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TITLE: Orthopaedic Rehabilitation Training System (ORTos) for Improved Patient Compliance and Rehabilitation Monitoring in Lower Extremity Trauma

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14. ABSTRACT

This project aims to fabricate and clinically validate an effective, practical, reliable, and inexpensive biofeedback system that will provide information to patients undergoing Partial Weight Bearing (PWB) therapy to help them comply with load limitations and/or reach gait symmetry targets in post-PWB rehabilitation. The system to be used in this proposed study is the Orthopaedic Rehabilitation Training System (ORToS). During year 3 of the project, the ORToS system improvements and biofeedback software development were continued. Concurrently, engineering modifications were validated in healthy volunteers, and data analysis of archived data using Artificial Intelligence (AI) methods was initiated. Human subject protection was continued with the University of Utah IRB and the MRMC OHRP. Results and significant findings: a) data analysis identified that the longitudinal change in the number and the cadence of steps during the recovery period are more effective outcome predictors than the load-bearing prescription alone (the paper has been accepted for publication.) Analysis of the correlation between radiographic image-based assessment of recovery and the identified variables and the manuscript preparation are pending; b) The system hardware modifications improved the reliability, fabrication time, and cost of clinical devices. A no-cost extension for the project has been authorized, and the clinical study will be completed during the next year of the project.

15. SUBJECT TERMS

lower extremity fractures, load, rehabilitation

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MEMORANDUM

To: ORToS Group

From: Kylee North **Signature:**

Date: 10/12/2022

Subject: Preclinical Round 1

Attachment: **none**

CC: **Robert Hitchcock, Tomasz Petelenz, Grange Simpson, Austin Whitely, Walt Geiger**

Scope:
Results from the first round of testing for the preclinical trial. Participants did 3 to 4 walking trials:

1. Full Weight-bearing (FWB)
2. 75% Partial Weight-bearing 75PWB – only completed if FWB read more than 75% body weight
3. 50% Partial Weight-bearing 50PWB
4. 25% Partial Weight-bearing 25PWB

Testing was completed on the app, the firebase, writing to the SD card

Equipment:
Based on the shoe sizes for the participants listed in table 1, 3 Insole Assemblies (IA) were built as indicated by the *

Table 1: Participant shoe sizes

Study #	Initials	Shoe Size	BC size
PC.001	BH	11	Large*
PC.002	LH	6	Medium*
PC.003	TN	9	Medium*
PC.004	TP	10	Medium
PC.005	JH	11	Large

Instrumentation Modules (IM): This stage of the preclinical used the IM's with the MSP chips programmed for synchronous data transmission.

SD card: Cards had to be formatted and recorded binary data

Test Protocol

- Participants signed informed consent
- Participants were fitted with appropriately sized boot cast
- Participants walked down a hall way FWB (no crutches) while the IM and app

recorded loading data.

- Between each trial the app had to be closed and reopened and connected to Bluetooth in order for feedback to be isolated to just that trial.
- Three PWB Rx were test in order determined by participant – 75% PWB was not done on patients whose FWB trial was less than 75% body weight
- Participants used a scale to learn what the PWB Rx felt like and repeated the Rx down a hall-way using crutches. Procedure was repeated for each PWB Rx

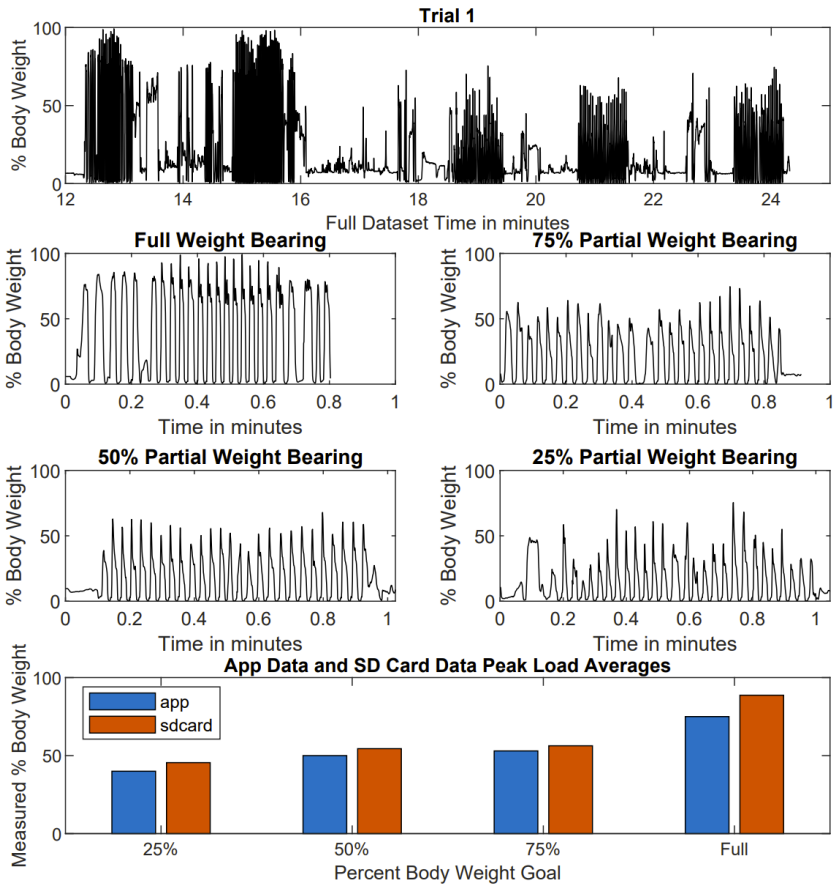
Data Reduction:

Figure plotting:

- Data from SD card put through binary viewer application, then binary parse MATLAB code to separate into heel lateral and medial arrays.
- MATLAB code written for each participant identified time intervals by hand for 25PWB, 50PWB, 75PWB, and FWB, then plotted them to a subplot shown.
- Data Stored in Box/020_ORToS_W81XWH2010266_2020/032 Patient Files

Testing Notes:

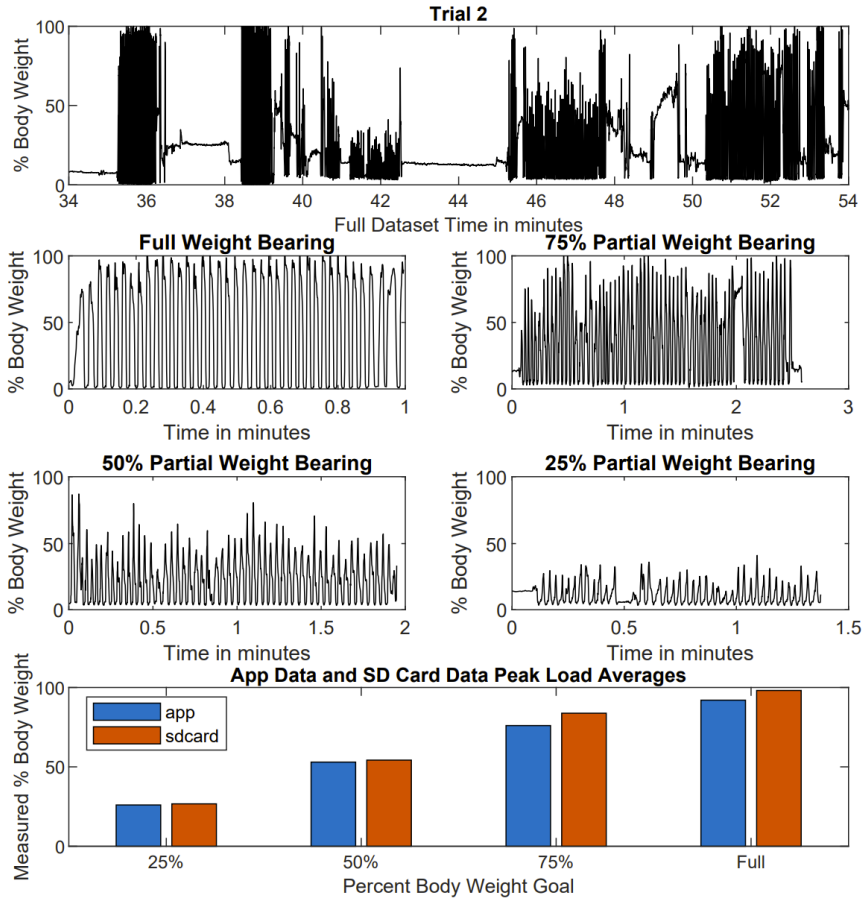
PC.001 on Aug 24, 2022



SD - not serialized
IM.006
Test done by: Kylee North
ptwt: 175

Time	WB Rx	App % WB	Notes
12:40	FWB	70-80%	Was a short walk
12:44	FWB	71%	More consistent walk than previous
12:48	25% PWB	40%	
12:50	50% PWB	50%	
12:53	75% PWB	53%	

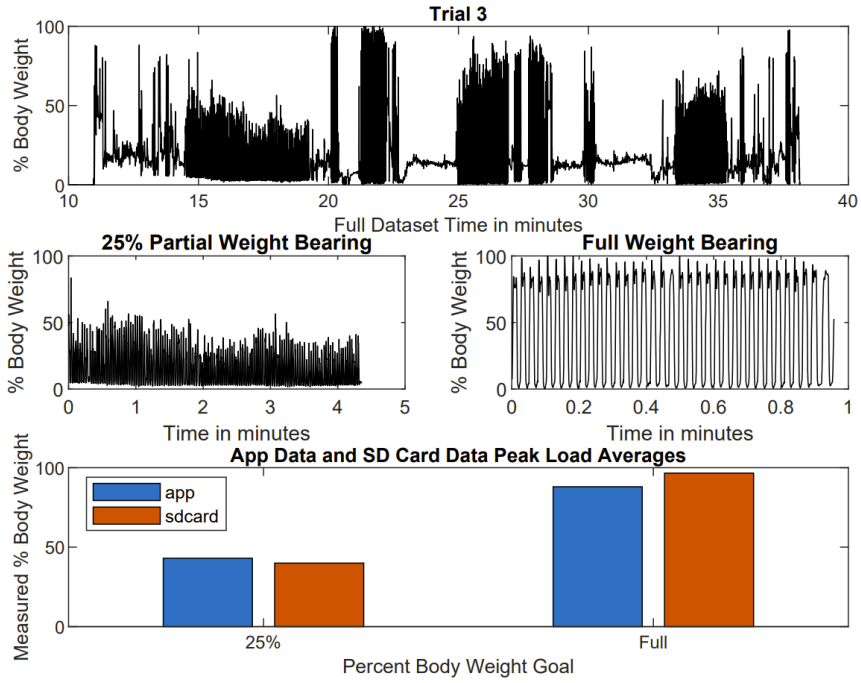
PC.002 on May 5, 2022



SD.008
IM.005
Test done by: Kylee North
ptwt: 127

Time	WB Rx	App % WB	Notes
10:17	FWB	92%	Debug
10:19	FWB		New App
10:23	25% PWB	26%	really had to concentrate
10:27	50% PWB	53%	
10:31	75% PWB	76%	Hardest to replicate

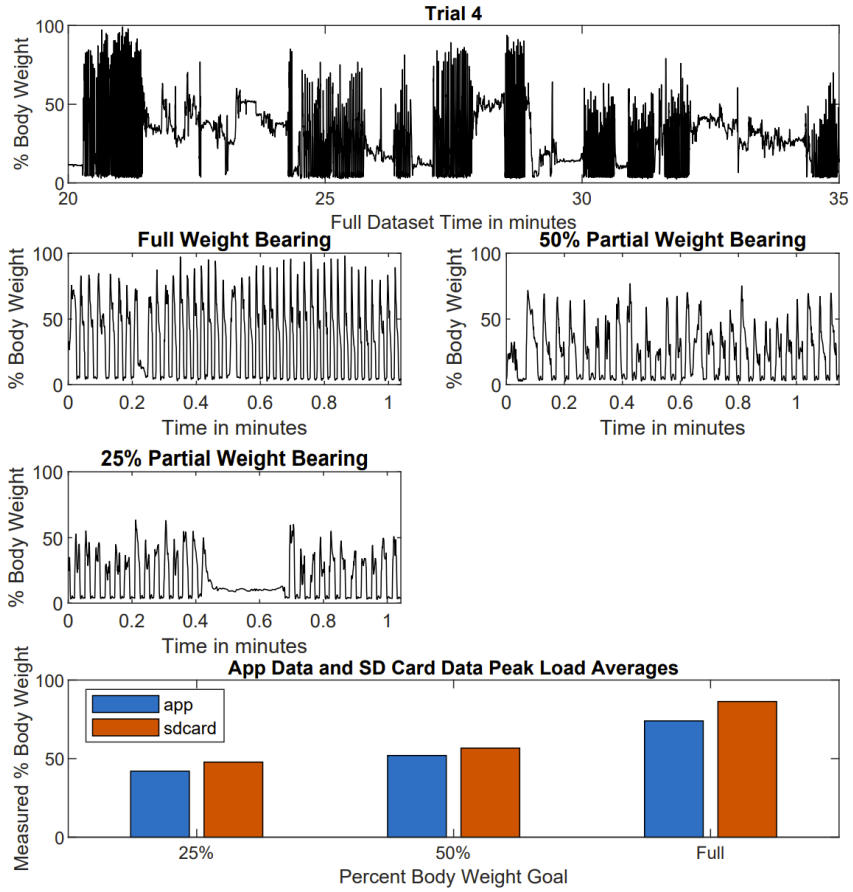
PC.003 on April 15, 2022



SD.008
IM.005
Test done by: Kylee North
ptwt: 149

Time	WB Rx	App % WB	Notes
12:39	25% PWB	43%	Debug app, gave feedback
12:45	FWB	88%	
12:50			
12:58			Newest app version

PC.004 on May 10, 2022

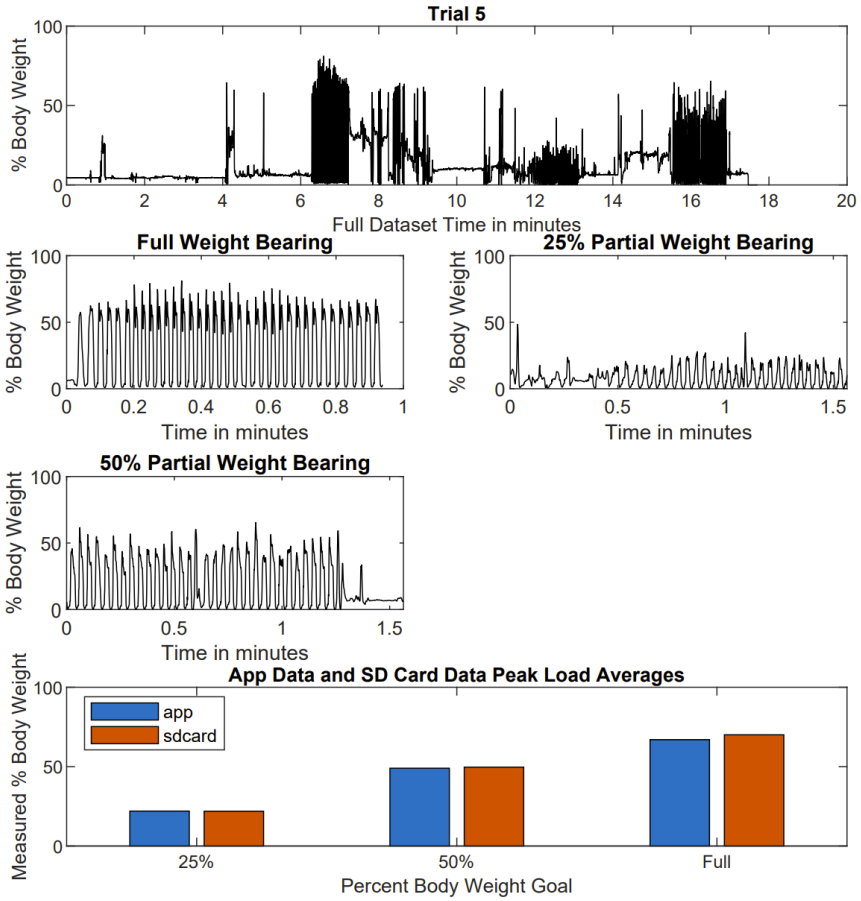


SD.008
IM.005
Test done by: Kylee North
ptwt: 167

Time	WB Rx	App % WB	Notes
1:26	FWB	74%	Debug
1:31	50% PWB	52%	App had trouble updating
1:38	25% PWB	47%	
1:42	25% PWB	42%	Adjusted crutches

No 75% as FWB was only 74%

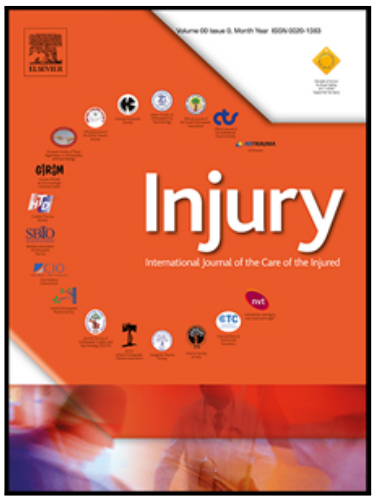
PC.005 on June 6, 2022



SD.008
IM.00?
Test done by: Kylee North
ptwt: 213

Time	WB Rx	App % WB	Notes
8:34	FWB	67%	
8:38	25% PWB	22%	
8:43	50% PWB	49%	

No 75% as FWB was only 67%



Early Postoperative Step Count and Walking Time Have Greater Impact on Lower Limb Fracture Outcomes than Load-Bearing Metrics

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Title

Early Postoperative Step Count and Walking Time Have Greater Impact on Lower Limb Fracture Healing than Load-Bearing Metrics

Title:

Early Postoperative Step Count and Walking Time Have Greater Impact on Lower Limb Fracture Outcomes than Load-Bearing Metrics

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Highlight

Wearable sensors inform rehabilitation protocols for lower extremity trauma patients

Step count and walking time may be most important for long-term rehabilitation outcomes.

