Smart Crutches

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Abstract

Crutches or similar walking aids are commonly used post-injury or corrective surgery in combination with physiotherapy exercises. However, a lack of noticeable progress during recovery can be demotivating, reducing willingness to complete exercises and thereby cause recovery time to be much longer than necessary. This study investigates how proven injury recovery feedback from Smart Crutches and an Exercise Tracking System can improve user sentiment and increase motivation to participate in physiotherapy exercises.

1. Introduction

A survey carried out by a group of 40 current or previous crutch users showed that 75% had been prescribed rehabilitation exercises. However, less than half completed the exercises as regularly as recommended. The group were presented with research showing that rehabilitation exercises are vital for regaining strength after injury [1]. From here, 82% stated that they would be more motivated to complete exercises if they could observe the benefit over time.

A key feature of recovery is reduced weight bearing; from non weight bearing (commonly abbreviated as NWB), gradually increasing to full weight bearing (FWB). Measuring the variation in percentage of supported body weight over time could inform both the user and doctor of recovery rate. This would also provide reassurance to the user and valuable medical feedback to the physiotherapist for improved diagnosis and recommendations.

Research has also shown that performing exercises designed to rehabilitate through rebuilding of strength and ROM in the affected area can reduce the average hospital stay from 7.2 days to 4.2 days [2]. The improved rate of recovery is particularly important for leg injuries and operations, as immobility can have a significant impact on mood and well-being. Complications can include depression, anxiety and feelings of helplessness. Additionally, gamification has also been proven to improve attitudes toward exercise [3], specifically motivation.

Therefore, in this study, crutches have been fitted with an accelerometer, gyroscope and force sensor in the foot, in order to collect usage data. An exercise tracking system with a rewards program was also developed, to investigate how feedback could improve exercise quality and adherence to a rehabilitation plan. Both the crutch and exercise tracking data was then visualised in a mobile application for the user, with its impact on user motivation and value to a physiotherapist investigated. The additional benefit of this is that a physiotherapist can be provided with accurate data of a user's engagement with their recovery program[1].

The following hypotheses were presented for investigation:

1. Regular monitoring of crutch usage and exercise performance can provide valuable data to physiotherapists, enabling more informed decisions about prescribed exercises.
2. Demonstrated strength improvement through analysis of crutch data will improve user sentiment and motivation to complete a full exercise program.
3. A home exercise tracking system can be used to improve the technique with which users perform prescribed physiotherapy exercises.
4. An exercise tracking system can be used to increase the number of users who fully complete prescribed exercises.

The hypotheses will be tested through controlled experimental validation, user testing and feedback.

2. Background

2.1. Crutch Usage

Post-operations such as a hip replacement or lower limb damage, it has become common practice for users to be prescribed crutches. However, whilst some studies have expressed preference for complete immobilisation initially post-surgery, research has suggested that this can decrease the strength of cartilage [4]. At the other extreme, studies have found that "full weight bearing in the early post-operative phase is believed to endanger the stability of the reconstruction and the surgical result" [5] by increasing the risk of "disrupting the operated

[1] Where recovery program is defined as the combination of prescribed crutch usage and physiotherapy exercises

tissues" [4]. Instead, movement early-on in the recovery process has been found to increase the likelihood of a quicker recovery time [6]. Many studies have therefore concluded that PWB immediately post-surgery allows the affected area to begin to heal whilst minimising potential further damage caused by placing too much weight through the affected limb.

PWB is achieved by a physiotherapist allocating a percentage of the user's weight that should be placed through the crutch(es). This corresponds to their stage in the recovery process; As a user progresses through their recovery process, their pain level should gradually decrease and the strength and range of motion (ROM) in their limb should return. This allows greater weight to be supported by their leg, increasing the weight bearing percentage over time. However, it has been observed by multiple studies [5] [7] [8] that, once out of the hospital setting and away from the guidance of their physiotherapist, many users struggle to maintain the prescribed PWB threshold. This is a conscious decision for some users, who may lack the motivation, or experience levels of pain higher or lower than what may be expected at that stage of their recovery. Yet this behaviour is subconscious in other users, with many finding difficulty in determining how much of their weight is being place through the crutch.

