*— Wrist-worn sensors have increased in popularity in health care settings. As the use of wrist-worn sensors increases, a better understanding is needed of how to detect changes in behavior as well as an ability to quantify such changes. We introduce a statistical method to address this need. In this study, we used Fitbit Charge Heart Rate devices with two separate populations to continuously record data. There were eight participants in the healthy control group and nine in the hospitalized inpatient rehabilitation group. We performed comparisons both within the groups and between groups on the gathered step count and heart rate data. The inpatient rehabilitation group showed improved step count changes between the first half of the study participation and the second half. Heart rate did not show significant changes for either the healthy control group or inpatient rehabilitation group across time. We conclude that our statistical change analysis applied to wrist-worn sensors can effectively detect changes in physical activity that provides valuable information to patients as well as their healthcare care providers.**

Key words— Physical activity monitoring; wearable sensors; Fitbit; fitness tracking; inpatient rehabilitation; pervasive computing.

I. Introduction

In recent years, wrist-worn devices such as pedometers and fitness trackers have increased in popularity as people aspire to be more physically active and aware of their overall health. One of the most popular consumer-grade physical activity monitors is the Fitbit. Fitbits are quite popular because of their ease of use and relatively inexpensive price. Wrist-worn devices, such as the Fitbit, are able to provide rich information on user activity such as physical activity, heart rate, and sleep quality. Physical activity is estimated by pedometers and fitness trackers in terms of the steps taken by the wearer [1]. Besides personal fitness, objective measurements of physical activity are useful for measuring physical activity for healthcare purposes. For example, wrist-worn devices have been the subject of research in studies with aims ranging from assessing the daily walking structures of post-stroke adults [2] to qualitatively evaluating the physical activity of children in rehabilitation [3].

In this study, we investigate sensor-based measurements of physical activity for individuals undergoing inpatient rehabilitation. In inpatient rehabilitation, clinical observations by therapists are typically used to characterize patient progress and make treatment decisions. It can be beneficial for physical therapists to obtain objective physical activity information for patients during their stay in inpatient rehabilitation. There are several benefits of sensor-based physical activity measurements, including overcoming the inaccuracy of self-report by patients. Patients often do not remember their activities or have a biased interpretation of how well they are doing, consequently leading to either an over or under estimation of their performance. In comparison to human observation alone, wrist-worn devices are able to perform continuous tracking of physical activity. Furthermore, the data collected more accurately tracks physical activity, thus reducing the subjectivity introduced by human observation. Finally, wrist-worn devices such as the Fitbit can gather fine-grained physical activity data about patients that physical therapists cannot otherwise observe.

Several studies and review articles in this growing area of research include a call for both further studies on the efficacy of these devices [4], their uses in a clinical setting [3], [5], [6], and convenient and efficient ways to analyze the data generated by their use [7]. In this paper, we aim to analyze fine-grained, continuous physical activity and heart rate data collected from Fitbits worn by individuals in two groups: REHAB and CONTROL. The REHAB group consisted of patients undergoing inpatient rehabilitation at a large inpatient rehabilitation facility. To provide a comparison for the physical activity of rehabilitation patients over the course of recovery, we also collected continuous physical activity data from a healthy population, the CONTROL group. We analyze the longitudinal physical activity data collected from both groups to gain insights into the detected changes over time in both an inpatient setting and a free-living setting. As part of our analysis, we introduce statistical methods to investigate individual change within the groups and change between the groups to determine activity level differences that exist between different demographic groups.