Increased activity improves long-term outcomes for lower extremity fractures

No correlation found between patient and injury characteristics and loading behaviors

Abstract

Introduction: Weight-bearing protocols for rehabilitation of lower extremity fractures are the gold standard despite not being data-driven. Additionally, current protocols are focused on the amount of weight placed on the limb, negating other patient rehabilitation behaviors that may contribute to outcomes. Wearable sensors can provide insight into multiple aspects of patient behavior through longitudinal monitoring. This study aimed to understand the relationship between patient behavior and rehabilitation outcomes using wearable sensors to identify the metrics of patient rehabilitation behavior that have a positive effect on 1-year rehabilitation outcomes.

Methods: Prospective observational study on 42 closed ankle and tibial fracture patients. Rehabilitation behavior was monitored continuously between 2-6 weeks post-operative using a gait monitoring insole. Metrics describing patient rehabilitation behavior, including step count, walking time, cadence, and body weight per step, were compared between patient groups of excellent and average

rehabilitation outcomes, as defined by the 1-year Patient Reported Outcome Measure Physical Function t-score (PROMIS PF). A Fuzzy Inference System (FIS) was used to rank metrics based on their impact on patient outcomes. Additionally, correlation coefficients were calculated between patient characteristics and principal components of the behavior metrics.

Results: Twenty-two patients had complete insole data sets, and 17 of which had 1-year PROMIS PF scores (33.7 ± 14.5 years of age, 13 female, 9 in Excellent group, 8 in Average group). Step count had the highest impact ranking (0.817), while body weight per step had a low impact ranking (0.309). No significant correlation coefficients were found between patient or injury characteristics and behavior principal components. General patient rehabilitation behavior was described through cadence (mean of 71.0 steps/min) and step count (logarithmic distribution with only ten days exceeding 5,000 steps/day).

Conclusion: Step count and walking time had a greater impact on 1-year outcomes than body weight per step or cadence. The results suggest that increased activity may improve 1-year outcomes for patients with lower extremity fractures. The use of more accessible devices, such as smart watches with step counters combined with patient reported outcome measures may provide more valuable insights into patient rehabilitation behaviors and their effect on rehabilitation outcomes.

Keywords: Weight-bearing, lower extremity fracture rehabilitation, patient monitoring, wearable sensors, patient-reported outcome measures.

Highlights

Wearable sensors inform rehabilitation protocols for lower extremity trauma patients

Step count and walking time may be most important for 1-year rehabilitation outcomes.

Increased activity improves 1-year outcomes for lower extremity fractures.

No correlation found between patient and injury characteristics and loading behaviors. **Introduction**

Lower extremity fractures (LEFx) are the most common type of fractures globally, occurring at a rate of 420 cases per 100,000 in 2019[1]. These fractures are complex injuries with long rehabilitation periods that negatively affect patients' function and quality of life[2, 3]. The mechanical environment during healing plays a significant role in LEFx recovery[4-6], with the magnitude[7], type of loading[8], loading rate[9], and number of loading cycles[10] all impacting the healing process. During LEFx rehabilitation clinicians prescribe weight-bearing protocols[11, 12]. While weight -bearing protocols are the standard-of-care following LEFx, they are not based on objective data and vary between clinics and providers[11]. They also only consider the magnitude of loading, ignoring other important patient behavior metrics.

Past studies on weight-bearing protocols have reported only on patient compliance, not on the relationship between rehabilitation behavior and fracture or patient-reported outcomes[13-15]. These studies concluded that patients are not compliant with weight-bearing protocols. Additionally, the effect of early versus delayed weight-bearing has been examined via randomized controlled trials[16-18]. Early weight-bearing was observed to be safe, and in some studies, resulted in better outcomes. However, patients were not monitored as part of the study; thus, details pertaining to which patient rehabilitation behaviors contributed to outcomes cannot be determined. A significant limitation of all the previous studies investigating weight-bearing is the focus on the magnitude of loading, or percentage of body weight placed on the injured limb, to the exclusion of other patient behaviors such as daily step counts, cadence, and weight-bearing variance. Without wearable sensors, the relationship between patient rehabilitation behaviors and LEFx outcomes cannot be established.

Wearable sensors are transforming medicine by enabling longitudinal monitoring of patient behaviors and physiologic data. Wearable gait sensors overcome limitations of traditional motion capture gait analysis by allowing remote monitoring in real-world environments at a reduced cost[19, 20]. Our

research group developed a wearable gait insole system that contains multiple sensor to track patient rehabilitation behaviors such as body weight during ambulation, as well as rehabilitation activity metrics including step count, cadence, and loading variance [21, 22]. The insole gait monitoring system demonstrated long-term accuracy, reliability, and can be produced at a relatively low cost in a laboratory setting [23-25]. This allows for flexibility in fitting the insole to each patient and managing the costs to allow for scalable clinical trials.

The main goal of this work is to examine what patient behaviors positively impact 1-year rehabilitation outcomes in addition to quantifying general patient behavior during LEFx rehabilitation, specifically with closed ankle and tibial shaft fractures. By utilizing wearable gait monitoring insoles during early rehabilitation, we can continuously track and analyze patient rehabilitation behaviors. Outcomes were evaluated using the 1-year Patient Reported Outcome Measurement Information System® Physical Function (PROMIS PF) score, which is a validated clinical tool used to assess patients' outcomes across multiple domains, including physical function and pain. [26-29]. Patients were separated into two groups based on their 1 yr PROMIS-PF score and their metrics of patient rehabilitation behavior were compared between the two outcome groups using advanced analytic techniques. The integration of validated clinical measures with wearable sensor data can transform rehabilitation by providing objective insight into the impact of surgical and rehabilitation protocols on patient outcomes. The results from this study can be used to challenge current rehabilitation protocols and improve patient outcomes.

Methods

Design:

The study is a Level III retrospective analysis of an IRB approved 3-year prospective clinical observational study using an insole gait monitoring system to correlate early (2-6 weeks post-operative) patient rehabilitation behavior of AO/OTA classification 42-44 fractures to 1-year fracture outcomes. The gait monitoring insole was placed inside the patient's Controlled Ankle Motion (CAM) boot cast which

patients were instructed to wear at all times. The gait monitoring insole continuously monitored patient rehabilitation behaviors[21] starting at 2 weeks post-operative until the clinician prescribed the CAM boot to be discontinued sometime between 6 and 12 weeks post-operative. Patients were treated per standard of care defined by the treating clinician based on fracture pattern, location, and chosen fixation. Fracture outcome was defined as the 1-year PROMIS PF t-score. All PROMIS measures are scored on a t-score metric with a range of 1-100 with 50 being the referent population mean and 10 points as the standard deviation[30].

Subjects:

Adult patients (N=42) with closed tibial fractures or bimalleolar ankle fracture (AO/OTA classification 42-44 fractures) treated at the (*removed for blinding)* Level I trauma center who met the inclusion criteria (18 years of age or older, spoke English, weighed between 45.3-113.4 kg, lived within 161 kilometers of the hospital, and did not have multiple injuries) were recruited prior to surgery.

Data Analysis - Gait Monitoring Insole Data Interrogation:

The gait monitoring insoles includes three force sensors that sample at 16 Hz for 28 to 94 days. Each patient's data set was fed through a data pipeline that calculated total load, normalized the values to patient's body weight and adjusted the temporal component to weeks post-operative. Expanding on a validated code[22], twenty-one daily metrics which define patient rehabilitation behaviors were calculated from the insole data (see Supplementary Table 1 for full list of metrics). A 7-day moving window average was applied to cadence (steps per minute) and body weight per step (BWS). On days patients either did not wear the boot or did not walk, metric values were set to NaN (not a number). Figure 1 shows a flow chart of the entire data analysis procedure, including the insole data pipeline.

Data Analysis – Effects of Patient Rehabilitation behavior on Fracture Outcomes

One year PROMIS PF was obtained via an email link to a secure online version of the questionnaire (N=17). Patients were separated into two outcome groups: excellent (PROMIS PF $\geq$ 55 t-score) and average outcomes (PROMIS PF < 55 t-score). This cutoff of 55 was chosen as the range of 45 – 55 on the t-score scale is considered "within normal limits" and half a standard deviation (S.D.) is considered "meaningful change"[31]. To examine the effects of early weight bearing we examined insole data from the first 6 weeks postoperatively. Rehabilitation behavior metrics were compared between outcome groups at the following time point bins: 0-3, 3-4, 4-5, and 5-6 weeks post-op. Two-tailed student T-tests were performed assuming unequal variances with a p-value of less than 0.03 determining statistical significance between each time point for all twenty-one rehabilitation behavior metrics. A p-value of <0.03 was chosen to increase the robustness of comparisons due to the small number of participants.

To determine which of the 21 metrics of patient rehabilitation behaviors had the greatest impact on 1-year outcomes, a Fuzzy Inference System (FIS), was used to analyze the data. An FIS is a type of mathematical model that can be used to analyze complex data sets. The basic idea behind FIS is that it uses a set of "rules" to make decisions or predictions based on input data. For this study, the FIS looked at the average p-values across all 4 time points and the number of significant differences for each metric to produce a ranking score between 0 and 1, which we called the Impact Score. This ranking system allowed us to differentiate between metrics that had a significant impact on 1-year outcomes and those that did not [32] (see Supplementary Table 1).

Principal Component Analysis (PCA) was performed following the same method as described by Olney et al.[33]. The data was structured such that each metric was averaged by post-operative weeks for up to 6 weeks for each patient and organized in separate rows. Missing data points were set to zero. The PCA had two purposes: 1) to determine if patients in the excellent and average outcome groups clustered into a rehabilitation behaviors (i.e., a principal component) and 2) to perform dimensionality reduction. All 94 variables (21 metrics * 4 time points + 10 overall behavior metrics = 94) were fed into the PCA

and the resulting principal components that describe 80% of the variation in the data were fed into a correlation matrix with patient characteristics to investigate their influence on patient rehabilitation behavior.

Data Analysis – General Patient Rehabilitation Behavior

All daily patient loading data at all time points were combined to produce histograms for step count and cadence. Average boot cast use time for all patients was calculated by post-operative week. A scatter plot was generated of step count and BWS data from the first 6 weeks post-op, labeled by weight-bearing protocol.

Results

Patient Characteristics

Of the 42 enrolled patients, 22 participants had complete insole data sets (37.6 $\pm$15.8 y/o,13 Females, 9 Males, 27.0 $\pm$ 6.4 BMI), 17 of whom completed the 12-month PROMIS PF. On average, the insoles collected data for 70 $\pm$ 20.5 days, patients did not load their injured limb every day of recording, resulting in an average of 42 days $\pm$ 16.6 of data per patient and a total of 809 days of sensor loading data across all patients. Of the 20 participants not included in this study 7 were lost to follow-up or were removed from the study, 2 failed to wear the boot cast, and 11 had some insole error during the recording time. Various patient characteristics including, patient demographics, weight-bearing prescriptions, PROMIS PF, and OTA fracture classifications are presented in Table 1. There was no significant difference between any category of outcome groups (excluding PROMIS PF which was used to separate patients by group).

Effects of Patient Rehabilitation behavior on Fracture Outcomes

There was a significant difference between the outcome groups in several metrics. Step count had the highest Impact Score of 0.817 (FIS ranks Impact Scores from 0-1, with 1 being the highest). The

following two highest impact metrics were related to step count and included the sum of BWS (an interaction term between step count and BWS, weighted more towards step count, Impact Score = 0.448), and walking steps (step count for only steps that are consecutive, or during walking, Impact Score = 0.431). Walking time was also a high impact metric with a Impact Score of 0.328. For all metrics listed, the excellent outcome group had higher values compared to the average outcome group and these values increased between week 3 to week 5. Figure 2 displays the results for two of the top-ranked metrics, step count and walking time, and for BWS, which was predicted to score high but was ranked towards the middle with an Impact Score of 0.309. Table 2 details weekly averages, P-Values, and Impact Scores for metrics of interest.

The PCA did not cluster between outcome groups for any of the principal components (PC). Six principal components were needed to explain 80% of the data variance. PC5 (4.8% of variance) had the highest correlation to 1-year PROMIS PF (r = -0.66) but none of the 94 metrics had a correlation coefficient of absolute value > 0.6 in PC 5. PC1 explained 42.6% of the variance and 68/94 metrics had correlation of absolute value > 0.6, PC 2 explained 12.1% and 8/94 metrics had significant correlation. Calculating correlations between the first 6 PCs and patient demographic data produced only one significant correlation (r = 0.88) between PC1 and the 2 week Partial Weight-Bearing Prescription (PWB Rx). There were no significant correlations between the 1-year PROMIS PF and patient characteristics. Figure 3 shows the correlation coefficients between patient characteristics and the 1-year PROMIS PF with the first 6 principal components.

General Patient Rehabilitation Behavior

Step counting produced a logarithmic distribution, with a sum of 10 days (out of a total of 809 days) from all patients exceeding 5,000 steps a day. Cadence had a Gaussian distribution with a mean of 71.0 $\pm$ 10.9 steps/min. Patients wore the boot cast between 0 – 23 hours a day. A box plot of the wear time by week is shown in Figure 4 along with distribution of the step count and cadence for all patients.

Figure 5 shows that BWS maxes out below 100% in the scatter plot, which is typical for insole measurement systems, as peak loads can be reduced by up to 30%(34). The scatter of data points indicates a weak correlation between step count and BWS.

Discussion

Surgeons rely on previous training and clinical experience, rather than objective data, to guide weight-bearing protocols in rehabilitation therapy due to a lack of objective evidence. At the same time, patients have difficulty interpreting and following these protocols, leading to improper application of body weight on the injured limb. While there have been advances in surgical techniques and fixation methods, there have been few improvements in evidence-based rehabilitation protocols following surgery.

This work aims to advance the field of rehabilitation towards data-driven protocols using objective data from wearable sensors and subjective patient-reported outcomes to understand what patient behaviors positively impact closed ankle and tibial fracture rehabilitation outcomes. Wearable sensors allow for continuous data collection, which presents new challenges in data analysis[34]. To address these challenges, this study employed computational tools of Principal Component Analysis (PCA) and Fuzzy Inference Systems (FIS) to analyze high-dimensional gait data[34, 35]. PCA was used to reduce the dimensionality of the data and identify correlations with patient and injury characteristics, while FIS was used to identify specific patient rehabilitation behaviors that had the greatest impact on outcomes. FIS proved to be a powerful tool for this application, as it has the flexibility to incorporate repeated measures, work with large datasets with few subjects, and can be tailored to focus on specific loading metrics that distinguish different outcomes.

FIS analysis found that daily step count and walking time had the most impact on 1-year outcomes. These metrics track active, dynamic loading, which has been shown to facilitate better healing compared to static loading[8]. Interestingly, metrics related to body weight support and overall loading

have a large impact on outcomes. This was surprising because partial weight-bearing protocols have traditionally only focused on BWS, or the amount of weight placed on the limb.

Developing post-surgical rehabilitation protocols based on daily step counts or walking time has many advantages over BWS. BWS monitoring requires a device that can withstand high magnitude loads for up to 90 days, which presents engineering challenges. In contrast, step count and walking time can easily be tracked through widely available mobile devices[36] or externally worn inertial sensors[37]. These metrics are also more accessible and understandable to patients, as opposed to the complex and often poorly understood concept of BWS. Additionally, BWS provides a limited view of patient activity. As shown in the Figure 5, there are data points that have high BWS (greater than 70%) but can have anywhere between 200 to 6,000 steps/day. Overall, this study suggests that tracking step count and walking time could be a valuable aspect of patient care following lower extremity fractures.

Both step count and walking time metrics demonstrated that patients in the excellent outcome group were more active than those in the average outcome group (Table 2, Figure 2). This trend aligns with previous research suggesting that increased activity improves outcomes in LEFx rehabilitation (12, 33, 34) and early weight-bearing positively impacts rehabilitation. This is particularly interesting given that most patients (76%) were prescribed non-weight-bearing (NWB) during the observation period (2-6 weeks post-op) and that both outcome groups had the same number of patients prescribed WBAT (n = 2, see Table 1). Additionally, all patients had high activation (Patient Activation Measure (PAM) -13 > 55.2), indicating high engagement in their healthcare. It is well known that patients struggle to comply with weight-bearing protocols[13, 14, 38, 39], and this was also confirmed to be the case on this patient cohort[15]. Patients did not cluster or show any trends based on weight-bearing prescription in the scatter plot in Figure 5. However, when combining data from both outcome groups, there was a significant positive correlation between the weight-bearing prescription and the first principal component of loading (PC1, r = 0.88, Figure 3), suggesting that patients prescribed WBAT are more active than those prescribed NWB. However, this finding is limited by the small number of WBAT patients (n=4), the large

variation in patient activity patterns (see Figure 5) and the difficulty in directly interpreting principal components. Therefore, we cannot conclusively determine the effect of a WBAT vs. NWB prescription on patient activity and these warrants future studies in this area. The correlation coefficient between weight-bearing prescription and 1-year PROMIS PF was not significant (r = -0.05, Figure 3), indicating that within this study sample the weight-bearing prescription was not correlated with 1-year patient outcomes

One of the unique aspects of this study is it is one of the few datasets continuously monitoring patient rehabilitation behavior following tibial or ankle fracture. Thus providing new insights into the general behavior of patients during closed ankle and tibial shaft fracture rehabilitation. Our analysis revealed that patients in the study were more sedentary compared to the uninjured population. The logarithmic distribution of the step count data showed that for most days, patients walked less than 1,000 steps a day, see Figure 4. Out of a total of 809 days of sensor recording from all patients, only ten days exceeded 5,000 steps in a day, which less than that threshold is considered a sedentary lifestyle[40]. Additionally, patients had a lower average walking cadence of 71.0 steps per minute, while the average for uninjured people is around 100 steps per minute.[41]. This information is important for the clinical team to understand as increased sedentary behavior can negatively impact rehabilitation and patient quality of life. Thus, this information should be considered when planning rehabilitation programs, and in encouraging patients to be more active during rehabilitation.