These findings have caused the area of instrumented crutches to be well-researched. 'Smart Crutches' have been extensively used as a method of monitoring user usage, through monitoring characteristics such as the tilt of the crutch or load applied. Two significant such projects in this area are an "Instrumented crutch tip for monitoring force and crutch pitch angle" [9] and an "Augmentation of forearm crutches with wireless sensors for lower limb rehabilitation" [10]. The instrumented crutch tip provides a lightweight and retro-fittable solution, allowing the monitoring of crutch usage away from a hospital or lab setup, but did not provide immediate feedback to users. The study used force and pitch angle monitoring to improve the state of the art, but failed to report observations of crutch usage such as percentage of users that used their crutches correctly or incorrectly. The second study implemented sensors in both crutches to "account for users which may unevenly distribute their weight through the crutches" [10]. In contrast to the Instrumented tip, this team used load monitoring to close the feedback loop by providing haptic feedback when the force was greater than the prescribed threshold. However, it was not discussed if or how this threshold could be altered. In further contrast to the instrument tip, the augmented crutches monitor the tilt angle through analysis of the grip force applied to the angle. No analysis or comparison is provided as to why this design choice was made or any improved performance that it may have offered.

This study aims to first confirm the results found by those mentioned above regarding crutch usage, with respect to load bearing and tilt angle. The second aim is to develop a novel device providing intuitive bio-feedback which can be easily modified within an app. This app will also provide data about the usage of the crutches.

2.2. Physiotherapy Exercises

As stated in Section 1, studies have shown that performing physiotherapy exercises can reduce the recovery time. The same study also showed that users who performed such exercises "continued to out-perform the control group[2]" [2] in outcome parameters such as "pain, stiffness and physical function" [2]. However, the prescription of exercises is both time and resource intensive, requiring a physiotherapist to frequently engage with the user to ensure the exercises are being performed regularly and correctly. Furthermore, as the user progresses in their recovery process, exercises must be modified to suit the user's changing condition.

Provided exercises are performed correctly and fully, it has been proven that there is no difference in recovery between users carrying out their physiotherapy program at home when compared to control users doing the same in a hospital [11]. However, as with crutch usage and technique, when a user returns home a significant decrease in the performance of the exercise has been observed [12]. Often users will only "undertake exercises that they find easiest or from which they perceived they would derive the most benefit" [12]. Variation in the compliance of users also occurred due to motivation, as well as due to ability to fit the program in their standard day-to-day lives.

This research suggests the need for a home-based system providing instruction as well as motivation to patients that have been prescribed physiotherapy exercises. This would also maximise the speed and extent of a user's recovery, whilst minimising cost of consultation. Previous work implementing such a device has been found to focus on either sensor or camera-based tracking [13]. Of this research, a relevant project to this study is "Kinetic for rehabilitation" [14], describing a "low-cost automated assistant to help users perform rehabilitative physical therapy" [14], which "sends a summary of the completed exercise session to the attending physical therapist" [14]. However, this research does not address tracking the number of repetitions (reps) of an exercise completed, nor motivating users to perform their exercises.

A further study went on to develop "a monitoring system for home-based physiotherapy exercises"[13]. In contrast to the study mentioned above, this home-based system produced a "repetition count of an exercise in the given session"[13]. It made use of a Microsoft Kinect sensor, also to be used in this study, as it contains a depth and an RGB camera. However the home-based system goes one step further, having developed a Bayesian network to actively detect which exercise is being performed. This is less of a concern in this study, as the working assumption is that the patients are provided their physiotherapy exercises in a given order, and progress through this chronologically, hence removing the need for specific exercise detection. This is because it tracks the number of reps performed and, upon the desired number being reached, automatically moves onto the next exercise.

[2]Where the control group performed significantly less rehabilitative exercises.

3. System Design

3.1. Smart Crutches

The crutches produced in this study have been designed to serve two purposes:

1. To regularly record and upload movement and weight bearing data, to be analysed and displayed in-app.
2. To continuously encourage the user to use a load bearing percentage determined by a physiotherapist.