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II. Related Work

In the literature, research has investigated sensor-based physical activity monitoring for inpatient rehabilitation [5], [6], [8], elderly populations [9]–[15], and healthy young populations [16], [7], [4]. Beginning with rehabilitation, the Stroke Inpatient Rehabilitation Reinforcement of ACTivity (SIRRACT) trial was the first international, multi-facility trial to deploy wearable sensors for patients undergoing stroke rehabilitation [5]. Data were collected from tri-axial accelerometers worn on each ankle from 135 participants in 11 different countries. Therapists fit the sensors on participants in the morning and removed the sensors in the evening. From the collected acceleration signals, walking bouts were identified. Metrics related to walking bouts were computed, including: speed, duration, number of walking bouts, average walking speed, total time walking, total distance, and total steps taken. The participants were split into two groups: one only receiving feedback regarding their walking speed and one receiving, in addition to walking speed information, feedback in the form of activity graphs. The results indicated no significant differences between the two feedback groups in daily time spent walking (15.1 ± 13.1 minutes for walking speed feedback only compared to 16.6 ± 14.3 minutes for activity graph feedback). Additional findings of the study included 30% of participants decreased their total daily walking time over the course of inpatient rehabilitation and the majority of walking bouts only lasted between 10 and 30 seconds [5]. More recent studies investigating walking bout feedback during inpatient rehabilitation are published by Hornby and colleagues [6] and Mansfield and colleagues [8].

Outside of inpatient rehabilitation, there have been a handful of studies utilizing sensors to track physical activity for elderly populations [9]–[15], and healthy young populations [16], [7], [4]. For example, Tan and colleagues [9] designed an indoor activity monitoring system by using a Fitbit Flex wrist-worn fitness tracker and radio frequency identification (RFID). Furthermore, since we utilize Fitbits for data collection from healthy adults and individuals undergoing inpatient rehabilitation, research investigating the accuracy of Fitbit devices are highly relevant. Several studies have evaluated the Fitbit line of products for measuring the accuracy of computed steps taken for healthy young adults [16], [7], [4] and older adults [15], [2]. While the percentage of errors for healthy individuals appears to be tolerable for most applications, pedometers and fitness trackers have been found to not work as well with older adults who walk slowly or people with gait impairments [1], [17], [18].

III. Methods

To gain insights into physical activity levels during inpatient rehabilitation, we compared two subject groups, a REHAB (inpatient rehabilitation patients) group and a CONTROL (healthy adults) group.

A. Participants

Participants in the REHAB group were recruited from the inpatient rehabilitation population at a large inpatient rehabilitation facility. In the United States, patients in inpatient rehabilitation facilities are required to obtain a minimum of 3 hours of therapy a day. This can be any combination of physical, occupational, or speech therapy with the therapy regimen tailored to the impairments/needs of the patient. The ratio of different types of therapy can change from day to day depending on improvement throughout the stay. The study was approved by a regional hospital institutional review board and all participants gave written informed consent. For the REHAB group, patients were recruited by therapist recommendations based on the following criteria: mobile-capable, older than 18 years of age, English speaking, recently admitted, and appearing cognitively capable for the study, as measured by a Mini-Cog exam (score > 3 for participation) [19]. Nine participants (Male = 5, Female = 4) between ages 45 and 80 years old (61.7 ± 12.1 years of age) participated in the study during the duration of their inpatient rehabilitation stay. The number of full days they participated in the study ranged from 4 to 18 days (10 ± 4.2 days). To assess participants' physical activity two weeks prior to their hospitalization, an International Physical Activity Questionnaire for the Elderly (IPAQ-E) [20] was administered on the second day of participation.

The CONTROL group consisted of eight participants (Male = 4, Female = 4) between ages 18 and 60 years of age (25.5 ± 13.2 years of age) recruited from the general population in a university town. These participants were selected based on the following criteria: ability to receive text messages, willingness to wear Fitbits continuously for a two-week period, 18+ years of age, and in healthy condition. Participants in the CONTROL group were administered an IPAQ short form questionnaire to assess their physical activity prior to the study.

B. Instrumentation

Participants in both groups wore Fitbit Charge Heart Rate (HR) monitors on their wrists. The devices were placed on the wrist associated with the non-dominant arm. We asked participants to wear the Fitbits at all times. Data collected from the Fitbits included minute-by-minute step count and heart rate data for the duration of study participation.

For the REHAB group, we set up two Charge Heart Rate (HR) Fitbits for each patient, with one being attached and the other acting as a fully-charged alternate. The participants wore the devices at all times during inpatient treatment, except when pool therapy was employed. We administered daily check-ins to make sure the device was being worn and if it had been taken off for any reason. We also checked the skin integrity of patients and the Fitbits for adequate battery charge. Every four days, Fitbits were swapped for syncing data to the Fitbit servers, disinfecting, and charging.