Although this was conducted with 42 initial participants, we encountered some limitations, including a 48% dropout rate. Out of the 42 patients originally enrolled, 17% were lost to follow-up, 5% did not comply with their boot cast prescription, and 26% experienced some type of sensor failure. We used the remaining 22 complete datasets for a PCA and CORR matrix analysis, as illustrated in Figure 1. Out of the 22 datasets, 17 had a 1-year PF PROMIS score, which were used to compare metrics between the excellent and average outcome groups. Despite the limited number of complete datasets, we were able to collect a large amount of data from each patient, amounting to a total of 809 days of data. Therefore,

the data volume for this study lies more in the quantity of data collected from each patient rather than the number of patient datasets. We believe that the high dropout rate observed in our study provides valuable information for other research groups conducting similar studies. Clinical follow-up with orthopaedic trauma patients is known to be challenging with dropout rates reported between 65-72% at the 1-yr follow up[42]. Additionally, the likelihood of sensor failure rate during 25-90 days of continuous underfoot loading is expected. Understanding these limitations will help improve sensor design and inform and properly power future studies. However, due to the volume of loading data we collected this study provides valuable insights into the effects of patient loading behaviors on 1-year lower extremity fracture outcomes. Additionally, there are several factors that increase the reliability of the findings. One such factor is the lack of statistical differences between age, gender, fracture type, or weight-bearing prescription between two outcome groups (Table 1). This indicates that the observed differences between the two outcome groups are not due to any of these patient characteristics being more prevalent in one group compared to the other. The correlation matrix shown in Figure 3 also indicates that the 1-year PROMIS PF score and the principal components describing patient weight-bearing behavior had no significant correlations, meaning the variables of fracture type, gender, injury energy, outside average temperature (people did not walk more in warmer temperatures), patient activation, age, weight, height, or BMI did not affect rehabilitation behaviors. Another limitation is the lack of correlation between the 1-year PROMIS PF and PC1. This may be due to the PROMIS PF Computer Adaptive Test items given to LEFx patients not being specific enough to accurately measure the progression of physical function rehabilitation in patients with LEFx. This finding could be further explored by using the clinically specific measure of the Foot and Ankle Extremity Measure (FAAM) or a custom LE PROMIS PF measure that have items focused on lower extremity motion[43].

Understanding the relationship between patient rehabilitation behavior and LEFx outcomes can move the field towards data-driven protocols by informing the design of future clinical trials. We recommend that future studies consider measuring patient activity metrics in addition to patient loading.

This work demonstrates the utility of patient-reported outcome measures; however, we recommend that a more specific measure of lower extremity function, such as FAAM or a custom LE PROMIS PF short form that contains items that focus on load bearing, be used. Due to the high stochasticity in patient behaviors and the challenges of longitudinal studies, we recommend large enrollment numbers.

Conclusion

This study highlights the importance of utilizing objective data from wearable sensors in combination with patient reported outcome measures to gain a deeper understanding of patient rehabilitation behaviors and their impact on 1-year outcomes. Our findings indicate that step count and walking time are key metrics that have a positive influence on 1-year outcomes. Additionally, these preliminary results suggest that increased activity during early rehabilitation may lead to improved outcomes for patients with lower extremity fractures. These findings are crucial for the future development of data-driven rehabilitation protocols for lower extremity trauma patients, which have the potential to improve patient outcomes and reduce clinical variation. Furthermore, the use of wearable technology, such as smart watches in rehabilitation allows for more precise and accurate monitoring of patient progress, providing a more efficient and effective approach to rehabilitation.

Declaration of Interest

Dr. Kubiak discloses a financial relationship with Zimmer Biomet and DJO Global. Kylee North, Drs. Kubiak, Petelenz, and Hitchcock disclose patents related to the gait monitoring technology described in this manuscript, however, the gait monitoring technology was developed for research purpose and has not been commercialized. No royalties have been collected from the device.

Source of Funding: This work was supported by the U.S. Department of Defense (DOD) CDMRP under Award No. W81XWH1220089 and Award No.W81XWH12010266. The opinions, interpretations,

conclusions, and recommendations of this manuscript are those of the authors and are not necessarily endorsed by the Department of Defense.

Acknowledgement

This work was supported by the U.S. Department of Defense (DOD) CDMRP under Award No. W81XWH1220089 and Award No.W81XWH12010266. The opinions, interpretations, conclusions, and recommendations of this manuscript are those of the authors and are not necessarily endorsed by the Department of Defense.

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Figure legends

Figure 1: Data Analysis Flowchart. Gait monitoring insole data pipeline extracts rehabilitation behavior metrics from each patient and combines patient data sets to run three separate analyses.

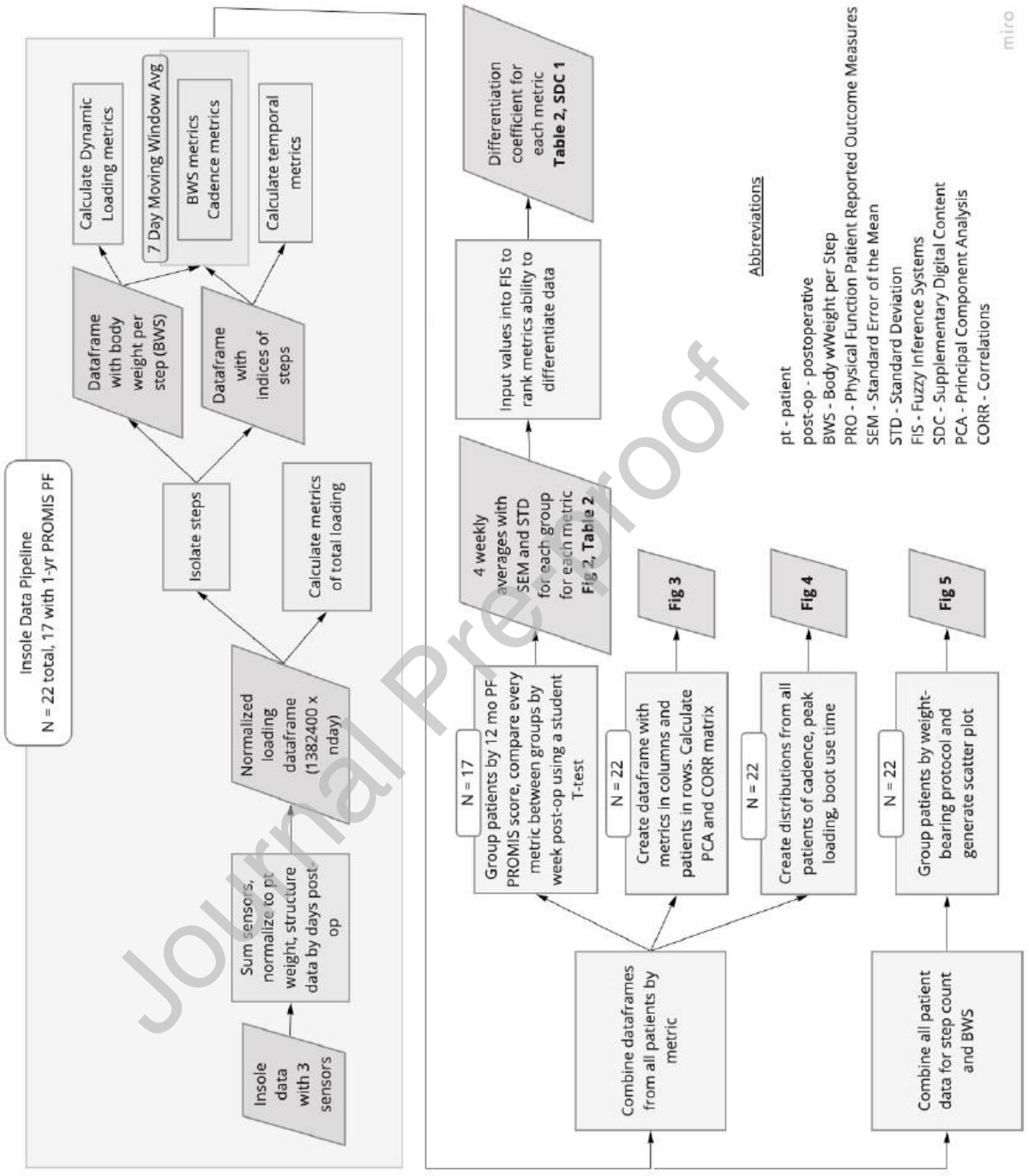


Figure 2. Effects of patient rehabilitation behavior on fracture outcomes. (Top) Step Count, (Middle) Walking Time, (Bottom) Body Weight per Step. Asterisk indicates P-value < 0.03.

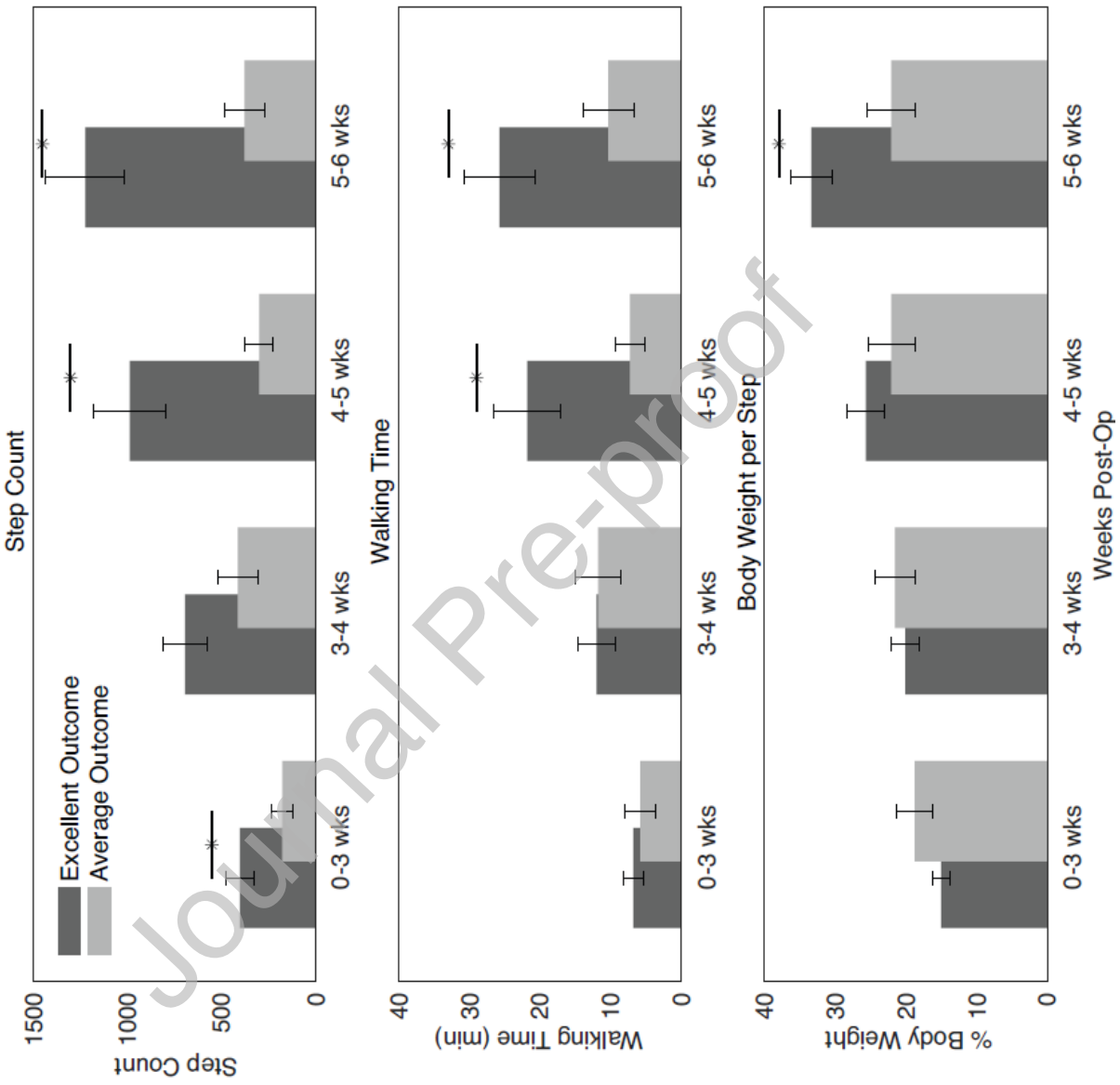


Figure 3: Correlation matrix of 1-year PROMIS PF and patient rehabilitation behavior metrics principal components correlated to patient characteristics.

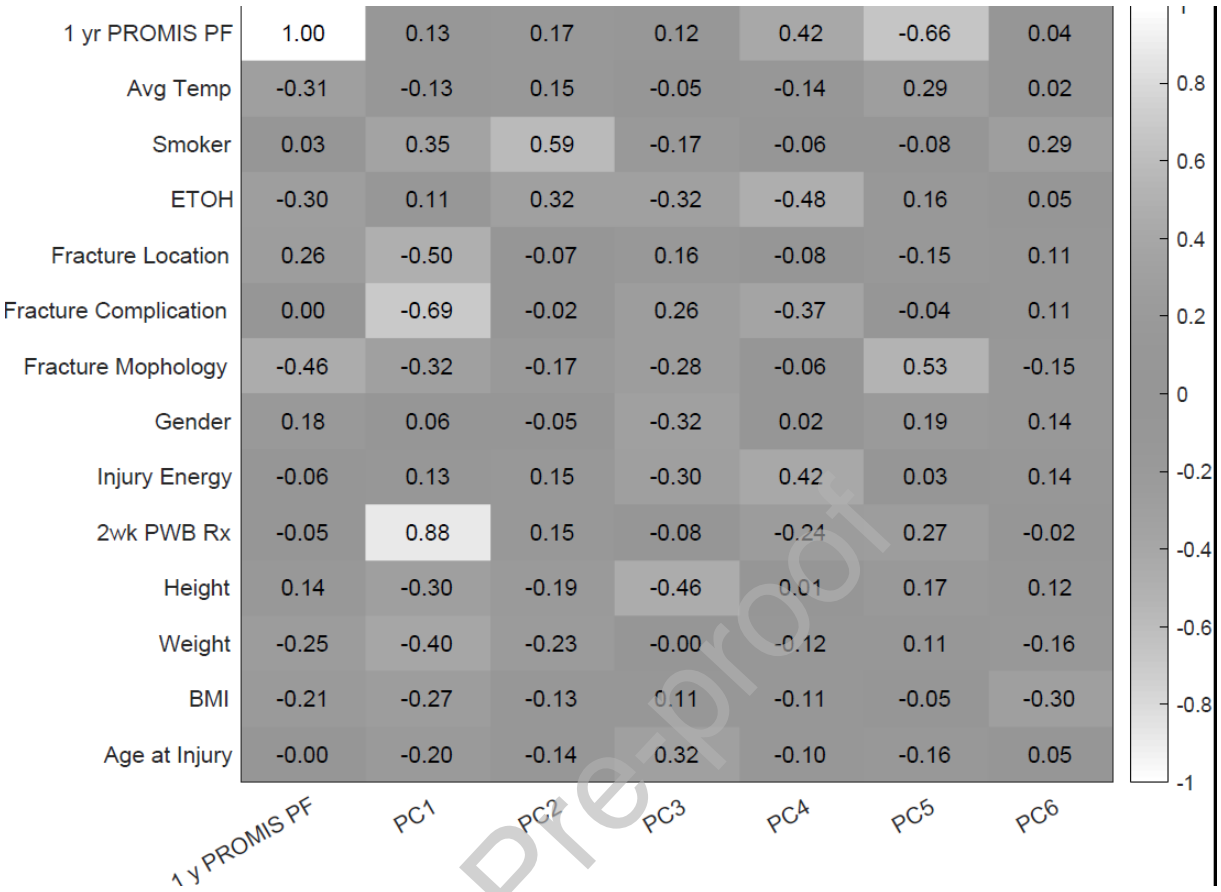


Figure 4: Graphs describing general patient rehabilitation behavior. (Top) histogram of step count, (Middle) histogram of cadence, (Bottom) box plot of controlled ankle motion (CAM) boot use time by weeks post-op.