The crutch angles and speed are measured, along with load bearing percentage[3]. Full recovery is recognised when load bearing has increased from 0% to 100%. There are three distinct gaits when using crutches which are four-point gait, partial weight bearing three-point gait and three point swing through gait, as seen in Figure 1.

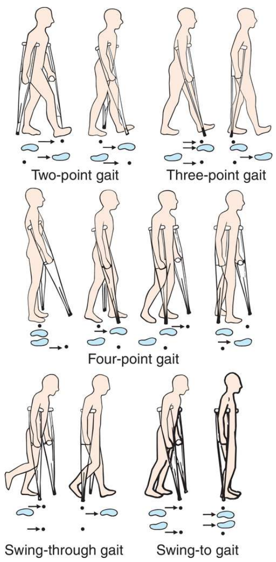


Figure 1: Types of gait when using Crutches [15]

To measure load bearing percentage, gait style and speed, the system would need to measure the movement, angle and force through the crutches. Movement and angle were recorded using an Inertial Measurement Unit (IMU), and the force through a Load Cell and amplifier combination. After sufficient data has been collected, the user's recovery progress can then be understood through analysis. While recovery progress determined through IMU data needs to be displayed through a visualisation, load bearing percentage data can be immediately fed back to the user. An ideal weight bearing percentage, determined by a physiotherapist, can be set as a threshold, and then recorded by a feedback system on board the crutches.

To fulfill purpose 1, a full gait cycle is recorded several times a day and securely uploaded to a storage location for processing. This requires non-volatile memory for storage, along with wireless connectivity for data upload. For purpose 2, weight bearing percentage is continuously measured, and the user alerted immediately when outside of a defined threshold.

[3]Load bearing percentage is defined as weight supported by a leg divided by total body weight.

Haptic feedback was chosen as it is only observable to the user, and consistently easy to detect when compared with visual or audible feedback. The ease of detection of visual or audible feedback depends on the environment - e.g. on a bright day, visual feedback may be hard to detect. The same is true for audible feedback in a loud environment.

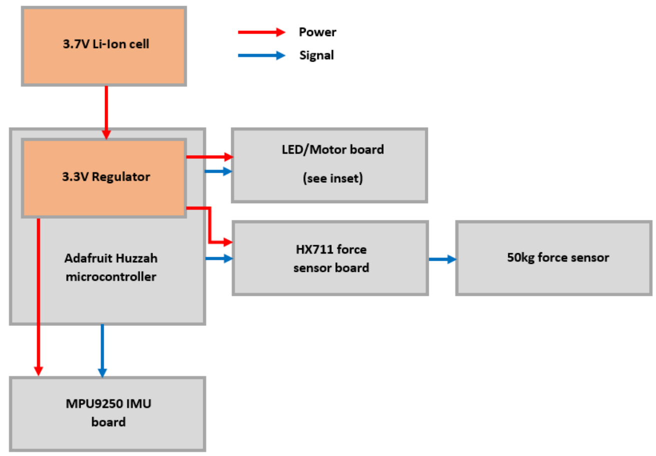


Figure 2: Hardware System Diagram for the Smart Crutch

The hardware system diagram is shown in Figure 2. A 18650 3.7V lithium cell was chosen as it offers high energy density, and fits within the crutch. In order to easily fit the system inside the crutch, each individual subsystem was made on a different board. The force sensing subsystem uses an off-the-shelf single strain gauge load cell, chosen for its low cost, weight and size. This was connected to a high amplification analog to digital converter (HALJIA HX711[16]). The weight sensor ADC and IMU interface with the Huzzah using I2C. The current requirements of the vibration motor exceeded the specification of the Huzzah's 3.3V regulator, so an NPN driver board was made, shown in Figure 3. LEDs were installed for indication during debugging.