For the CONTROL group, we provided participants with a single Fitbit Charge HR. Participants were provided with instructions for how to properly wear and sync the device. We sent daily text messages to remind participants to wear and sync the devices. Text instruction were also given when low battery status alerts were sent to the investigators from fitbit.com to charge the Fitbit that night during sleep, and then resume wear the following day. Fitbits were returned after the two weeks of data collection.

C. Data Analysis

We analyze daily physical activity (as measured by step count) and heart rate data, excluding the first and last days of data collection since they are not full days. Removing partial days of data ensures only complete days of monitoring are used as data points. We do this to determine if there is a net daily increase in mean physical activity, and to determine how heart rate changes over the course of the study.

TABLE I
Artificial Data Test Results

Week pairs	t-test p-value	Sliding pairs p-value	Baseline pairs p-value
W_A/W_B	0.2335	0.4642	0.1905
W_A/W_C	0.0520	0.3723	0.2980
W_A/W_D	p<0.0001*	0.1654	p<0.0001*

*=significant value

1) Individual Analysis

To perform individual level analysis, we divide the step and heart rate data into equal halves. We compare the first half of data collected to the latter half by computing one-tailed and two-tailed two-sample t-tests to determine if the means were dissimilar for the groups for both metrics (step count and heart rate), and if this corresponded to an increase or decrease in step count or heart rate between the halves. Since we are performing multiple t-tests, a p-value modification, such as the Bonferroni correction, should be applied to counteract the multiplicity problem. Instead, for this paper, we are utilizing p-values to determine if a change occurred (p<0.01), rather than utilizing p-values to test for significance.

In addition to comparing first and second halves of the collected data, we perform pairwise comparisons for data analysis. We apply the comparisons in two different approaches: baseline pairs approach and sliding pairs approach. In the baseline pairs approach, each day of full data collection X_{i} $(1 \leq i \leq D)$ is paired with the first day of full data collection X_1, as represented in equation (1):

$$Baseline\ Pairs: (X_1, X_2), (X_1, X_3) \ldots (X_1, X_D) \quad (1)$$

Where X_{i} corresponds to a full day of monitoring for up to D days, with X_1 being the first full day of monitoring, and X_{D} being the last full day of monitoring. For the sliding pair approach, each day is compared to the following day, as represented in equation (2):

$$Sliding\ Pairs: (X_1, X_2), (X_2, X_3), \ldots . (X_{D-1,} X_D) \quad (2)$$

We conduct paired t-tests for the metrics, utilizing the same critical value for significance determination (p<0.01). A one-tailed test was used with the step data to test for an increase in daily step count, and a two-tailed test was used to test for a change in heart rate.

We first test our pairwise change detection approaches on four artificially-generated datasets of normally distributed step count data. Each dataset consists of seven days. We generate the data around four different mean hourly step values for each artificial day. The four artificially generated weeks (weeks W_A, W_B, W_C, and W_D) have means of 150.0, 150.1, 151.0, and 200.0, respectively. Weeks W_B, W_C, and W_D are treated as the second week for a participant with week W_A as the first week of data, to see if our approach is sensitive enough to detect these changes. We first compute a t-test to determine if the mean step count per hour value produces significant weekly differences. The results indicate that changes in significantly different weeks used for the sliding pairs comparisons are not always detected, but the baseline pairs comparison does consistently detect an increase in the means (see Table I).

