

Visualizing Real-time Feedback of a Rehabilitation Trainer

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Abstract

Musculoskeletal injuries of the lower extremity are common within active populations participating in sport, particularly in female athletes. To assess injury mechanics, clinicians desire easy-to-use, cost-effective, transportable, and flexible functional assessment systems that provide immediate feedback. Initial research has shown that such systems reduce injury incidence, enhance motor learning, and improve safety for return to work or sport from rehabilitation. We have developed a novel, portable force platform and video system that provides real-time feedback to clinicians and patients. This system is used to assess landing mechanics, train improved performance on a series of trials, and evaluate retention of learning using post-training trials. Prior work has shown that the use of a portable system can identify athletes with aberrant landing mechanics and that immediate feedback can reduce risky landing behaviors.

The existing software to visualize force data from the force platform hardware is not ideal for use in a clinical setting, however. The existing software is an off-the-shelf data acquisition tool that is designed to visualize data from a variety of sensors. This generic data acquisition software is more fully-featured than what we require for our force platform, and is therefore difficult to use by a clinician without specific training. Furthermore, the licensing fees of the existing data acquisition software present barrier for use in the intended clinical setting. This paper describes a custom software effort to implement a data acquisition platform with the goals of providing an open-source, and more clinic-friendly software – making the system easier to use by those with a non-technical background while reducing overall system costs.

1 Introduction

Female athletes pose an at-risk population for activity-related injuries, particularly for injuries of the lower extremities. Research [8] [10] [14] has shown that providing visual feedback of the lower-body mechanics of participants can reduce the instances of injuries, improve motor learning, and can improve the safety for returning to activity after injury. More importantly, providing *immediate* feedback has been shown to be especially helpful [5]. To support the goal of reducing injury and improving the rehabilitation after surgery, it is desirable to have a portable, cost-effective, and flexible system for assessing body mechanics.

This paper outlines a collaborative effort shared by the Health Professions Department and the Department of Computer Science at the University of Wisconsin-La Crosse. The Health Professions personnel are conducting IRB-approved trials on the jump and landing activities of female athletes participating in youth sports using a novel visual feedback system composed of commercially available high-speed cameras as well as load cells used to measure force data. This system can then project a video feed and a visual representation of the force data to a screen that can either be viewed in real-time or immediately after capturing a post-jump trial. To visualize the data, a commercial data acquisition software package has been replaced by a custom software tool being developed by the Computer Science personnel.

The primary research for this project is in its health and physical therapy implications. The goals are to be able to provide a rehabilitation trainer that satisfies portability, ease-of-use, and cost-sensitive aspects as needed by clinical staff at local health clinics. The camera and load cells of the feedback system uses commodity hardware – leading to a cost-effective solution to the physical components of the feedback system. These components have been assembled into a custom portable system that can be moved from site to site, as needed. Originally, the camera and force data were accessed using off-the-shelf data acquisition software.

However, this presented two problems. First, the data acquisition software requires a yearly licensing fee – a negotiated cost, on the order of thousands of dollars per year. Second, this software was powerful in that it allows data to be gathered from a variety of sources, and is very flexible in how that data is presented – but requires the operator have a technical background in order to configure and operate, due to this flexibility. Since the hardware components of the system are standard, they can be integrated into custom software – presenting an interesting computer science and software engineering challenge.

Figure 1 shows the type of feedback that is helpful for health providers when preventing and/or correcting the lower-body mechanics of patients. This feedback shows the patient in a mirrored, real-time video when the patient jumps from a small platform. Clinicians can also replay this video to point out and correct joint positions at different points in their landing. The patient can attempt more jump trials, and watch their motion and joint positions in real-time to get immediate visual feedback of their corrections. The feedback also displays a representation of their loading symmetry – the left-to-right, and forward-to-

backward force of their landing. During a jump trial, the patient jumps directly onto the force plate load cells and the force data is visualized (in the implementation shown in this figure) with a “balance beam” representation – for example, the left-to-right symmetry is depicted with the angle of the cyan beam. This symmetry representation is synchronized with the video to show simultaneously show the correlation of their joint positions and symmetry. One final item of feedback displayed is the maximum ground reaction force (GRF), the maximum downward force detected by the force plates. This is a measure of how softly a patient has landed. The GRF value is not updated in real-time, since it is a peak value.

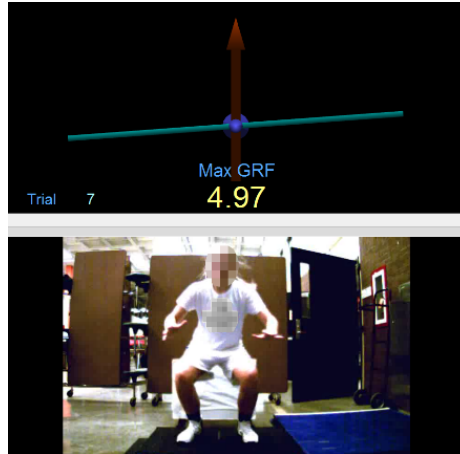


Figure 1: Combined symmetry and frontal plane video feedback (post-trial).

The software being developed for this project solves the two problems present in the commercial software solution. Our tool is being written in Microsoft C#.NET using the Windows Presentation Foundation (WPF) for the UI and LiveCharts for UI elements, and will be released as an open-source project when testing and clinical trials are completed. The program has a simplified user interface, displaying the only sensor data and video feed as needed, and guiding the user through the minimal options and setup needed to record a trial. The feedback does not need to exactly match the commercial data acquisition software visually, but should display the same information.