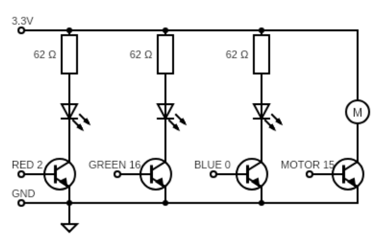


Figure 3: NPN Driver Board for interfacing the LEDs with the Microcontroller

WiFi was chosen as the communication protocol, due to the ease of implementation, as well as not requiring an intermediary device for uploading to the internet unlike Bluetooth. However, a strong disadvantage of WiFi is the higher power draw[4], but in the interest of faster development, the trade-off was deemed necessary. The ESP8266 based Adafruit Feather HUZZAH was found to satisfy the data storage, battery management and WiFi requirements.

The system was powered from a 18650 Li-Ion 2700mAh battery, capable of powering the crutch for 4 days before needing to be recharged. The Adafruit Huzzah contains all BMS (battery management system), fully recharging the battery over USB in 5 hours. A system design is shown in Figure 4.

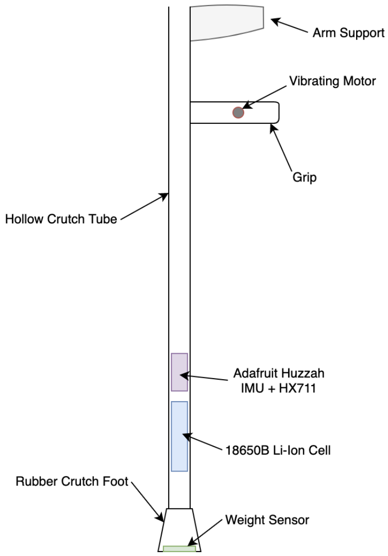


Figure 4: System Design for the Smart Crutch

The Arduino library for ESP8266 was used due to the comprehensive libraries available. The program written interfaces with the sensors and vibration motor, collects data samples and uploads to a Google sheet. A flowchart for the crutch's operation is shown in Figure 10.

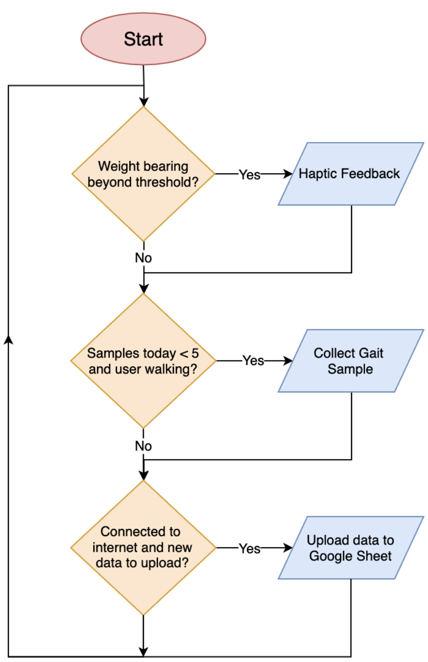


Figure 5: Smart Crutch software flow diagram

Due to the low data and volume requirements of the evaluation and testing stages, Google Sheets was chosen as the database of choice for simplicity. An additional benefit to Sheets is the easy to use Python library, reducing the complexity of data retrieval and accelerating the development of the data analysis software. The data flow is shown in Figure 6.

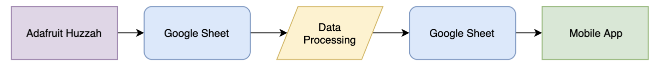


Figure 6: Data flow diagram

Once the data is stored in a Google sheet, it is processed, analysed and re-uploaded. The mobile app then displays this processed data. An endpoint was created using Google Scripts, enabling simple HTTP requests from the crutch to insert new data. The biggest setback during the development of the software was an issue connecting to the Google Sheets Script, which would result in a heap overflow error. After investigating, a change to the open-source ESP8266 Arduino library was made as a result[5]. A python script was written to continuously check for newly uploaded data. Two values are computed.

1. Average weight through the crutch.
This value allows both the user and their physiotherapist can observe the recovery progress, on a weekly or monthly scale. The average weight on the floor is calculating by comparing the data to a small threshold to identify contact[6]. For each batch of data sent, the average weight through the crutch was calculated by calculating the mean value of values above this threshold.