TABLE II
REHAB Step Count Results

Participant (D)	One-tailed p-value	Two-tailed p-value	Sliding pairs p-value	Baseline pairs p-value
1 (7)	0.1829	0.4917	0.3671	0.0424
2 (10)	0.2827	0.5654	0.2263	0.0012*
3 (16)	0.0225	0.0446	0.2082	p<0.0001*
4 (18)	p<0.0001*	p<0.0001*	0.3242	0.0079*
5 (7)	0.0161	0.0322	0.0792	0.0312
6 (11)	0.0593	0.1186	0.1908	0.0014*
7 (9)	0.2584	0.5168	0.3829	0.0032*
8 (4)	0.3422	0.6845	0.3308	0.0093*
9 (8)	0.0686	0.1371	0.4150	0.0670

D=number of full days monitored, *= significant value

TABLE III
REHAB Average Heart Rate Results

Participant (D)	One-tailed p-value	Two-tailed p-value	Sliding pairs p-value	Baseline pairs p-value
1 (7)	0.4265	0.8529	0.9556	0.1041
2 (10)	0.0019*	0.0038*	0.5731	0.0456
3 (16)	0.2340	0.3415	0.7101	0.0006*
4 (18)	0.0030	0.0061	0.3130	0.0002
5 (7)	0.0178	0.0357	0.0929	0.0007*
6 (11)	0.0670	0.1340	0.3442	0.0577
7 (9)	0.0458	0.0915	0.9842	0.0498
8 (4)	0.2541	0.5082	0.9654	0.4496
9 (8)	0.1087	0.2174	0.9159	0.0402

D=number of full days monitored, *= significant value

2) Intergroup Comparisons

To perform comparisons between the REHAB and CONTROL groups, we compare each group's step count and heart rate net change. Net change is computed by comparing the absolute values of the differences of corresponding days in the first and seconds halves of monitoring. The difference measurement is computed for all possible pairs of data using equations (3) and (4):

$$Difference\ for\ even\ D = \left| X_{\frac{D}{2}+m} - X_m \right| \quad (3)$$

$$Difference\ for\ odd\ D = \left| X_{\frac{D-1}{2}+m} - X_m \right| \quad (4)$$

Here $m = 0, 1, 2, \ldots D$ for each day of monitoring and X corresponds to a full day of monitoring, with X_1 being the first day of measurement.

After both sets of difference values for the CONTROL group and REHAB groups are generated for each metric, we compare them using a two-tailed unequal variance t-test to determine if the measure of variation was similar between the groups in regards to net changes in their first half to second half of monitoring.

TABLE IV
CONTROL Step Count Results

Participant (*D = 14*)	One-tailed p-value	Two-tailed p-value	Sliding pairs p-value	Baseline pairs p-value
1	0.3041	0.6083	0.4295	0.0023*
2	0.2560	0.5120	0.4733	0.0050*
3	0.0086*	0.0171	0.3325	0.0069*
4	0.2698	0.5396	0.3673	0.0015*
5	0.0491	0.0982	0.4140	0.1728
6	0.3099	0.6197	0.3923	p<0.0001*
7	0.0450	0.0901	0.4957	0.1276
8	0.3508	0.7016	0.4715	0.2079

D=number of full days monitored, *= significant value

TABLE V
CONTROL Average Heart Rate Results

Participant (*D=14*)	One-tailed p-value	Two tailed p-value	Sliding pairs p-value	Baseline pairs p-value
1	0.0078*	0.0156	0.8012	0.0014*
2	0.0016*	0.0032*	0.8493	0.3146
3	0.1365	0.2730	1.000	0.0005*
4	0.0182	0.0365	0.3291	p<0.0001*
5	0.4071	0.8142	0.8506	0.0021*
6	0.0002*	0.0003*	0.1902	p<0.0001*
7	0.1022	0.2044	0.8763	0.2568
8	0.2040	0.4080	1.0000	0.8657