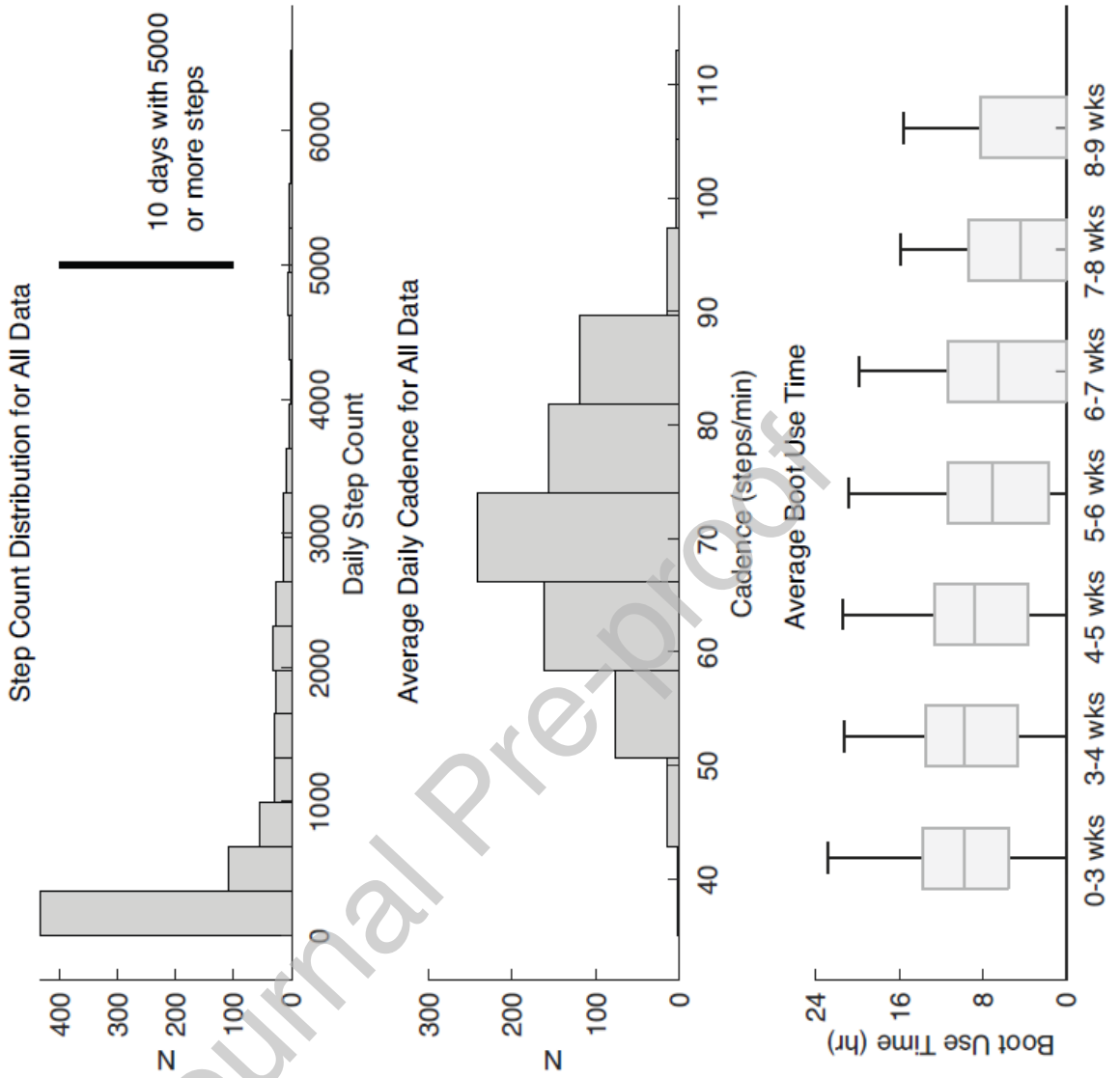


Figure 5: Scatter plot of step count and body weight per step (BWS) labeled by fracture type and weight-bearing prescription.

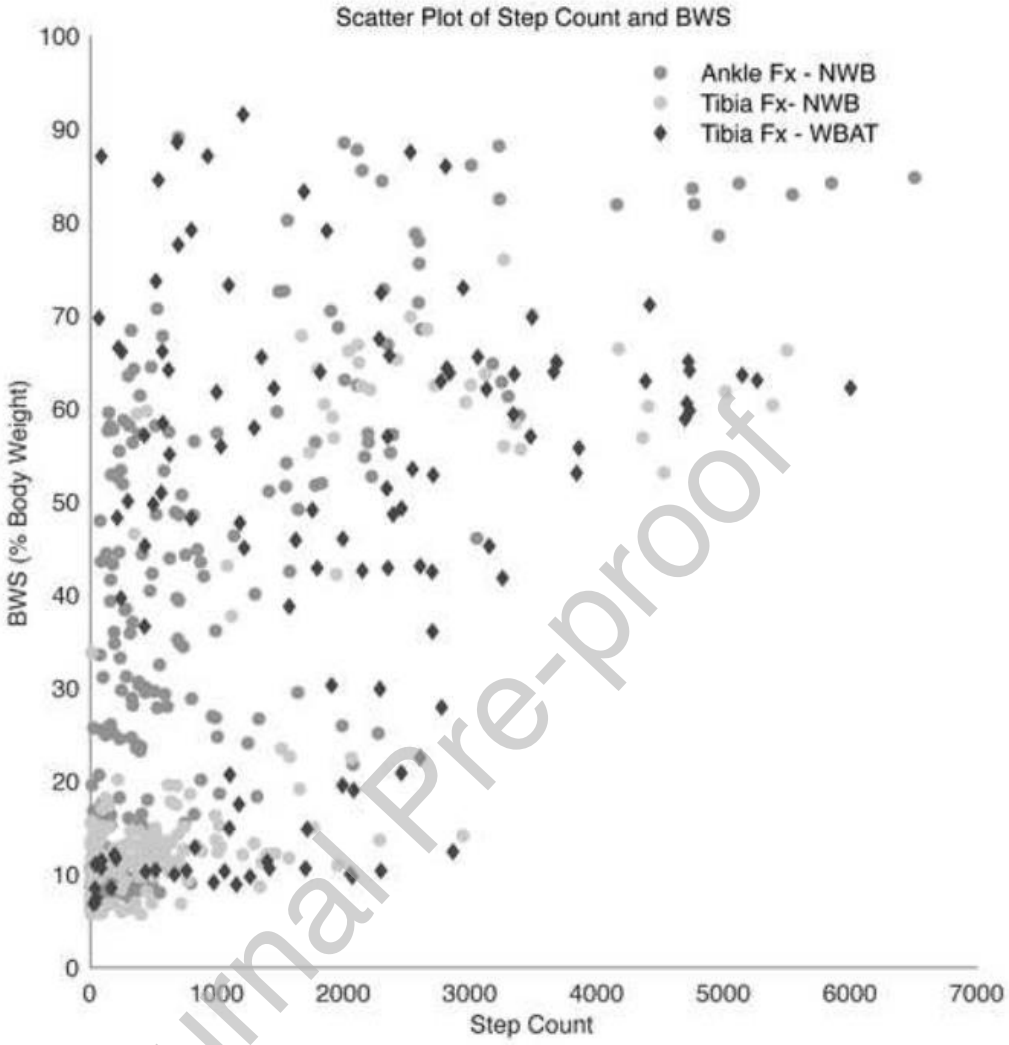


Table 1: Patient Characteristics

	Excellent Outcomes	Average Outcomes	P-Value	All Patients
Participants	9	8	NA	22
Age, y	37.8 (17.8)	30.8 (7.1)	0.30	37.6 (15.8)
Gender M / F	5/4	3/5	0.99	9/13

BMI, kg/m^2	24.2 (4.5)	30.6 (7.1)	0.05	27.2 (5.9)
Weight Bearing Prescription				
NWB / WBAT	7/2	6/2	0.99	16/5
PF PROMIS	59.1 (5.8)	47.5 (5.2)	NA	53.6 (8.0)
PAM-13	68.5 (6.0)	77.3 (13.2)	0.05	72.6 (10.7)
Fracture Location Classification			0.44	
OTA 42	4	3		9
OTA 43	2	0		3
OTA 44	3	5		9
Fracture Complexity Classification			0.08	
OTA A	6	2		10
OTA B	0	4		5
OTA C	3	2		6

Abbreviations: M – Male, F – Female, BMI – body mass index, NWB – Non-Weight-Bearing, WBAT – Weight-Bearing As Tolerated, PF PROMIS – Physical Function Patient Reported Outcome Measurement Information System, PAM-13– Patient Activation Measure, OTA – Orthopedic Trauma Association

Table 2: Results from Select Metrics Separated by Time and Outcome Group

Metric	FIS Ranking	Time Frame	Excellent Outcome Group	Average Outcome Group	P-Value
Step Count (steps/day)	0.817	Weeks 0-3	401.8 (331.6)	179.8 (573.7)	**0.021***
		Week 3-4	691.8 (715.6)	410.9 (873.2)	0.083
		Week 4-5	985.8 (490.9)	298.2 (1371.4)	**0.001***
		Week 5-6	1222.6 (617.9)	375.9 (1507.4)	**0.0005***

Top 20% Cadence (steps/min)	0.422	Weeks 0-3	90.5 (20.4)	89.7 (10.2)	0.843
		Week 3-4	94.7 (12.4)	88.6 (9.6)	**0.012***
		Week 4-5	93.5 (19.4)	83.7 (7.9)	**0.004***
		Week 5-6	94.4 (13.3)	95.8 (7.7)	0.571
Walking Time (minutes)	0.328	Weeks 0-3	7.1 (8.9)	5.7 (10.6)	0.602
		Week 3-4	11.8 (12.3)	12.0 (17.6)	0.97
		Week 4-5	22.4 (12.3)	7.4 (31.2)	**0.006***
		Week 5-6	26.0 (16.5)	10.4 (34.6)	**0.016***
Cadence (steps/min)	0.309	Weeks 0-3	66.2 (14.0)	73.1 (6.9)	**0.012***
		Week 3-4	69.9 (9.1)	68.0 (14.1)	0.435
		Week 4-5	66.8 (14.2)	67.6 (7.9)	0.766
		Week 5-6	70.6 (13.5)	70.6 (7.7)	0.1
BWS (% body weight)	0.309	Weeks 0-3	15.0 (17.6)	18.8 (9.4)	0.196
		Week 3-4	20.1 (20.0)	21.5 (15.4)	0.675
		Week 4-5	25.7(24.6)	22.1 (20.1)	0.399
		Week 5-6	33.4 (25.6)	22.1 (22.4)	**0.013***
Boot Cast Use Time (hours)	0.309	Weeks 0-3	9.4 (5.8)	9.3 (5.1)	0.93
		Week 3-4	9.8 (4.9)	8.4 (6.0)	0.182
		Week 4-5	8.7 (5.0)	7.7 (5.7)	0.349
		Week 5-6	7.8 (4.4)	5.4 (5.4)	**0.008***
Mean of All Loading (% body weight)	0.183	Weeks 0-3	7.4 (4.2)	7.5 (4.2)	0.942
		Week 3-4	8.6 (5.5)	8.8 (4.0)	0.838
		Week 4-5	9.3 (6.0)	9.2 (4.6)	0.906
		Week 5-6	10.5 (8.7)	10.6 (5.0)	0.919

*Highlights significance (P-value < 0.03)

Quarterly Technical Progress Report

Award Number:	W81XWH2010266
Log Number:	BA170194
Project Title:	**Orthopaedic Rehabilitation Training System (ORToS) for Improved Patient Compliance and Rehabilitation Monitoring in Lower Extremity Trauma**
Principal Investigator Name:	Tomasz Petelenz, PhD
Principal Investigator Organization and Address:	UNIVERSITY OF UTAH, THE 201 PRESIDENTS CIR SALT LAKE CITY UT 84112-9049
Principal Investigator Phone and Email:	801-585-1804; email: tomasz.petelenz@utah.edu
Report Date:	14 JUL 2022
Report Period:	15 APR 2022 – 14 JUL 2022

1. Accomplishments:

What were the major goals of the project?

Major goals of the project are divided into Technical Objective 1 and 2. Only relevant Major Tasks and Subtasks that are relevant to the reported stage of the project are listed here.

TO 1 - Fabrication and validation of the ORToS system for use in clinical study; months 1-14
MT1.2. Fabrication process scale up and validation; Months 1-10
TO 2 – Clinical study to determine the role; months 11-24
MT2.1. Study protocols, IRB review and approval; months 3-6
ST 2.1.1. IRB approval; months 6-8
MT2.2
MT 4. Project management; months 1-24

What was accomplished under these goals?

TO 1; MT 1.1.

1. Fabrication of ATLAS to use in the clinical study:

    a. Structural components for the insoles have been fabricated, and devices have been assembled for use in the clinical study.

    b. Occasional sensor failures still occurred. We have initiated root cause analysis and CAPA, which will be continued during the next reporting period.

2. IM enclosure (housing), IM electronic PCB, and battery
    a. New IM battery and electronics case design has been completed, prototype devices have been fabricated, and mechanical and sealing tests are in progress.
    b.

TO 2; MT 2.1; ST 2.1.1.

1. Clinical study
    a. 5-subject device feasibility study.
    The 5-subject feasibility study was started, and we completed the first round of data collection in 5 subjects.
    Data analysis and verification are now in progress.

    b. Clinical study in patients with fractures.
    The IRB Continuing Review application was approved on January 22, 2022, by the University of Utah IRB. The CR approval documentation has been submitted to the HRPO.

    c. Enrollment. We plan to start enrollment for the clinical study in July 2022.

    d. Changes to the enrollment protocol. Until the asynchronous data transfer is completed, we are planning to enroll subjects and initiate the study using a block randomization strategy. An amendment has been submitted to the University of Utah IRB, and the subsequent approval will be submitted to the HRPO. The enrollment will not be initiated until the amendment has been approved by both institutions.

3. Biofeedback.

Biofeedback software development continued. As reported previously, biofeedback software includes a biofeedback App and backend software for data transfer. The work included:

    a. Graphical User Interface and App development focused on finalizing data transfer from the IM to the App.

b. Synchronous data transfer software, which has been completed and successfully tested.

c. Asynchronous data transfer, which may not be possible using the current IM design. Therefore, we have initiated the IM transition to a new firmware platform based on a highly integrated 32-bit ARM Cortex M4 CPU. (Fig. 1)

d. Firmware development is in progress, and the original synchronuous IM data sampling and transfer functionality has been completed. Software development for asynchronous data transfer is in progress, and we plan to complete it in the reporting period.

e. IM PCB design has been initiated, and the new IMPCB will be completed in the next reporting period.

f. Sofware code is developed using a micropython programming environment. This change will result in faster development time and ease of modifications in the future (if needed) and will enable the use of functions already available for the new nRF5240 microcontroller.

g. The next steps will focus on testing the new system and designing and fabricating a dedicated PCB.

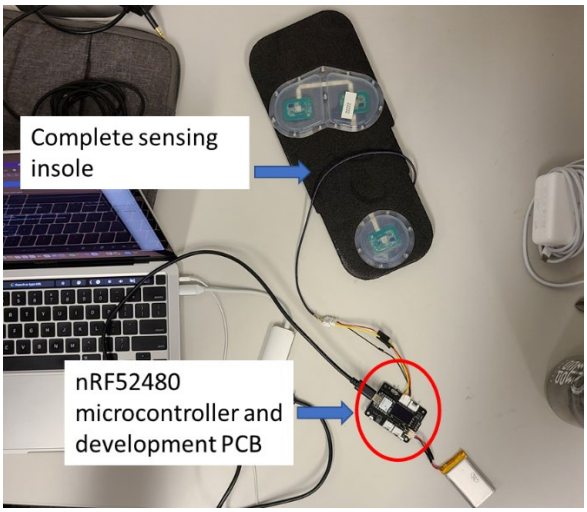


Figure 1. New IM using nRF52480 microcontroller.

MT 4. Administrative tasks

1. Administrative tasks are continued.
2. Project management
   a. Team meetings have been conducted 1x per week. As the COVID-19 restriction abate, meetings are now being conducted in person.

   b. Weekly team meetings will continue in the next reporting period.

Describe the Regulatory Protocol and Activity Status (if applicable).

A continuing Review (CR) application was submitted to the University of Utah IRB. After the review has been completed, updated study documents will be submitted to the HRPO.

(a) ***Human Use Regulatory Protocols***

TOTAL PROTOCOLS:

The ORToS project will include 2 study protocols:

- Protocol 1 – Pilot Study in volunteers protocol, HRPO assigned number E01300.1a
- Protocol 2 – Clinical study protocol, HRPO assigned number E01300.2a
  - The clinical study design has been completed.

- The study has been approved by the HRPO.

PROTOCOL(S):

Protocol 1 of 2:

Protocol E01300.1a:

Title: Pilot study of the Orthopaedic Training and Rehabilitation System (ORToS) in healthy volunteers

Target required for clinical significance: - N/A – This is a pilot study design for the initial form-and-fit evaluation of the devices to be used in the clinical study.

Target approved for clinical significance:

Submitted to and Approved by:

The University of Utah IRB, Protocol number: IRB_00133885

Status:

Due to engineering development delays, enrollment has not started. We plan to start enrollment in the next reporting period.

TOTAL PROTOCOLS: 2 - An amendment to the study protocol is pending

PROTOCOL 1 of 2: - No change from prior report

Protocol E01300.1a: approved

Title: Pilot study of the Orthopaedic Training and Rehabilitation System (ORToS) in healthy volunteers

Target required for clinical significance: N/A (this is an initial study in healthy volunteers that will be conducted to verify the performance of the ORToS system that will be fabricated for the clinical study to be conducted in this project.

Target approved for clinical significance: 5 (amended application pending)

SUBMITTED TO AND APPROVED BY:

- Submitted to the University of Utah IRB, 6/10/2020; IRB_00133885
- Approved 16 JUL 2020

STATUS:

(i) Number of subjects recruited/originally planned target: 5/5
Number of subjects screened/originally planned target: 5/5
Number of patients enrolled/original planned target:5/5
Number of patients completed/originally planned target: 0/5

(ii) Report amendments submitted to the IRB and USAMRMC HRPO for review:

The continuing Review application for this protocol has been submitted to the University of Utah IRB. The CR application has been reviewed and approved. The approval letter was submitted to the HRPO via the ebrp.org portal.