2. Instantaneous angle at impact with floor.
There are three types of angle to consider when calculating the angle at which the crutch has hit the floor; Pitch, Roll and Yaw, which are the rotations around the x, y and z axes respectively. This can be seen in Figure 7. These values are calculated using

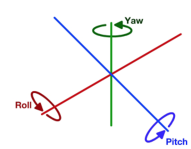


Figure 7: Diagram Demonstrating the Difference Between Pitch, Roll and Yaw

Equations 1, 2 and 3 below.

$$pitch = \frac{180}{\pi}\arctan\left(\frac{accel_x}{\sqrt{accel_y^2 + accel_z^2}}\right) \tag{1}$$

$$roll = \frac{180}{\pi}\arctan\left(\frac{accel_y}{\sqrt{accel_x^2 + accel_z^2}}\right) \tag{2}$$

$$yaw = \frac{180}{\pi}\arctan\left(\frac{accel_z}{\sqrt{accel_x^2 + accel_z^2}}\right) \tag{3}$$

[6] If the force measured is above this threshold, it is concluded that the crutch has made contact with the floor.

The analysis of these values can assess in what manner the crutch is hitting the floor. This allows both the user and the physiotherapist to determine whether the crutch is being used correctly[7]. The angles when hitting the floor were calculated using a combination of accelerometer and weight sensor data.

3.2. Exercise Tracker

The exercise tracker was implemented using the Robot Operating System (ROS) with a Kinect sensor, skeleton tracker and API server as individual ROS nodes.

The OpenNI launcher [17] is a driver for depth sensing cameras and supports the Kinect camera used in this study. Skeletal tracking is implemented using the OpenNI tracker [18] library. The launcher broadcasts the OpenNI skeleton frames, where each frame represents the position of a limb. Through Rviz [19], a visualization tool, the feasibility of the OpenNI tracker was confirmed visually and the poses of correct exercises captured. These correct exercises were performed by a physiotherapist who is an expert in leg exercises. The node broadcasts limb positions every 0.05s (20fps). An additional ROS node then listens to the tracker, and inserts the current skeletal profile to a queue. The queue is processed sequentially by comparison to the perfect execution of the exercise.

The exercise tracker hosts a REST API endpoint accessed by the mobile application and, when called, activates the Kinect camera (previously set up) to start tracking the user. Once the user has been identified by the vision system, the system identifies their exercises and returns feedback to the mobile application. If the exercise was incorrectly executed, a percentage score is returned which signifies the 'correctness' of the movement. The feedback returned is shown in Figure 8.

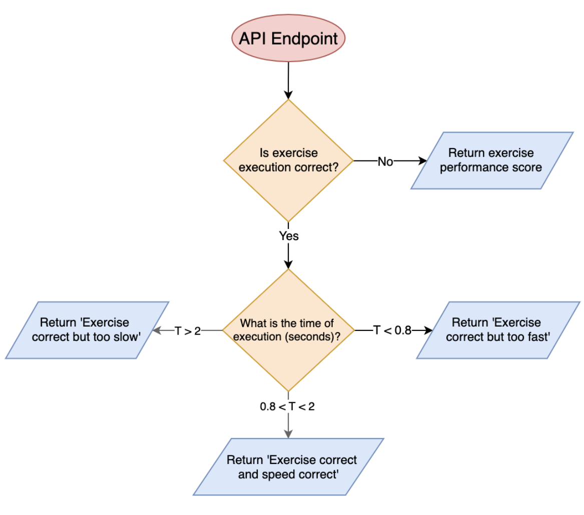


Figure 8: Flowchart for the Operation of the Exercise Tracker

The algorithm for the detection and classification of exercises was implemented using the coordinates of different parts of the user's body. These are then translated to vectors in 3D space, which are compared to vectors taken as the correct implementation of the exercise. If the angle between the vectors is below a defined threshold, then they would count as a match. This threshold was defined through experimental validation - more information can be found in Section 4.2.2.