D=number of full days monitored, *= significant value

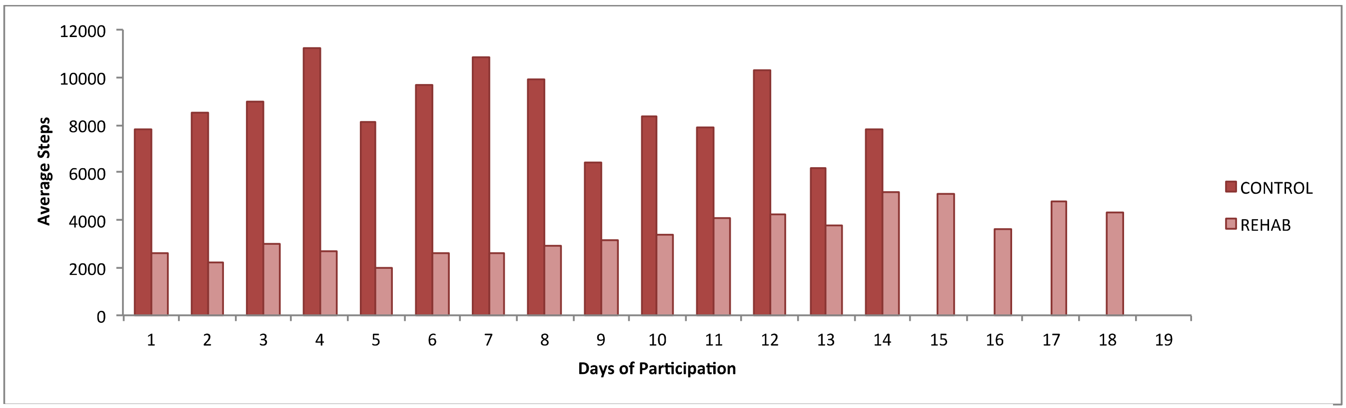

Fig. 1. Average steps for CONTROL and REHAB groups. The average steps for the CONTROL group and REHAB group during each day of their participation in the study. The individuals in the CONTROL group each participated for 14 days, while the REHAB group had varying lengths of stay at the inpatient rehabilitation facility.

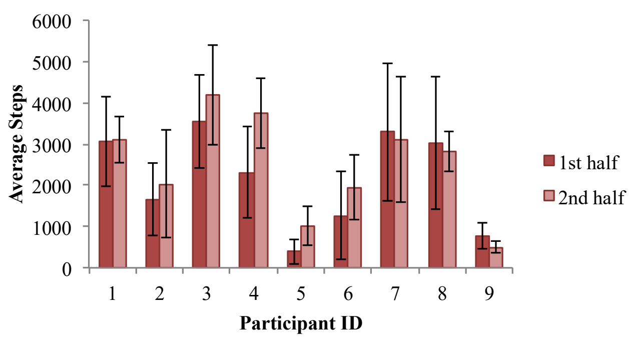

Fig. 2. Average steps for the REHAB group. The average steps during the participants' 1st half of therapy compared to their 2nd half of therapy with error bars.

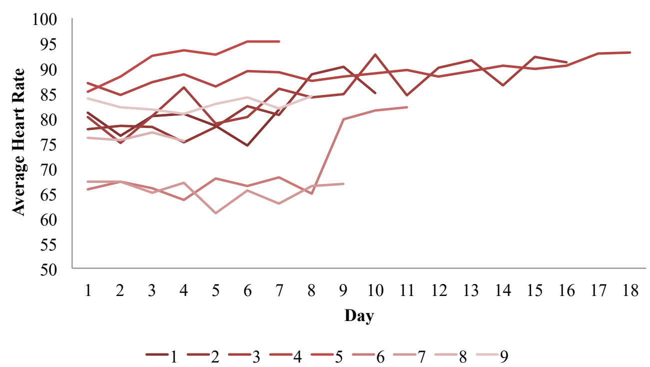

Fig. 4. Average heart rate for the REHAB group. The average heart rate for each day of the study. Participants are labeled by their identification number.

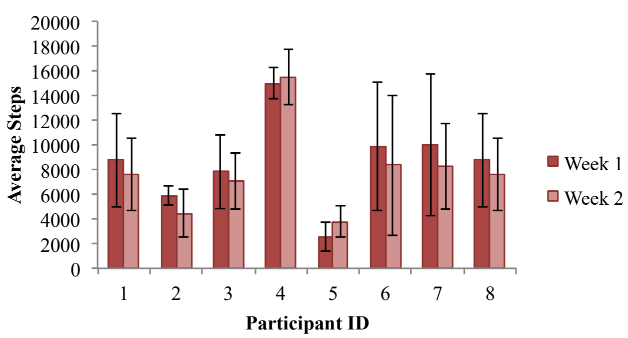

Fig. 3. Average steps for the CONTROL group. The average steps during the participants' 1st week compared to their 2nd week with error bars.