(iii) Adverse event/unanticipated problems involving risks to subjects or others and actions or mitigation plans:

Nothing to Report

PROTOCOL 2 of 2: An amendment to the study protocol is pending

Protocol E01300.2a: An amendment requesting the change in the randomization pattern has been submitted to the University of Utah IRB. This change will allow us to start enrolling subjects while the development and testing of the asynchronous data transfer software are in progress.

Title: Orthopaedic Rehabilitation Training System (ORToS) for Rehabilitation Monitoring and Feedback in Bimalleolar Fracture Patients

University of Utah IRB Protocol number: IRB_00138934

SUBMITTED TO AND APPROVED BY:

- Submitted to the University of Utah IRB; expiration date: 02/09/2022, IRB_00138934
- Submitted for HRPO approval
    - Award Management Human Use Documents BA170194

STATUS:

- The Continuing Review application was submitted to the University of Utah IRB on DEC 15, 2021. The CR approval documentation will be submitted to HRPO after the UofU IRB approval has been received.
- IRB CR numberR_12/15/2021 7:42 AM Continuing Review, IRB_00138934 Orthopaedic Rehabilitation Training System (ORToS) for Rehabilitation Monitoring and Feedback in Bimalleolar Fracture Patients

(iii) Adverse event/unanticipated problems involving risks to subjects or others and actions or mitigation plans:

Nothing to Report

(b) Use of Human Cadavers for Research Development Test & Evaluation (RDT&E), Education or Training – Not Applicable

TOTAL ACTIVITIES*:*

Not Applicable

ACTIVITIES:

TOTAL ACTIVITIES: not applicable

ACTIVITES: *not applicable*

(c) Animal Use Regulatory Protocols – Not applicable
TOTAL PROTOCOL(S): 0
PROTOCOL(S): not applicable
Protocol (_of_total): 0/0
Submitted to and Approved by: not applicable
Status: not applicable

TOTAL PROTOCOL(S): 0/0

PROTOCOL (_ of _ total): 0/0
Protocol [ACURO Assigned Number]:
Title:
Target required for statistical significance:
Target approved for statistical significance:

SUBMITTED TO AND APPROVED BY: 0/0
STATUS: NOT APPLICABLE

What do you plan to do during the next reporting period to accomplish the goals and objectives?

During the next reporting period:

1. Finalize App asynchronuous data communication and back-end calculation software
2. Complete insole error root cause analysis and CAPA
3. Initiate patient enrollment into the synchrounous data collection arm of the clinical study.
4. Continue patent and literature update
5. Continue project administration and management.

2. Products: List any products resulting from the project during the reporting period. If there are no products to report for the current quarter, state "Nothing to report."

Preliminary results have been presented at the ICAMPAM Conference:

North, K et al., Determining Clinically Relevant Gait Parameters Measured from Load Monitoring Insole Worn During Tibial Fracture Rehabilitation Using Fuzzy Inference Systems, ICAMPAM 2022, Jun 2022, Keystone Co.

3. Participants & Other Collaborating Organizations

What individuals have worked on the project?
Provide the following information for (1) Project Directors (PDs)/ PIs; and (2) each person who has worked at least one-person month per year on the project during the reporting period, regardless of the source of compensation (a person month equals approximately 160 hours of effort).

1. Tomasz Petelenz, PhD, Project PI
   Contribution: Pilot study protocol submission to the UU IRB and HRPO, overall project planning and management, engineering management of electronic components, FLEx system design modifications.
2. Robert Hitchcock, PhD, Co-PI
   Contribution: Engineering management of mechanical components design and fabrication, personnel hiring
3. Kylee North Graduate Student
4. Contribution: design, literature studies, data analysis, managing undergraduate research assistants, identifying software developers and coordinating App development process.
5. Jim Agutter Project Investigator
   Contribution: directing the design of the feedback system, identification
6. Austin Whiteley Student Research Assistant
   Contribution: 3d modeling of insole component in Solid Works and Fusion360; parts fabrication and assembly.
7. Grange Simpson Undergraduate Assistant – electronic testing and embedded software development
8. Undergraduate students Assembly and testing tasks,

4. Changes/Problems: The PD/PI is reminded that the recipient organization is required to obtain prior written approval from the awarding agency Grants Officer whenever there are significant changes in the project or its direction. If not previously reported in writing, provide the following

a. Actual Problems or delays and actions to resolve them

During the current reporting period the project encountered difficulties that delayed the completion of engineering tasks and the clinical feasibility studies. The problems encountered included:

- Supply chain issues continue, resulting in delays in component shipments and the unavailability of parts.
- COVID-19 restrictions limited the laboratory in-person work for students which delayed progress

b. Anticipated Problems/Issues

1. We anticipate that the supply chain problems causing further delays in the availability of components will continue.
2. Due to continuing issues with MSP430 firmware and incompatibilities with the newer generation BLE (BT ver 5) hardware, we are migrating the IM firmware to new, higher performance alternative, as described in the prior sections of this report.

5. Special Reporting Requirements:

Quad Charts: The Quad Chart (available on https://www.usamraa.army.mil) has been and submitted with attachments.

6. Attachments

Updated Quad Chart.
A pdf copy of the poster presentation.

Determining Clinically Relevant Gait Parameters Measured from Load Monitoring Insole Worn During Tibial Fracture Rehabilitation Using Fuzzy Inference Systems

Kylee North[1], Grange Simpson[1], Amy Cizik[2], Robert Hitchcock[1]

[1]Department of Bioengineering, [2]Orthopeadic Trauma, University of Utah, Salt Lake City, UT 84112

INTRODUCTION

Despite lower extremity fractures being common injuries that affect all demographics, little is known about how patient weight-bearing behavior during rehabilitation contributes to long term outcomes. Using wearable sensors for longitudinal monitoring of patient weight-bearing behavior would allow clinicians to develop data driven rehabilitation protocols. The objective of this study was to categorize gait parameters measured from an underfoot load monitoring insole (Fig 1) during lower extremity fracture rehabilitation based on the parameters which separated patients who healed well compared to those who did not using Fuzzy Inferences System (FIS).

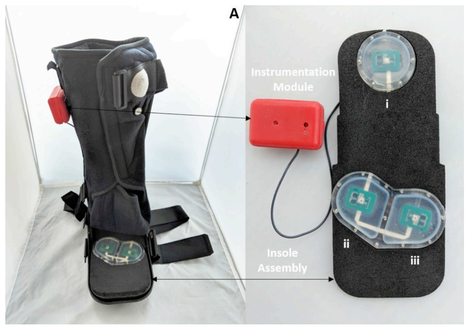


Figure 1. Underfoot Load Monitoring System. Contains 3 sensors in locations of peak underfoot loading; heel, medial forefoot and lateral forefoot. Instrumentation module contains battery power, a microprocessor, and data storage. No battery change is needed for up to 12 weeks[1,2].

METHODS

Patients with closed tibial fractures or bimalleolar ankle fractures were recruited prior to surgery in this IRB approved 3-year observational study. An underfoot load monitoring insole continuously recorded patient weight bearing until the physician prescribed the boot cast to be discontinued, see Figure 1. A custom code was developed to extract peak loads from the longitudinal underfoot load

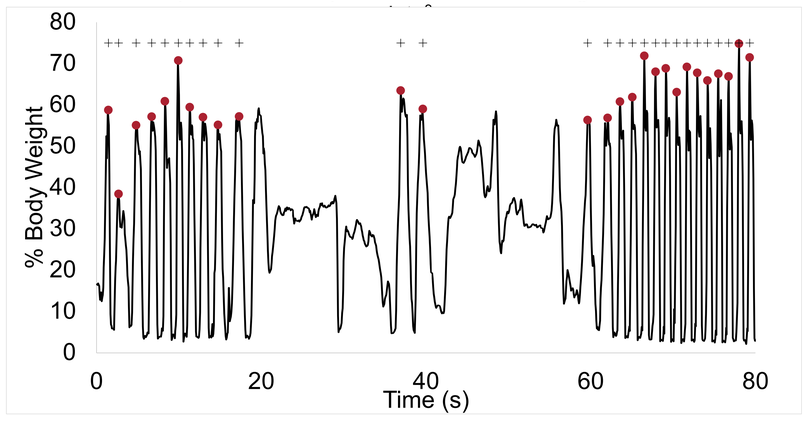


Figure 2. Example of underfoot waveform and points on waveform that were used to calculate patient weight-bearing parameters. Red circle = peak loading per step, + = step timing used to calculate cadence and walking time.

The code was modified to extract more parameters that describe patient weight-bearing behavior over time. The window of time that had the most sensor data was the first 4 weeks of wearing the boot cast. 22 parameters were averaged by week and 5 other parameters were calculated that describe overall patient behavior for a total of 93 unique parameters.

Patients were grouped into two groups based on 1 year physical function outcome score: Excellent Outcomes, and Average Outcomes. A FIS was developed to rank parameters based on their ability to differentiate between excellent and good long term outcome groups. The two input criteria were 1. Average two-tailed patient t-test P-value for the set, 2. number of significant P-Values ($p < 0.03$) in the set.

RESULTS

Of the 42 patients enrolled, 17 had both 1 year physical function outcome score and continuous insole data (33.7 ±14.5 y/o, 60% female, and 93% white). 9 patients had Average Outcomes, 8 had Excellent Outcomes. The FIS revealed that gait parameters related to number of footsteps, especially at later time windows, differentiated the two outcome groups the best. Walking time moderately differentiated the two groups, and mean of all loading, cadence, static loading, and distribution statistics parameters variables did not have strong differentiation between the two groups.

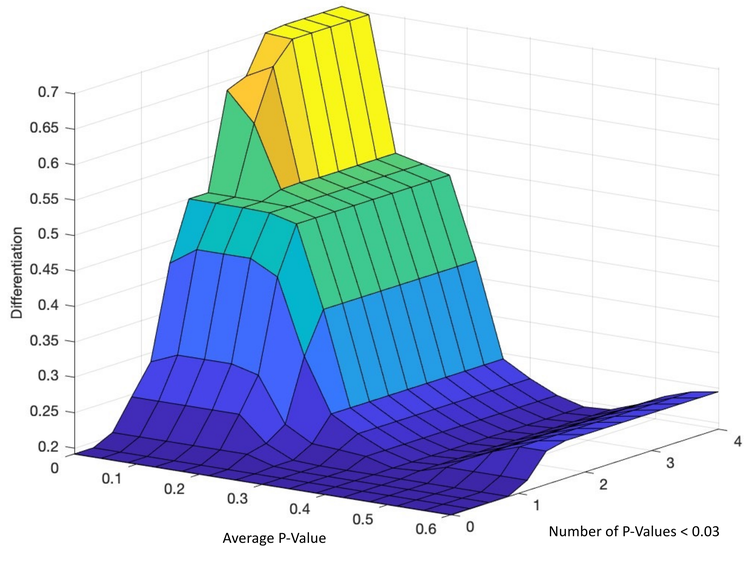
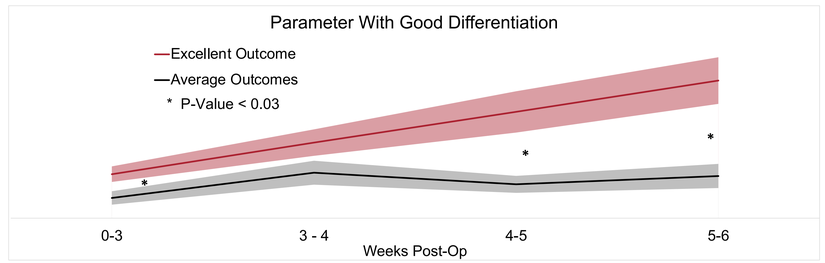
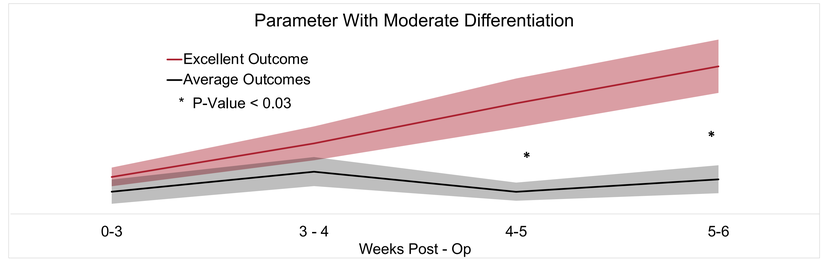


Figure 3. Resulting surface map from Fuzzy Inference System. As Average P-Value decreases and Number of P-Values < 0.03, the ability of the parameter to differentiate data improves.





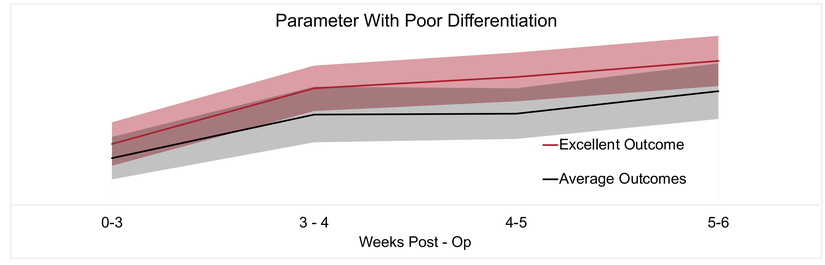


Figure 4. Examples of parameters FIS was able to successfully rank based on ability to differentiate between patient outcome groups.

CONCLUSION

FIS proved to be a powerful tool for automated gait parameter classification due to their ease of implementation, adaptability, and having graphical inputs that are intuitive for clinicians to understand and optimize. While this FIS was implemented on a pilot study with a small patient size, it produced important preliminary results of what gait patterns to focus on when designing future clinical trials with larger number of participants. As patient monitoring using wearable sensors becomes more common, knowing what gait parameters to measure will be critical for informing clinical care.

References:

1. North K, et al. Longitudinal monitoring of patient limb loading throughout ankle fracture rehabilitation using an insole load monitoring system: a case series. Current Orthopaedic Practice. 2017;28(2)
2. Lajevardi-Khosh A, et al. Characterization of compliance to weight-bearing protocols and patient weight-bearing behavior during the recovery period in lower extremity fractures: a pilot study. Current Orthopaedic Practice. 2019 Jul 1;30(4):395-402.
3. Lajevardi-Khosh A, et al. Development of a step counting algorithm using the ambulatory tibia load analysis system for tibia fracture patients. Journal of Rehabilitation and Assistive Technologies Engineering. 2018

This work was sponsored by CDMRP W81XWH1220089 & CDMRP W81XWH2010266

Quarterly Technical Progress Report

Award Number:	W81XWH2010266
Log Number:	BA170194
Project Title:	**Orthopaedic Rehabilitation Training System (ORToS) for Improved Patient Compliance and Rehabilitation Monitoring in Lower Extremity Trauma**
Principal Investigator Name:	Tomasz Petelenz, PhD
Principal Investigator Organization and Address:	UNIVERSITY OF UTAH, THE 201 PRESIDENTS CIR SALT LAKE CITY UT 84112-9049
Principal Investigator Phone and Email:	801-585-1804; email: tomasz.petelenz@utah.edu
Report Date:	14 JUL 2022
Report Period:	15 APR 2022 – 14 JUL 2022

1. Accomplishments:

What were the major goals of the project?

Major goals of the project are divided into Technical Objective 1 and 2. Only relevant Major Tasks and Subtasks that are relevant to the reported stage of the project are listed here.

TO 1 - Fabrication and validation of the ORToS system for use in clinical study; months 1-14
MT1.2. Fabrication process scale-up and validation; Months 1-10
TO 2 – Clinical study to determine the role; months 11-24
MT2.1. Study protocols, IRB review and approval; months 3-6
ST 2.1.1. IRB approval; months 6-8
MT2.2 Clinical Study
ST 2.2.1. Subject recruitment
ST 2.2.2. Data collection
ST 2.2.3. Data analysis and dissemination
MT 3. Sustaining engineering
MT 4. Project management; months 1-24

What was accomplished under these goals?
TO 1; MT 2.1., **MT3**

1. Fabrication of ATLAS to use in the clinical study:
    a. Fabrication of insole components for clinical study devices continued
    b. Occasional sensor failures still occurred.
        i. CAPA root cause analysis revealed frequent insole interconnections failures, corrected by replacing the interconnecting cables. Subsequent assemblies confirmed the quality of new interconnects
        ii. Wire bond failures at the junction between ceramic boards and ZSC31014. CPA is in progress. Initial analysis points to the aging of ceramic board thick film traces. Mitigation includes inspection and cleaning of wirebond pads; it is in progress, and current results appear promising.

2. IM enclosure (housing), IM electronic PCB, and battery
    a. The new IM enclosure has been completed
    b. New higher capacity Li-ion battery replacement has been completed
    c. Figure 1 shows the new IM housing attached to the CAMWalker boot and case details.

3. New IM electronics (Figure 2).
    a. The IM electronics has been migrated to a new microcontroller platform. The reason for updating the microcontroller platform was due to the inability to implement the asynchronous data collection with simultaneous BlueTooth on the legacy MSP4305528 microcontroller.
    b. The new microcontroller, nRF52840, is an ARM Cortex M4 processor with high performance, very low power floating point, 64MHz CPU, integrated BlueTooth wireless communication module, and a large number of integrated data processing and communication functions. The new microcontroller allows faster data acquisition (potentially between 250 and 300 Hz from a 3-sensor assembly) and uses a micropython programming environment.
    c. The legacy IM firmware has been migrated to the new device using the XIAO Seeeduino evaluation system.
    d. Testing of the new electronics is pending.
    e. Concurrently, the new microcontroller circuitry was developed and will be implemented using a PCB with the same form factor as the legacy IM PCB. (Figure 3.)