Another approach initially considered for obtaining the skeletal profile was to utilize the 2D RGB camera on the Kinect, in order to identify the position of ArUco markers[8] [20], which were attached to the user. The advantage of this method is that the fiducial markers[9] can be concentrated on parts of the body most used during different exercises. However, this method would introduce a complicated set up for the user, so was avoided in the interest of maintaining the simplicity of setup so that no extra knowledge would be required by the user[10]. A machine learning classifier was also considered, but not pursued due to the unavailability of training data. A further difficulty influencing this decision was the black-box nature of ML classifiers, preventing one from understanding the reasoning for the output. This in turn prevents the system from providing useful feedback on which limbs in particular are causing the exercise to be marked as failed. This feedback is required to validate the model against correct and incorrect exercises. In contrast, with the vector threshold solution, it is straightforward to understand why an exercise is detected as correct or incorrect. Figure 9 gives a complete overview of how the exercise tracker works.

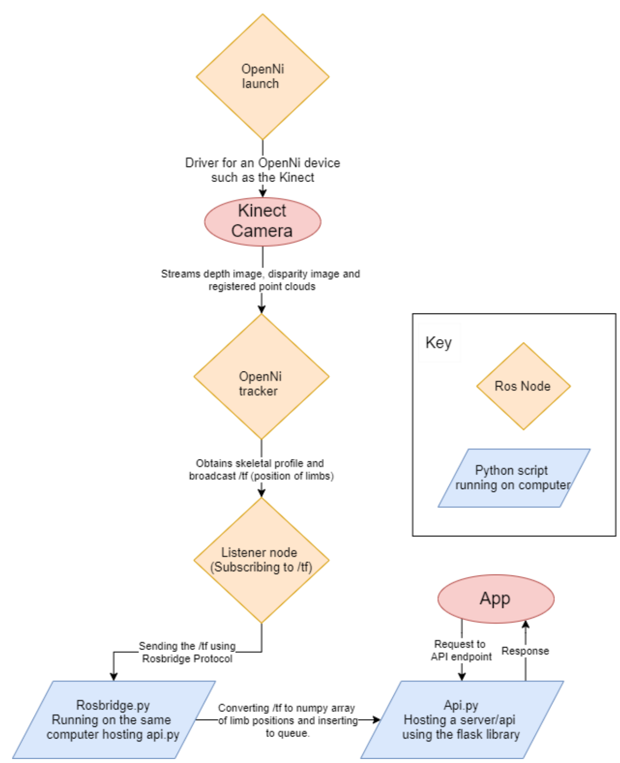


Figure 9: System diagram for exercise tracker

[7]Correct usage is defined as hitting the ground at an angle in the same plane as direction of movement, reducing strain on the upper body.

[8]ArUco markers are binary square fiducial markers that can be used for camera pose estimation.

[9]A fiducial marker is an object placed in the field of view of an imaging system which appears in the image produced, for use as a point of reference or a measure.

[10]Thus preventing the need for the presence of a technician.

3.3. Mobile App

The purpose of the app is to display analysed crutch data, provide an interface for the exercise tracker, communicate feedback and provide encouragement to exercise.

For the exercise tracking section, the app first displays instructions on how to perform the required exercise. These instructions are in written form, alongside a video demonstrating the exercise. The app then sends an API request to the server hosting the Exercise Tracker, initialising tracking for that particular exercise. Post-exercise, the app receives feedback from the Exercise Tracker API. If the exercise was correctly performed, it displays a green tick and plays a sound with positive connotations, in order to inform the user of their success. The app does not provide any negative feedback from incorrect exercises as results from initial testing results showed negative feedback such as this was discouraging. The audio feedback (or lack thereof) enables the user to focus on performing their exercises, instead of constantly having to check the screen in order to receive feedback. Once an exercise has been correctly performed for the required number of repetitions, the app transitions to the next exercise, with new instructions and a new demonstration video.