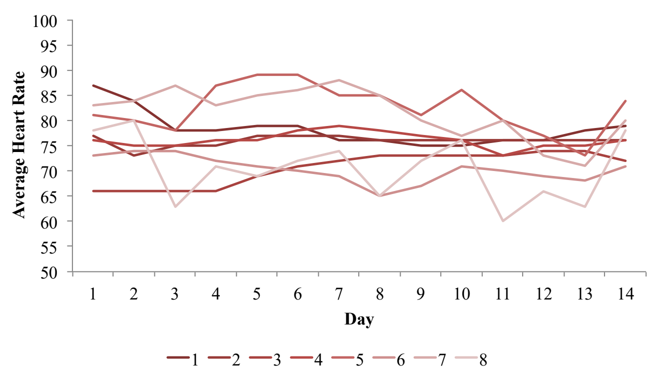

Fig. 5. Average heart rate for the CONTROL group. The average heart rate for each day of the study. Participants are labeled by their identification number.

IV. RESULTS

Tables II-V contain results for the individual comparison tests for all participants. Reported statistics include one-tailed and two-tailed t-test results for comparing first and second halves of collected data, as well as t-test results for sliding pairs comparison and baseline pairs comparison. For the intergroup comparisons, the p-values are $p<0.0001$ and $p=0.8502$ for the step count difference comparisons and heart rate difference comparisons, respectively. To visually display the data and results, Fig. 1 shows average steps for each group. Figs. 2 and 3 show the individual average step count for the both halves of participation, and Figs. 4 and 5 display REHAB and CONTROL participants' average daily heart rate.

V. DISCUSSION

In this paper, we analyze continuously collected longitudinal physical activity data for an inpatient rehabilitation participant group (REHAB) and a healthy control group (CONTROL). Our analysis aims to gain insights into the detected changes over time for these two different demographic groups. Our discussion of the detected changes is divided into three categories: individual participant step count change within the groups, individual participant heart rate change within the groups, and the change between the groups.

1) Individual Analysis-Step Count

For the REHAB group, the sliding pairs comparison tests suggests there are no significant changes from one day compared to the next (see Table II). Six of the nine patients show significant changes in step count over their treatment with the baseline pairs comparison and zero show notable change when analyzed with the sliding pairs comparison. This leads to the conclusion that day-to-day changes are too gradual to be detected using these tests, as the differences between the paired values generated with Equations (1) and (2) are being compared with the paired t-tests. However, there is more change overall in the REHAB group compared to the CONTROL group when considering the first half of the data compared to second half. Only REHAB participant #4 demonstrates significant change in both the one-tailed ($p<0.0001$) and two-tailed ($p<0.0001$) tests when comparing the halves. These values suggest significant differences between the first and second halves of treatment, corresponding to an increase in the means from the first to second half of treatment. However, this difference could be due to the variable monitoring periods for REHAB group participants. With the sliding pairs comparisons, the tests could prove to be more useful with larger sample sizes to compare when considering both cases. This is visible in Table III because inpatients with longer stays generally show significant differences in the baseline pairs comparison test. REHAB participant #4 breaks this trend, showing significance in the baseline pairs comparison ($p=0.0093$), but this may be due in part to the much smaller set of data collected for #4.

The CONTROL group data suggests that overall the participants mean step counts do not vary when treating each week as a separate data set, except in the case of CONTROL participant #3 (see Table IV). Only participant #3 shows significance in the one-tailed test ($p=0.0086$) with no participants having significant two-tailed test p-values. The CONTROL group also shows little variation with the paired sliding t-test, indicating that changes from one day to the text are not large enough to be significant. However, five of the eight CONTROL participants have significant changes in step count in the baseline pair analysis, which is the more sensitive of the pairwise approaches. Even though the day to day change of the participants is not dramatic enough to be significant, the overall change from the first monitored day is noteworthy for the CONTROL group.