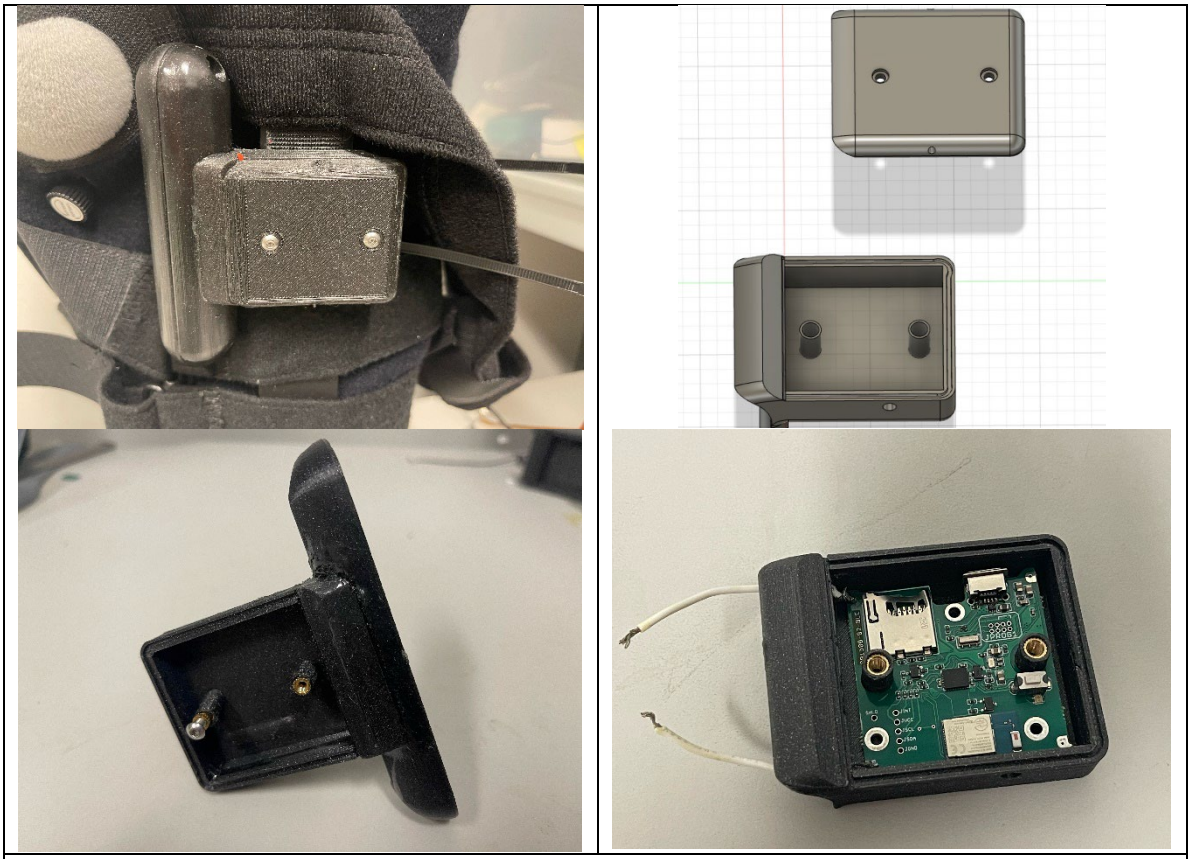


Figure 1. IM enclosure:
Top left: IM assembly attached to the CAMWalker boot
Top right: IM electronics section of the enclosure
Bottom left: IM cover with the battery enclosure section
Bottom right: IM electronics inside the enclosure (before the battery enclosure section has been attached.)

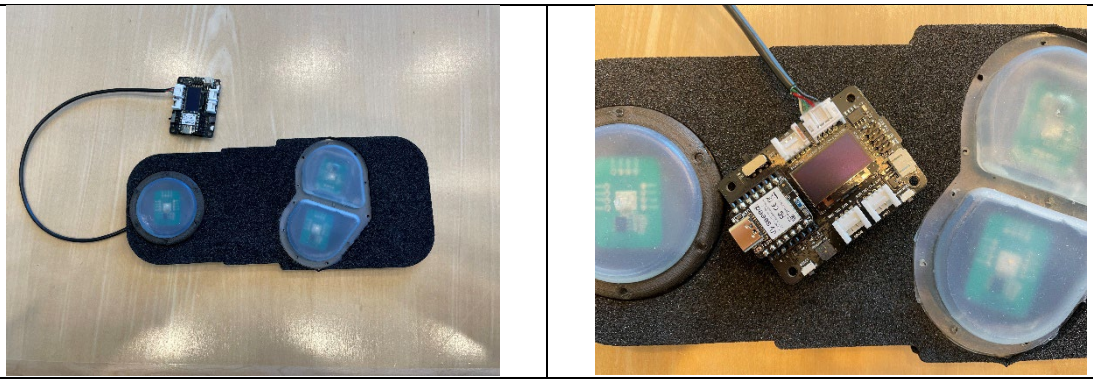


Figure 2. ORToS CAMWalker boot insole with the nRF52840 microcontroller evaluation assembly.

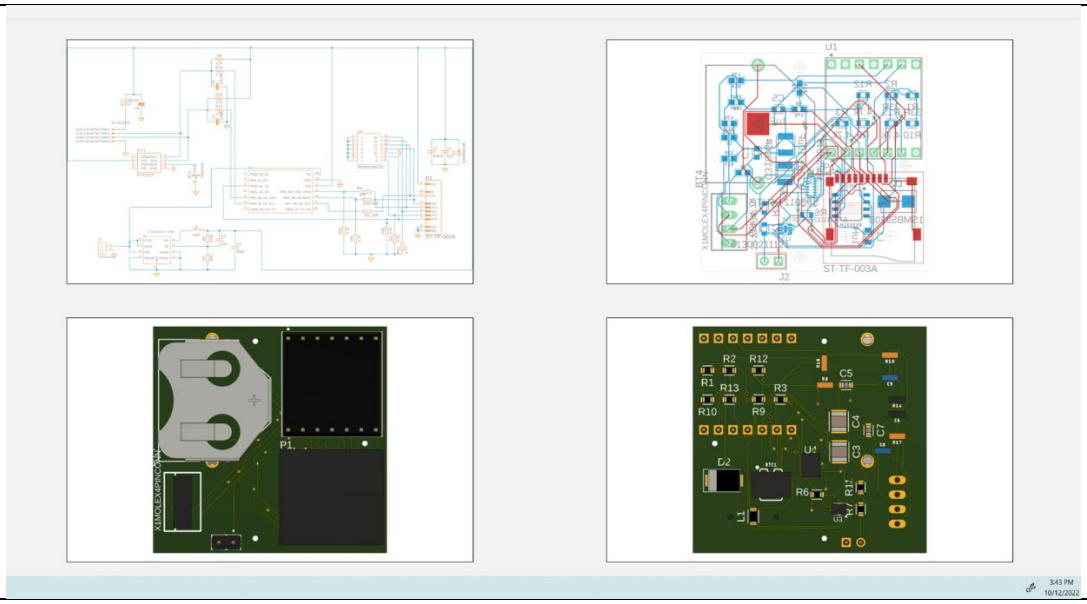


Figure 3. New IM PCB:
Top left – Schematic diagram
Top right: PCB layout (copper traces, top, and bottom superimposed)
Bottom left: IM PCB CAD rendition (top side)
Bottom right> IM PCB CAD rendition (Bottom side)
The dimensions of the PCB are approx. 40 mm x 40 mm.

TO 2; MT 2.2

1. Clinical study
   a. 5-subject device feasibility study.
      The 5-subject feasibility study data collection was completed using the new Android synchronous software package developed during this project.
   b. Data analysis of the 5 subject study. Figure 4 shows an example of underfoot load measurement data obtained in five trials in healthy subjects. Each graph consists of 4 segments, representing an overall data sequence during the trial, load bearing graphs for 25%, 50%, 75%, and 100% (full load bearing) weight bearing, and the bottom chart illustrates the results recorded by the App and on the IM SD card of the ORTOS system.

   c. Clinical study in patients with fractures.
      The IRB Continuing Review application was approved on January 22, 2022, by the University of Utah IRB. The CR approval documentation has been submitted to the HRPO. An amendment for protocol correction, allowing for separate synchronous and asynchronous data collection, is pending at the University of Utah IRB, and the approval will be submitted to the HRPO.

   d. Enrollment. The enrollment of patients with lower extremity fractures has been delayed due to app development delays and is planned to start in November 2022.

4. Biofeedback.

Biofeedback software development continued. As reported previously, biofeedback software includes a biofeedback App and backend software for data transfer. The work included:

   a. Continued development of the Graphical User Interface and App development focused on finalizing data transfer from the IM to the App.

   b. Synchronous data transfer software was completed and successfully tested in the 5-person trial.

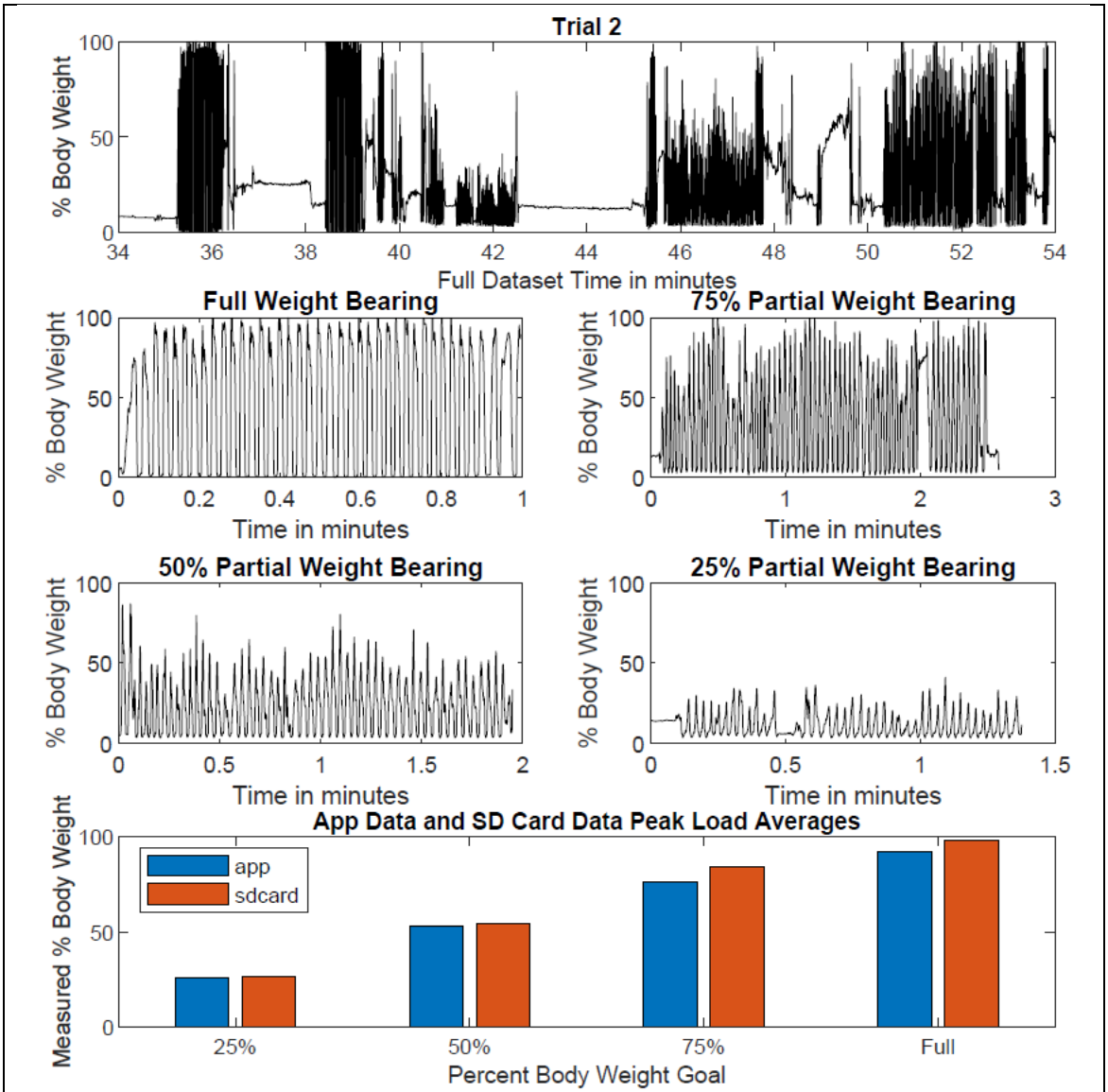


Figure 4. Example of data from the 5-person (healthy volunteers) study.
Top panel: racorded raw data segment
Middle panel (2 sections): example of data record at 25%, 50%, 75% and 100% weight bearing
Bottom panels: Comparison of data recorded in the IM SD card and using the Android software.

MT 4. Administrative tasks

1. Administrative tasks are continued.
2. Project management
    a. Team meetings have been conducted 1x per week. As the COVID-19 restriction abate, meetings are now being conducted in person.

    b. Weekly team meetings will continue in the next reporting period.

Describe the Regulatory Protocol and Activity Status (if applicable).

A Continuing Review (CR) application was submitted to the University of Utah IRB. After the review has been completed, updated study documents will be submitted to the HRPO.
There are no changes to report with this report.

(a) ***Human Use Regulatory Protocols***

TOTAL PROTOCOLS:

The ORToS project will include 2 study protocols:

- Protocol 1 – Pilot Study in volunteers protocol, HRPO assigned number E01300.1a
- Protocol 2 – Clinical study protocol, HRPO assigned number E01300.2a
    - The clinical study design has been completed.
        - The study has been approved by the HRPO.

PROTOCOL(S):

Protocol 1 of 2:

Protocol E01300.1a:

Title: Pilot study of the Orthopaedic Training and Rehabilitation System (ORToS) in healthy volunteers

Target required for clinical significance: - N/A – This is a pilot study design for the initial form-and-fit evaluation of the devices to be used in the clinical study.

Target approved for clinical significance:

Submitted to and Approved by:

The University of Utah IRB, Protocol number: IRB_00133885

Status:

Due to engineering development delays, enrollment has not started. We plan to start enrollment in the next reporting period.

TOTAL PROTOCOLS: 2 - An amendment to the study protocol is pending

PROTOCOL 1 of 2: - No change from a prior report

Protocol E01300.1a: Approved

Title: Pilot study of the Orthopaedic Training and Rehabilitation System (ORToS) in healthy volunteers

Target required for clinical significance: N/A (this is an initial study in healthy volunteers that will be conducted to verify the performance of the ORToS system that will be fabricated for the clinical study to be conducted in this project.

Target approved for clinical significance: 5 (amended application pending)

SUBMITTED TO AND APPROVED BY:

- Continuing review application has been submitted to the University of Utah IRB (CR_5/18/2022)
- Approved 7 JUN 2023 (exp.date: 50 MAY 2023)

STATUS:

(i) Number of subjects recruited/originally planned target: 5/5
Number of subjects screened/originally planned target: 5/5
Number of patients enrolled/original planned target:5/5
Number of patients completed/originally planned target: 0/5

(ii) Report amendments submitted to the IRB and USAMRMC HRPO for review:

The Continuing Review application for this protocol has been submitted to the University of Utah IRB. The CR application has been reviewed and approved. The approval letter was submitted to the HRPO via the ebrp.org portal.

(iii) Adverse event/unanticipated problems involving risks to subjects or others and actions or mitigation plans:

Nothing to Report

PROTOCOL 2 of 2: An amendment to the study protocol has been approved

Protocol E01300.2a: An amendment requesting the change in the randomization pattern has been approved by the University of Utah IRB. This change will allow us to start enrolling subjects while the development and testing of the asynchronous data transfer software are in progress.

Title: Orthopaedic Rehabilitation Training System (ORToS) for Rehabilitation Monitoring and Feedback in Bimalleolar Fracture Patients

University of Utah IRB Protocol number: IRB_00138934, Amendment number: AM_00045253.

From: irb@hsc.utah.edu
To: Tomasz J Petelenz
Cc: Kylee North; Sophia Hill; Ashley Neese; MICHAEL MILLER; Morgan Dauk
Subject: ERICA IRB Notification: Amendment Outcome
Date: Tuesday, August 9, 2022 5:10:18 PM

IRB: IRB_00138934

Responsible Investigator: Tomasz Petelenz

Title: Orthopaedic Rehabilitation Training System (ORToS) for Rehabilitation Monitoring and Feedback in Bimalleolar Fracture Patients

Date: 8/9/2022

FWA Designation: Federal Oversight

This Amendment Application (Randomization change) has been reviewed and approved by a University of Utah IRB convened board. The convened board approved your amendment request for this study on 8/9/2022. The amendment approval is effective as of 8/9/2022. The approval of this amendment request does NOT change the expiration date of this research study as noted below.

Your study will expire on 1/21/2023.
Any future changes to this study must be submitted to the IRB prior to initiation via an amendment form.

DOCUMENTS

Informed Consent Document
IRB#138934_ORTOS_ICF v.07.21.2022_clean.docx

Click AM_00045253 to view the application and access the approved documents.

Please take a moment to complete our customer service survey. We appreciate your opinions and feedback.

Figure 4. IRB Amendment approval letter.