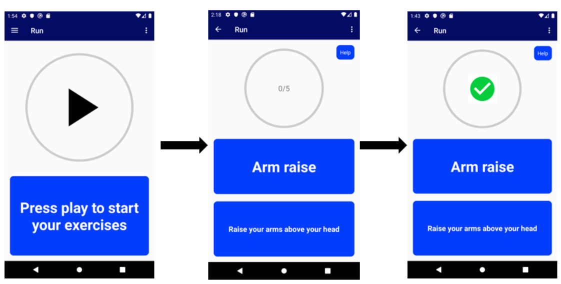
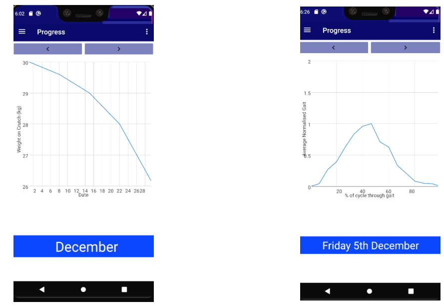


Figure 10: Flowchart for the Operation of the Exercise Tracker in the App

Another key component in the App is the display of the data that has been gathered from the crutch and processed by the data processing module. The data was pulled from the Google Sheets page, where the processed data was placed using the Google Sheets API. This API provided the authentication and fetching required. This data is then displayed onto a graph, using the GraphView library, in order to create graphs that could be updated in real time as data comes in. Graphs provide easy visual feedback of the users progress. Feedback given to the user shows how much weight has been placed on their crutches over time shown in Figure 11a, and a graph of their gait shown in Figure 11b. 11a is designed to encourage a user, and 11b provides analysis of their gait to a physiotherapist.

The UI was designed with the goal of being as accessible as possible. All text boxes are sized so that they could adapt to a user's system settings, to accommodate users with impaired vision using larger font sizes. The UI elements are responsive to the screen size, beneficial for accessing the app on tablets.



(a) Average Weight Bearing Over Time for the Month of December

(b) A Single Gait Cycle Measured On a Particular Day in December

Figure 11: In-App Graphs using Mock Data

4. Evaluation and Results

4.1. Crutch System

To evaluate the crutch system against the relevant initial hypotheses, experiments were devised to answer the following questions:

1. Does the crutch data contain features demonstrating injury recovery over time which would be valuable to a physiotherapist?
2. Would a crutch user's sentiment and motivation to complete an exercise program be improved by the data analysis presented in the app?

For 1, a crude analysis of the weight sensor data is enough to demonstrate how the average weight through the crutches decreases over time. This demonstrates improvement where the user is regaining leg strength, demonstrated in-app in Figure 11a. A group member's physiotherapist was asked if this was valuable, and reported: "It can often be difficult to assess a user's state of recovery in a half hour consultation. Regular data on a user's load bearing percentage would be of great advantage, allowing me to provide better recommendation on the recovery window, and a suitable exercise program". Furthermore, the accelerometer and gyroscope data provide key information about how the user is using the crutch. Using correct crutch technique will not only allow a user to recover quicker, but will also avoid straining another part of their body.

For 2, 10 respondents to the initial survey in Section 1 were invited to complete a user-testing session. In the session (of which 6 attended), the users interacted with the app, with mock data demonstrating increased weight bearing percentage and therefore improved leg strength over time. They were asked to imagine that they had been using crutches for three weeks, and had so far adhered to a prescribed exercise program. Typically, users will strictly adhere to an exercise program for a few weeks before losing interest [21]. The users were then asked to rate, on a scale of one to five, whether the displayed results would encourage them to adhere to an exercise program. The results were 4, 5, 4, 2, 4, and 4, producing an average of 3.83. The user who responded with '2' explained "While the feedback shows improvement, there's no evidence that the exercises have caused this". Another user suggested that while this was true, the data analysis was encouraging to them and they would not risk stopping exercising in case their recovery slowed. The initial survey group discussed in Section 1 and their answers about motivation were used as a control group.

Ideally, a complete trial with at least one injured user, from first use of crutches, to independent walking, would have been undertaken, but due to the time constraints of the project, and the fact that full recovery often takes upwards of 6 months, this was not possible. Nevertheless, the usefulness of the data for exercise recommendations has been demonstrated, along with a positive response to recovery tracking in a user consultation.