2) Individual Analysis-Heart Rate

For the REHAB group, only participants #2, #3, and #5 yield significant values for any of the comparisons. Participant #2 shows significant changes in both the one-tailed ($p=0.0019$) and two-tailed ($p=0.0038$) tests, pointing to an overall increase in mean heart rate throughout the stay (see Table III). Since the sliding pairs comparison tests do not return significant p-values, the day to day changes, and changes from the baseline value, are roughly the same throughout the stay. Similarly, for participant #5, there is a significant p-value ($p=0.0007$) for the baseline pairs comparison test, indicating a substantial change from the baseline value. For participant #3 there is only a significant difference in the baseline pairs comparison ($p=0.0006$), which suggests notable differences from baseline occurring over time. With only two participants showing a significant baseline pairs comparison p-value, as a group the participants did not exhibit a significant change in heart rate during their inpatient hospitalization.

The CONTROL group exhibits many average daily heart rate changes in the baseline pairs comparison test, with participants #1, #3, #4, #5, and #6 showing significant differences (see Table V). However, the sliding pairs comparison test does not yield significant p-values for the group, as the day to day changes are too similar for the test to detect. Of the participants who have significant baseline values, #1, #2, and #6 also exhibit significant values for the one-tailed and two-tailed half to half tests. Participant #1 has a significant one-tailed test ($p=0.0078$) and participants #2 and #6 had significant one-tailed ($p=0.0016$, $p=0.0002$) and significant two-tailed ($p=0.0032$, $p=0.0003$) tests. So, though there is a higher level of change from the baseline throughout monitoring for the CONTROL group, only three of the five who show a change also have a notable increase in average daily heart rate.

The lack of significant p-values for the majority of the REHAB participants shows that, in general, the average daily heart rates of the patients fluctuate little throughout their stays. When compared with the higher level of baseline change present in the CONTROL group, this lower level of change can be attributed to the REHAB patients being sedentary for a larger portion of the day than the CONTROL group. This may be due to only daily heart rate values being calculated. If a smaller time window is used for computing average heart rates, such as an hour by hour average, it is likely that this lack of significant differences would change for the REHAB group, and that the higher level of change for the CONTROL group origins would become clearer.

3) Group Analysis

Overall, the step count comparisons between the REHAB and CONTROL groups show that the mean difference value of the inpatient populations, 1156 steps, is significantly different than then the mean value for the CONTROL group ($p<0.0001$), 3802 steps (see Fig. 1). This large mean difference in step count can be explained by considering the difference in age and setting for the participants. The CONTROL group is from a younger, more active population in a free-living setting, while the REHAB group is older and has set times for ambulatory movement.

There is no significant difference between the mean difference values for the average daily heart rates ($p=0.8502$). Thus, the average daily heart rates for participants when compared with their second half of the period of monitoring shows similar variation for both the CONTROL and REHAB groups. This lack of significant variation of heart rate between groups could be due to the short duration of data collection, as well as the variation that is present within a group.

VI. Conclusions

In this paper, we analyze longitudinal physical activity data collected from inpatient rehabilitation participants (REHAB group) and healthy control subjects (CONTROL group) to gain insights into changes over time. The results indicate that our methods are able to effectively capture significant changes in the physical activity and heart rate data for both the REHAB and CONTROL groups. Specifically, we conclude that the average step count of the CONTROL group is significantly greater than the REHAB group. The REHAB group shows a greater difference in steps between the first and second half of therapy treatment when compared to the first and second half of participation duration for the CONTROL group. This suggests that the REHAB group is improving their physical activity and not just experiencing normal variations in walking that are present in the CONTROL group. Average daily heart rates show approximately the same variation between groups and do not significantly change within the groups.

In summary, the data analysis approach and results we presented are valuable for the pervasive computing community because we provide evidence that wrist-worn sensor data can be analyzed to gain highly useful insights for inpatient rehabilitation. Our approach is also effective for comparing physical activity across demographic groups. Future work will include a larger sample size for both groups and will aim to recruit participants that are more closely related in age. We also aim to define significance of a detected change using corrected p-values, or a new framework for significance testing.

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