SUBMITTED TO AND APPROVED BY:

- Submitted to the University of Utah IRB; expiration date: 02/09/2022, IRB_00138934
- Submitted for HRPO approval
    - Award Management Human Use Documents BA170194

STATUS:

- No change.
- Continuing review application will be submitted in DEC 2022

(iii) Adverse event/unanticipated problems involving risks to subjects or others and actions or mitigation plans:

Nothing to Report

(b) Use of Human Cadavers for Research Development Test & Evaluation (RDT&E), Education or Training – Not Applicable

***TOTAL ACTIVITIES**:*

Not Applicable

***ACTIVITIES**:*

***TOTAL ACTIVITIES**: not applicable*

***ACTIVITES**: not applicable*

(c) Animal Use Regulatory Protocols – Not applicable

TOTAL PROTOCOL(S): 0

PROTOCOL(S): not applicable

Protocol (_ of _ total): 0/0

Submitted to and Approved by: not applicable

Status: not applicable

TOTAL PROTOCOL(S): 0/0

PROTOCOL (_ of _ total): 0/0

Protocol [ACURO Assigned Number]:

Title:

Target required for statistical significance:

Target approved for statistical significance:

SUBMITTED TO AND APPROVED BY: 0/0

STATUS: NOT APPLICABLE

What do you plan to do during the next reporting period to accomplish the goals and objectives?

During the next reporting period:

1. Finalize App asynchronuous data communication and back-end calculation software
2. Complete insole error root cause analysis and CAPA
3. Initiate patient enrollment into the synchrounous data collection arm of the clinical study.
4. Continue patent and literature update
5. Continue project administration and management.

2. Products: List any products resulting from the project during the reporting period. If there are no products to report for the current quarter, state "Nothing to report."

Nothing to report.

3. Participants & Other Collaborating Organizations

What individuals have worked on the project?
Provide the following information for (1) Project Directors (PDs)/ PIs; and (2) each person who has worked at least one-person month per year on the project during the reporting period, regardless of the source of compensation (a person month equals approximately 160 hours of effort).

1. Tomasz Petelenz, PhD, Project PI
Contribution: Pilot study protocol submission to the UU IRB and HRPO, overall project planning and management, engineering management of electronic components, FLEx system design modifications.
2. Robert Hitchcock, PhD, Co-PI
Contribution: Engineering management of mechanical components design and fabrication, personnel hiring
3. Kylee North Graduate Student
4. Contribution: design, literature studies, data analysis, managing undergraduate research assistants, identifying software developers and coordinating App development process.
5. Jim Agutter Project Investigator
Contribution: directing the design of the feedback system, identification
6. Austin Whiteley Student Research Assistant
Contribution: 3d modeling of insole component in Solid Works and Fusion360; parts fabrication and assembly.
7. Grange Simpson Undergraduate Assistant – electronic testing and embedded software development
8. Undergraduate students Assembly and testing tasks

following

a. Actual Problems or delays and actions to resolve them

During the current reporting period the project encountered difficulties that delayed the completion of engineering tasks and the clinical feasibility studies. The problems encountered included:

- Supply chain issues continue, resulting in delays in component shipments and the unavailability of parts.
- COVID-19 restrictions and infections have again limited the laboratory in-person work for students which delayed progress. Currently, the lab is fully operational.

b. Anticipated Problems/Issues

1. We anticipate that the supply chain problems causing further delays in the availability of components will continue.

5. Special Reporting Requirements:

Quad Charts: The Quad Chart (available on https://www.usamraa.army.mil) has been submitted with attachments.

6. Attachments

Updated Quad Chart.

Quarterly Technical Progress Report

Award Number:	W81XWH2010266
Log Number:	BA170194
Project Title:	**Orthopaedic Rehabilitation Training System (ORToS) for Improved Patient Compliance and Rehabilitation Monitoring in Lower Extremity Trauma**
Principal Investigator Name:	Tomasz Petelenz, PhD
Principal Investigator Organization and Address:	UNIVERSITY OF UTAH, THE 201 PRESIDENTS CIR SALT LAKE CITY UT 84112-9049
Principal Investigator Phone and Email:	801-585-1804; email: tomasz.petelenz@utah.edu
Report Date:	14 JAN 2023
Report Period:	15 OCT 2022 – 14 JAN 2023

1. Accomplishments:

What were the major goals of the project?

Major goals of the project are divided into Technical Objective 1 and 2. Only relevant Major Tasks and Subtasks that are relevant to the reported stage of the project are listed here.

TO 1 - Fabrication and validation of the ORToS system for use in clinical study; months 1-14
MT1.2. Fabrication process scale-up and validation; Months 1-10
TO 2 – Clinical study to determine the role; months 11-24
MT2.1. Study protocols, IRB review and approval; months 3-6
ST 2.1.1. IRB approval; months 6-8
MT2.2 Clinical Study
ST 2.2.1. Subject recruitment
ST 2.2.2. Data collection
ST 2.2.3. Data analysis and dissemination
MT 3. Sustaining engineering
MT 4. Project management; months 1-24

What was accomplished under these goals?
TO 1; MT 2.1., MT3

1. Fabrication of the ORToS system to use in the clinical study:
    a. Fabrication of insole components for clinical study devices continued (Figure 1)
    b. Five complete sensor systems are available for the study. Insoles for individual subject will be completed upon subjects' enrollment.
    c. Insole completion process:
        i. After the subject signs the ICF and is enrolled into the study, his/her foot measurements are collected using a Brannock device.
        ii. The insole is custom made for the subject and delivered the clinic.

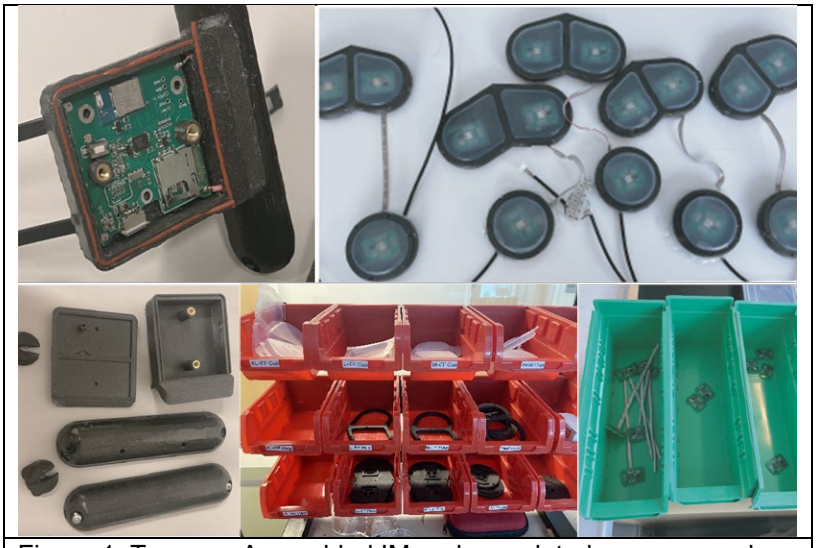


Figure 1. Top row: Assembled IM and completed sensors ready for inserting into custom-made subject insoles.
Bottom row: IM components, insole mechanical and electronic compoenets ready for assembly.

2. Biofeedback.
Biofeedback software development continued. Nothing to report at this time.

MT 4. Administrative tasks

1. Administrative tasks are continued.
2. Project management
    a. Team meetings have been conducted 1x per week with the exception of the University closure and Holiday period.
    b. Weekly team meetings will continue in the next reporting period.

Describe the Regulatory Protocol and Activity Status (if applicable).

A Continuing Review (CR) application was submitted to the University of Utah IRB. After the review has been completed, updated study documents will be submitted to the HRPO.
There are no changes to report with this report.

(a) ***Human Use Regulatory Protocols***

TOTAL PROTOCOLS:

The ORToS project will include 2 study protocols:

- Protocol 1 – Pilot Study in volunteers protocol, HRPO assigned number E01300.1a
- Protocol 2 – Clinical study protocol, HRPO assigned number E01300.2a
    - The clinical study design has been completed.
        - The study has been approved by the HRPO.

PROTOCOL(S):

Protocol 1 of 2:

Protocol E01300.1a:

Title: Pilot study of the Orthopaedic Training and Rehabilitation System (ORToS) in healthy volunteers

Target required for clinical significance: - N/A – This is a pilot study design for the initial form-and-fit evaluation of the devices to be used in the clinical study.

Target approved for clinical significance:

Submitted to and Approved by:

The University of Utah IRB, Protocol number: IRB_00133885

Status:

Due to engineering development delays, enrollment has not started. We plan to start enrollment in the next reporting period.

TOTAL PROTOCOLS: 2 - has been approved by the University of Utah IRB and by the HRPO

PROTOCOL 1 of 2: - No change from a prior report

Protocol E01300.1a: Approved

Title: Pilot study of the Orthopaedic Training and Rehabilitation System (ORToS) in healthy volunteers

Target required for clinical significance: N/A (this is an initial study in healthy volunteers that will be conducted to verify the performance of the ORToS system that will be fabricated for the clinical study to be conducted in this project.

Target approved for clinical significance: 5 (amended application pending)

SUBMITTED TO AND APPROVED BY:

- Continuing review application has been submitted to the University of Utah IRB (CR_5/18/2022)
- Approved 7 JUN 2023 (exp.date: 50 MAY 2023)

STATUS:

(i) Number of subjects recruited/originally planned target: 5/5
Number of subjects screened/originally planned target: 5/5
Number of patients enrolled/original planned target:5/5
Number of patients completed/originally planned target: 5/5

(ii) Report amendments submitted to the IRB and USAMRMC HRPO for review:

The Continuing Review application for this protocol has been submitted to the University of Utah IRB. The CR application has been reviewed and approved. The approval letter was submitted to the HRPO via the ebrp.org portal.

(iii) Adverse event/unanticipated problems involving risks to subjects or others and actions or mitigation plans:

Nothing to Report

PROTOCOL 2 of 2: Continuing Review of the study has been completed and approved.

Protocol E01300.2a: Continuing Review has been completed by the University of Utah IRB. The study has been approved through 28 DEC 2023.

Title: Orthopaedic Rehabilitation Training System (ORToS) for Rehabilitation Monitoring and Feedback in Bimalleolar Fracture Patients

The University of Utah IRB Protocol number: IRB_00138934.

IRB: IRB_00138934

Responsible Investigator: Tomasz Petelenz

Title: Orthopaedic Rehabilitation Training System (ORToS) for Rehabilitation Monitoring and Feedback in Bimalleolar Fracture Patients

CR: CR_12/15/2022 9:26 AM

Date: 1/3/2023

Effective 1/3/2023, the above-referenced Continuing Review with Amendment is approved to continue research procedures outlined in the University of Utah IRB-approved application and documents.

APPROVAL DOCUMENTATION

Review Type: Expedited Review

Expedited Categories: Category 8(b)

Risk Level: Minimal

Approval Date: 12/29/2022

Expiration Date: 12/28/2023

FWA Designation: Federal Oversight

APPROVED DOCUMENTS

Informed Consent Document
IRB#138934_ORTOS_ICF v.07.21.2022_clean.docx

Grant Application
BA170194_ProjectNArrative_17-08-28.pdf

ONGOING SUBMISSIONS FOR APPROVED PROJECTS

Continuing Review: The research protocol must be re-reviewed and re-approved prior to the expiration date via the continuing review application: http://irb.utah.edu/submit-application/reviews/index.php

Amendment Applications: All changes to the research application, protocol, or approved documents must be submitted and approved prior to initiation: http://irb.utah.edu/submit-application/amendments.php

Report Forms: The research must adhere to the University of Utah IRB reporting requirements for unanticipated problems and deviations: http://irb.utah.edu/submit-application/forms/index.php

Final Project Reports for Study Closure: The research application must be closed with the IRB once the research activities are complete: http://irb.utah.edu/submit-application/final-project-reports.php

Click CR_00046212 to view the application and access the approved documents.

Please take a moment to complete our customer service survey. We appreciate your opinions and feedback.

Figure 4. IRB CR approval letter.

SUBMITTED TO AND APPROVED BY:

- Submitted to the University of Utah IRB; expiration date: 12/28/2023, IRB_00138934
- Submitted for HRPO approval
    - Award Management Human Use Documents BA170194

STATUS:

- No change.
- Continuing review application will be submitted in DEC 2023

(iii) Adverse event/unanticipated problems involving risks to subjects or others and actions or mitigation plans:

Nothing to Report

(b) Use of Human Cadavers for Research Development Test & Evaluation (RDT&E), Education or Training – Not Applicable

TOTAL ACTIVITIES:

Not Applicable

ACTIVITIES:

TOTAL ACTIVITIES: not applicable

ACTIVITES: *not applicable*

(c) Animal Use Regulatory Protocols – Not applicable

TOTAL PROTOCOL(S): 0

PROTOCOL(S): not applicable

Protocol (_ of _ total): 0/0

Submitted to and Approved by: not applicable

Status: not applicable

TOTAL PROTOCOL(S): 0/0

PROTOCOL (_ of _ total): 0/0

Protocol [ACURO Assigned Number]:

Title:

Target required for statistical significance:

Target approved for statistical significance:

SUBMITTED TO AND APPROVED BY: 0/0

STATUS: NOT APPLICABLE

What do you plan to do during the next reporting period to accomplish the goals and objectives?

During the next reporting period:

1. Complete App asynchronuous data communication and back-end calculation software
2. Continue subject enrollment
3. Continue fabrication of devices for the study
4. Continue data collection and study management.
5. Prepare abstracts for submission to MHSRS
6. Continue patent and literature update
7. Continue project administration and management.
    a. Due to the delays in starting the clinical study, we anticipate the need to apply for a No Cost Extension to finish the clinical study.
    b. During the NCE, we are plnning to participate in the MHSRS if the project submission is accepted.

2. Products: List any products resulting from the project during the reporting period. If there are no products to report for the current quarter, state "Nothing to report."

Nothing to report.

3. Participants & Other Collaborating Organizations

What individuals have worked on the project?

Provide the following information for (1) Project Directors (PDs)/ PIs; and (2) each person who has worked at least one-person month per year on the project during the reporting period, regardless of the source of compensation (a person month equals approximately 160 hours of effort).

1. Tomasz Petelenz, PhD, Project PI
Contribution: Pilot study protocol submission to the UU IRB and HRPO, overall project planning and management, engineering management of electronic components, FLEx system design modifications.
2. Robert Hitchcock, PhD, Co-PI
Contribution: Engineering management of mechanical components design and fabrication, personnel hiring
3. Kylee North Graduate Student
Contribution: design, literature studies, data analysis, managing undergraduate research assistants, identifying software developers and coordinating App development process.
4. Austin Whiteley Student Research Assistant
Contribution: 3d modeling of insole component in Solid Works and Fusion360; parts fabrication and assembly.
5. Grange Simpson Undergraduate Assistant – electronic testing and embedded software development
6. Undergraduate students Assembly and testing tasks

4. Changes/Problems: The PD/PI is reminded that the recipient organization is required to obtain prior written approval from the awarding agency Grants Officer whenever there are significant changes in the project or its direction. If not previously reported in writing, provide the following

a. Actual Problems or delays and actions to resolve them

The supply chain issues and delays in ordering/receiving parts continued, although most have been resolved and currently we have a sufficient number of components start the clinical study.

b. Anticipated Problems/Issues

1. We anticipate that some supply chain problems causing further delays in the availability of components will continue.

5. Special Reporting Requirements:

Quad Charts: The Quad Chart (available on https://www.usamraa.army.mil) has been submitted with attachments.

6. Attachments

Updated Quad Chart.

Quarterly Technical Progress Report

Award Number:	W81XWH2010266
Log Number:	BA170194
Project Title:	**Orthopaedic Rehabilitation Training System (ORToS) for Improved Patient Compliance and Rehabilitation Monitoring in Lower Extremity Trauma**
Principal Investigator Name:	Tomasz Petelenz, PhD
Principal Investigator Organization and Address:	UNIVERSITY OF UTAH, THE 201 PRESIDENTS CIR SALT LAKE CITY UT 84112-9049
Principal Investigator Phone and Email:	801-585-1804; email: tomasz.petelenz@utah.edu
Report Date:	14 APR 2023
Report Period:	15 JAN 2023 – 14 APR 2023

1. Accomplishments:

What were the major goals of the project?

Major goals of the project are divided into Technical Objective 1 and 2. Only relevant Major Tasks and Subtasks that are relevant to the reported stage of the project are listed here.

TO 1 - Fabrication and validation of the ORToS system for use in clinical study; months 1-14
MT1.2. Fabrication process scale-up and validation; Months 1-10
TO 2 – Clinical study to determine the role; months 11-24
MT2.1. Study protocols, IRB review and approval; months 3-6
ST 2.1.1. IRB approval; months 6-8
MT2.2 Clinical Study
ST 2.2.1. Subject recruitment
ST 2.2.2. Data collection
ST 2.2.3. Data analysis and dissemination
MT 3. Sustaining engineering
MT 4. Project management; months 1-24

What was accomplished under these goals?
TO 1; MT 2.1., **MT3**

1. Fabrication of the ORToS system to use in the clinical study:
    a. Fabrication of insole components for clinical study devices continued. The insole final assembly is completed after each subject has been enrolled and signed the Informed Consent. At the time, foot measurements are taken using a Brannock device, a CAMWalker boot is selected, and insoles are fabricated. After a 2-week surgery recovery period, subjects return to the clinic for CAMWalker boot fitting and training. At that point, data recording starts, and patients return home.
    b. The flowchart of the study process is shown in Figure 1.