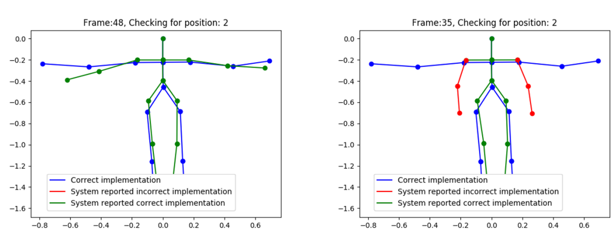
4.2. Exercise Tracking System

4.2.1 Setup

Before an exercise can be performed, it is essential to adjust the camera placement so that all limbs are always in the frame of the Kinect during the exercise. For the demonstration, as well as optimal use, the camera was located around waist height and around 2m from the user. The OpenNI tracker automatically can then automatically the user, and performs the necessary calibration in order to obtain a skeletal profile. The final step is to ensure that the server is running so that the application can call the API to activate the camera.

4.2.2 Testing

Firstly, the 2D RGB camera approach was tested. However, as mentioned in Section 3.2, users found that this method was intrusive and required time to set up with the tracking markers, which defeats the purpose of an exercise tracker designed to be a convenient mechanism to promote recovery exercises. The exercise tracker was calibrated using 6 users of varying heights and builds. These users performed exercises in front of the camera, to see if the tracker would classify their exercises as correctly completed. Completion of the experiments provided valuable information for tuning the algorithm and threshold of error allowed in angle difference between the vectors, improving performance for all body types. Figures 12a and 12b show a correct and incorrect execution decision reported by the system for overhead arm raises.



(a) Correct Performance (b) Incorrect Performance

Figure 12: Example of Exercise Evaluation Decisions

The tracker was then evaluated against another 6 users, for whom the system had not been calibrated. These users performed various exercises such as squats, standing knee raises and side leg raises. A qualified physiotherapist then observed the exercises, and gave an opinion on their correctness. This observation was then compared to the tracking system's result, results displayed in Table 1.

Exercise	Squat	Standing Knee Raises	Side Leg Raises
Exercises performed	5 per user (30 total)	5 per user (30 total)	5 per user (30 total)
Exercises deemed correct by physiotherapist	22	25	30
Exercises deemed correct by tracker	16	28	30
False positives	1	3	0
False negatives	7	0	0

Table 1: Matrix of Accuracies for Tracker, for Different Exercises

This shows that exercise tracking system was able to accurately detect 89.3% of correct exercises, and 75.8% of incorrect exercises. As the test subjects used the tracking system, the rate of incorrect exercises reduced, demonstrating working feedback.

5. Conclusion

The research has demonstrated that the majority of users would have increased motivation from observing positive recovery progress. This presents a great opportunity to improve the uptake of post-injury exercise, through crutch usage analysis and home tracking of exercise. Other benefits include reduced contact with a physiotherapist, who could review the exercise quality remotely and a user's weight bearing progress. Furthermore, the system enables physiotherapists to analyse the data in order to see which exercises a user is struggling with the most. From here they can cater to the patient's individual recovery needs. This in turn would enable physiotherapists to treat a greater number of patients and provide more informed decisions.

6. Future Work

Further investigation beyond the feasibility of this study into uses of the crutch and exercise data is necessary. This will require several end-to-end recovery trials, and involve evaluating the systems against:

1. Long term impact on user sentiment and commitment to exercise programs.
2. Physiotherapists' ability to better recommend treatment, with less frequent visits.

With regards to system improvements, the app currently has functionality for only a limited number of exercises for the Exercise Tracking module, that occur in a pre-defined order. This should be expanded to an extensive list, to allow bespoke programs depending on the user's condition. The system does also not currently report the reason an exercise was deemed incorrect. Adding additional communication from the tracking API through to the app would be necessary to improve exercise performance quality, by suggesting specific adjustments. A final addition to the system would be a partner system (either a web-app or mobile app) that could enable a family member or friend to supervise users. The partner application would also allow physiotherapists to monitor and adjust the exercises for their users remotely.

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