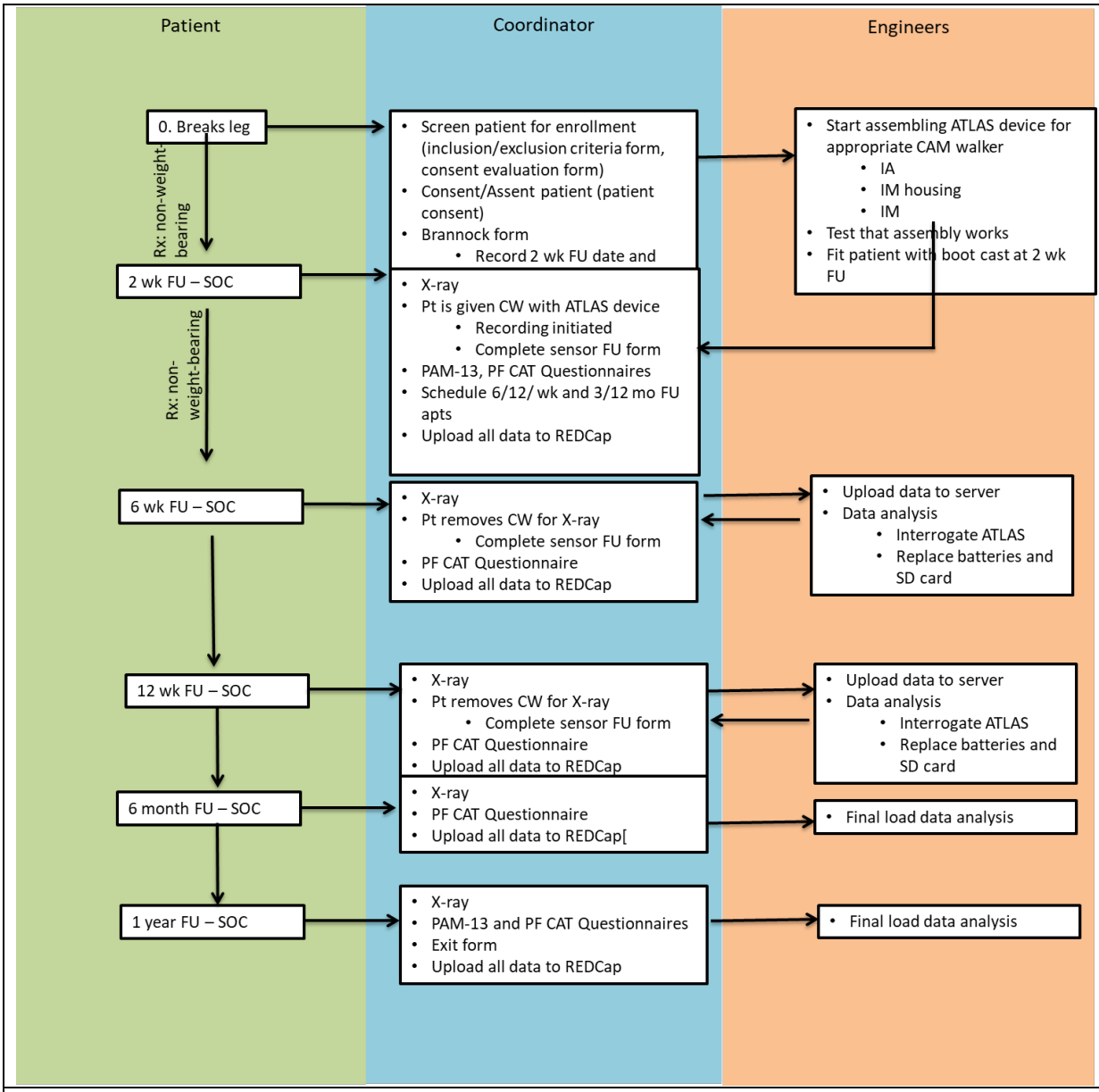


Figure 1. Flowchart of the study procedures.

2. A new recording module based on the Seeed XIAO microcontroller has been completed.
    a. Battery voltage drops were compromising the data collection
    b. Tests were conducted to determine the cause of these faults.
    c. The test data showed that, over time, there was an asynchronous data error.
    d. A new version of code was developed to correct this problem.
    e. Power consumption measurements indicated that the device will need recharging after eight days of use, consistent with charging requirements for other wearable electronics, such as activity monitors.
3. Inventory of parts for the study
    a. Updated inventory for clinical study components and assemblies.
    b. Sufficient components and materials are in place for the clinical study.
    c. Procedural adjustments were made to the BlueTooth communication protocol to preserve battery life.
    d. Tested for the source of excessive battery current draw and implemented a software correction.

4. Engineering development
    a. Three new sensor configurations have been tested
    b. New Merit sensors with ceramic caps have been tested and appear to be functioning very well
        i. Additional dynamic testing will be continued.
    c. If successful, the new sensor will:
        i. Eliminate a critical assembly step in insole fabrication.
        ii. Improved reliability and durability of the insole assembly.
        iii. Significantly lower the cost of each insole.

5. Biofeedback.
   Biofeedback software development continued. The software for asynchronous data recording will be completed and validated during the next development phase.

MT 4. Administrative tasks

1. Administrative tasks are continued.
2. Project management
    a. Team meetings have been conducted 1x per week except for the University closure and Holiday period.
    b. Weekly team meetings will continue in the next reporting period.

Describe the Regulatory Protocol and Activity Status (if applicable).

A Continuing Review (CR) application was submitted to the University of Utah IRB. After the review, updated study documents will be submitted to the HRPO.
There are no changes to report with this report.

(a) ***Human Use Regulatory Protocols***

TOTAL PROTOCOLS:

The ORToS project will include 2 study protocols:

- Protocol 1 – Pilot Study in volunteers protocol, HRPO assigned number E01300.1a
- Protocol 2 – Clinical study protocol, HRPO assigned number E01300.2a
    - The clinical study design has been completed.
        - The study has been approved by the HRPO.

PROTOCOL(S):

Protocol 1 of 2:

Protocol E01300.1a:

Title: Pilot Study of the Orthopaedic Training and Rehabilitation System (ORToS) in healthy volunteers

Target required for clinical significance: - N/A – This is a pilot study design for the initial form-and-fit evaluation of the devices to be used in the clinical study.

Target approved for clinical significance:

Submitted to and Approved by:

The University of Utah IRB, Protocol number: IRB_00133885

Status:

No changes at this time.

TOTAL PROTOCOLS: 2 - has been approved by the University of Utah IRB and by the HRPO

PROTOCOL 1 of 2: - No change from a prior report

Protocol E01300.1a: Approved

Title: Pilot Study of the Orthopaedic Training and Rehabilitation System (ORToS) in healthy volunteers

Target required for clinical significance: N/A (this is an initial study in healthy volunteers that will be conducted to verify the performance of the ORToS system that will be fabricated for the clinical study to be conducted in this project.

Target approved for clinical significance: 5 (amended application pending)

SUBMITTED TO AND APPROVED BY:

- Continuing review application has been submitted to the University of Utah IRB (CR_5/18/2022)
- Approved 7 JUN 2023 (exp. date: 50 MAY 2023)

STATUS:

(i) Number of subjects recruited/originally planned target: 5/5
Number of subjects screened/originally planned target: 5/5
Number of patients enrolled/original planned target:5/5
Number of patients completed/originally planned target: 5/5

(ii) Report amendments submitted to the IRB and USAMRMC HRPO for review:

The Continuing Review application for this protocol has been submitted to the University of Utah IRB. The CR application has been reviewed and approved. The approval letter was submitted to the HRPO via the ebrp.org portal.

(iii) Adverse event/unanticipated problems involving risks to subjects or others and actions or mitigation plans:

Nothing to Report

PROTOCOL 2 of 2: Continuing Review of the study has been completed and approved.

Protocol E01300.2a: Continuing Review has been completed by the University of Utah IRB. The study has been approved through 28 DEC 2023.

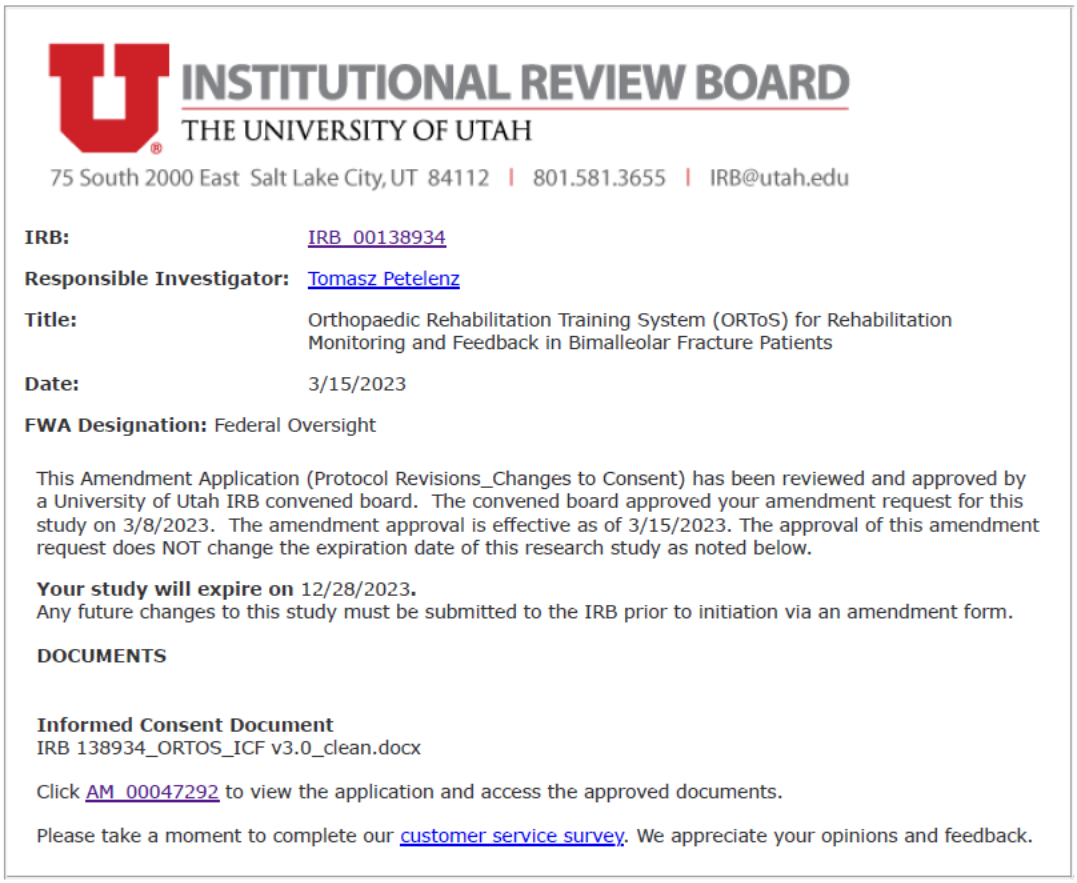
Title: Orthopaedic Rehabilitation Training System (ORToS) for Rehabilitation Monitoring and Feedback in Bimalleolar Fracture Patients

The University of Utah IRB Protocol number: IRB_00138934.

During the current reporting period, an amendment has been submitted to reflect protocol changes required to incorporate the results of the device development. Specifically, the randomization sequences were modified for the current synchronous recording software. The software development is ongoing, and the original randomization plan will be implemented as soon as the Android software has been completed and validated.

The Amendment documents have been submitted to ebrap.org and the HRPO:

AM_00045253 - AM_Protocol_revisions_approval_23-03-15
AM_00047292 - AM_Protocol Revisions_Changes to Consent_23-03-15



INSTITUTIONAL REVIEW BOARD
THE UNIVERSITY OF UTAH
75 South 2000 East Salt Lake City, UT 84112 | 801.581.3655 | IRB@utah.edu

IRB: IRB_00138934

Responsible Investigator: Tomasz Petelenz

Title: Orthopaedic Rehabilitation Training System (ORToS) for Rehabilitation Monitoring and Feedback in Bimalleolar Fracture Patients

Date: 3/15/2023

FWA Designation: Federal Oversight

This Amendment Application (Protocol Revisions_Changes to Consent) has been reviewed and approved by a University of Utah IRB convened board. The convened board approved your amendment request for this study on 3/8/2023. The amendment approval is effective as of 3/15/2023. The approval of this amendment request does NOT change the expiration date of this research study as noted below.

Your study will expire on 12/28/2023.
Any future changes to this study must be submitted to the IRB prior to initiation via an amendment form.

DOCUMENTS

Informed Consent Document
IRB 138934_ORTOS_ICF v3.0_clean.docx

Click AM_00047292 to view the application and access the approved documents.

Please take a moment to complete our customer service survey. We appreciate your opinions and feedback.

Figure 4. IRB Amendment approval letter.

SUBMITTED TO AND APPROVED BY:

- Submitted to the University of Utah IRB; expiration date: 12/28/2023, IRB_00138934
- The amendment was approved by the University of Utah IRB on March 15, 2023, and submitted for HRPO approval on March 31, 2023
    - Award Management Human Use Documents BA170194

STATUS:

- No change.
- Continuing review application will be submitted in DEC 2023

(iii) Adverse event/unanticipated problems involving risks to subjects or others and actions or mitigation plans:

Nothing to Report

(b) Use of Human Cadavers for Research Development Test & Evaluation (RDT&E), Education or Training – Not Applicable

TOTAL ACTIVITIES:

Not Applicable

ACTIVITIES:

***TOTAL ACTIVITIES*: not applicable**

***ACTIVITES*:** *not applicable*

(c) Animal Use Regulatory Protocols – Not applicable

TOTAL PROTOCOL(S): 0

PROTOCOL(S): not applicable

Protocol (_ of _ total): 0/0

Submitted to and Approved by: not applicable

Status: not applicable

TOTAL PROTOCOL(S): 0/0

PROTOCOL (_ of _ total): 0/0

Protocol [ACURO Assigned Number]:

Title:

Target required for statistical significance:

Target approved for statistical significance:

SUBMITTED TO AND APPROVED BY: 0/0

STATUS: NOT APPLICABLE

What do you plan to do during the next reporting period to accomplish the goals and objectives?

During the next reporting period:

1. Complete App asynchronuous data communication and back-end calculation software
2. Continue subject enrollment
3. Continue insole assemblies for individual patients enrolled in the study
4. Continue data collection and study management.
5. Continue engineering development in effort to use the new Merit Medical sensor.
6. Prepare data for presentation at MHSRS, if approved for the conference.
7. Continue patent and literature update

2. Products: List any products resulting from the project during the reporting period. If there are no products to report for the current quarter, state "Nothing to report."

Nothing to report.

3. Participants & Other Collaborating Organizations

What individuals have worked on the project?

Provide the following information for (1) Project Directors (PDs)/ PIs; and (2) each person who has worked at least one-person month per year on the project during the reporting period, regardless of the source of compensation (a person month equals approximately 160 hours of effort).

1. Tomasz Petelenz, PhD, Project PI
Contribution: Pilot study protocol submission to the UU IRB and HRPO, overall project planning and management, engineering management of electronic components, FLEx system design modifications.
2. Robert Hitchcock, PhD, Co-PI
Contribution: Engineering management of mechanical components design and fabrication, personnel hiring
3. Kylee North Graduate Student
Contribution: design, literature studies, data analysis, managing undergraduate research assistants, identifying software developers and coordinating App development process.
4. Austin Whiteley Student Research Assistant
Contribution: 3d modeling of insole component in Solid Works and Fusion360; parts fabrication and assembly.
5. Grange Simpson Undergraduate Assistant – electronic testing and embedded software development
6. Undergraduate students Assembly and testing tasks

4. Changes/Problems: The PD/PI is reminded that the recipient organization is required to obtain prior written approval from the awarding agency Grants Officer whenever there are significant changes in the project or its direction. If not previously reported in writing, provide the following

a. Actual Problems or delays and actions to resolve them

Study enrollment will be limited by the availablity of elligible subjects. We will continue reporting if any additional problems occur.

Due to the dealys with clinical study, we have requested and obtained a No-Cost Extension for the project. We expect that the enrollment will proceed without further delays.

b. Anticipated Problems/Issues

1. We anticipate that some supply chain problems causing further delays in the availability of components will continue.
2. We anticipate that software development for asynchronuous data recording will be complete in 4-6 weeks.

5. Special Reporting Requirements:

Quad Charts: The Quad Chart (available on https://www.usamraa.army.mil) has been submitted with attachments.

6. Attachments

Updated Quad Chart.
IRB Amendment approval letter,
Amendment submission form.

Award W81XWH2010266: Orthopaedic Rehabilitation Training System (ORTos) for Improved Patient Compliance and Rehabilitation Monitoring in Lower Extremity Trauma

PI: Petelenz, Tomasz J, University of Utah, UT **Budget:** $643,401

Topic Area: 12.420-Military Medical Research and Development **Mechanism:** W81XWH-17-R-BAA1

Research Area(s): SCS Coding **Award Status: 04/15/23**

Study Goals: The objective of this project is to fabricate and clinically validate an effective, practical, reliable and inexpensive biofeedback system that will provide information to patients undergoing PWB therapy that will help them comply with load limitations and/or reach gait symmetry targets in post-PWB rehabilitation. The system that will be used in this proposed study is the Orthopaedic Rehabilitation Training System (ORToS), based on the technology already developed and validated by our group in patients recovering from tibial and ankle fractures.

Specific Aims:

1. Fabrication and validation of the ORToS system for use in a clinical study;
2. Clinical study to determine the role of feedback in therapy compliance

Key Accomplishments and Outcomes:

1. Engineering modifications to the ORToS system to improve the reliability, fabrication time, and cost of clinical devices have been completed.
2. The feasibility study enrollment has been completed and the feasibility testing of the ORToS system is on-going to validate hardware and software modifications.
3. Major findings:
   a. Data analysis identified that the longitudinal changes in the number and the cadence of steps during the recovery period are more effective outcome predictors than the load-bearing prescription alone – accepted for publication in a journal
   b. Analysis of the correlation between image-based assessment of recovery and the identified variables and the manuscript preparation, are pending.
4. Enrollment for the feasibility study has been completed (5 subjects); testing is continued as needed for the validation of changes
5. Human subject protection approval for studies is maintained with the University of Utah IRB and the MRMC OHRP.

Publications: 1 publication accepted for publication, one manuscript preparation pending

Patents: none to date

Funding Obtained: $495,922