The remainder of the paper describes the background healthcare research on the effectiveness of real-time feedback in Section 2. Our software requirements are described in Section 3, and the architecture of our implementation appear in Section 4.

2 Related Work in Healthcare

Several studies have noted the higher incidence of injury in activities related to jumping and landing [8] [10], and that showing visual feedback of these activities can help guide patients away from poor landing behavior. The clinical trials of these previous works by Hewett, et al. [8], Myer, et al. [10], as well as our work, specifically focus on the injuries related to the anterior cruciate ligament (ACL) and patellofemoral joint. Work by Paterno

et al. [14], similarly focus on these injuries and note a greater risk of a second ACL tear after surgical reconstruction of the ACL. To reduce the instances of these injuries, and to assess and guide the progress of physical therapy after repairing these injuries with surgery, our work monitors impact force, loading symmetry as quantitative measures of joint stress in addition to qualitative measures by recording video of participants and patients. Clinicians can then identify abnormal landing mechanics, and guide patients toward correcting aberrant behavior.

Prior work has furthermore demonstrated the additional benefits of visual feedback when that feedback is either real-time or immediately after [5] [18] the activity. Others have further pointed out the benefit of non-invasive feedback [6]. An important feature of our work is to leverage this immediate feedback, and do so in a way that is easy to set up and administer (both the physical components and within the software). Several studies have established the importance of video feedback [7] [12] [13] [16] [17]. Nyman et al. [11] present additional evidence that symmetry is an important component of feedback, and prompt its inclusion into our work. Previous work [15] by members of our project have demonstrated preliminary data on the efficacy of combining video and symmetry into a single visual feedback system.

Since cost is an important factor in a feedback system, a very cost-effective hardware platform are in devices meant for video game systems. The Wii Balance Board [1] can be used to gather force data [3] to provide a low-cost GRF estimation. Similarly, the Microsoft Kinect [2] can provide video feedback [9] with low-cost game hardware. In addition to their cost, these devices also have the advantage that it is well-known how to interface with these devices, and an open hobbyist community exists for developing applications using the Wii Balance Board and Microsoft Kinect. However, Bartlett et al. [4] note that these low-cost devices are not ideal, as they pose limitations on the available resolution of the data they provide. For our work, we support a wide variety of camera hardware, by virtue of leveraging the webcam support built-in to the Microsoft development stack. Our testing has primarily used a The Imaging Source, LLC. DFK 23UV024 high-resolution, high-speed camera. The load cells used in our work is also heavily support by using the standard model GX-1 shear beam load cell – a common load cell produced by many manufacturers.

3 Software Requirements

The rehabilitation trainer software has only one primary user. This user is the clinician that will be in charge of using the software to collect data from a patient during jump trials. The functional requirements are detailed in the following subsections that address the various tasks that can be performed using this software.

3.1 Requirements

The functionalities of the rehabilitation trainer software are summarized below:

- The software must be able to access a USB 3.0 web camera in order to provide a live video feed of the jump trials. The live video feed that is shown on screen during jump trials will be recorded and saved for each jump trial performed.
- The software must provide a video player that will show the recorded video after each jump trial performed.
- The software must be able to read analog input from a USB data acquisition board connected to the force plates.
- The software must be able to record all data read from the force plates along with any calculations performed and save the data into a CSV file. The CSV file can then easily be opened inside of an excel spreadsheet for further review after any jump trial.
- In order to convert the voltage values that are read from the force plates into a newtons of force value, there must be a pre-determined gain multiplier for each of the 4 transducer channels on each force plate to successfully calculate this value. These gain multiplier values depend on the size and dimensions of the force plates that are being used to collect data from during jump trials. The clinician operating this software must specify the values to be used for the gain multipliers corresponding to the set of plates that are being used for the jump trials. See formula (1) below for how the newtons of force gets calculated for each channel 0 through 7.

$$Channel = TransducerVoltage * GainMultiplier \quad (1)$$

- For both the left and right force plate, each contain 4 transducers for capturing the force that gets applied to it. The software must sum these 4 transducers values on each plate during data collection in order to get the vertical ground reaction force (vGRF) applied to the plates individually. See formulas (2) and (3) below for how the left and right vertical ground reaction forces are calculated.

$$RightvGRF = Channel0 + Channel1 + Channel2 + Channel3 \quad (2)$$

$$LeftvGRF = Channel4 + Channel5 + Channel6 + Channel7 \quad (3)$$

- In order to get the total vertical ground reaction force that is applied to both plates, the software must be able to sum the values of the calculated left and right vertical ground reaction forces. See formula (4) below for how the total ground reaction force is calculated.

$$TotalvGRF = RightvGRF + LeftvGRF \quad (4)$$

- The symmetry of the force between the left and right plate must be calculated while data is being streamed from the force plates. See formula (5) below for how the live symmetry is calculated while data is being collected from the force plates.

$$LiveSymmetry = \frac{100 * 2 * (LeftvGRF - RightvGRF)}{(LeftvGRF + RightvGRF)} \quad (5)$$

- The symmetry of the force between the left and right plates must be calculated at the end of a jump trial using the max vertical ground reaction force values. See the formulas (6) below for how the maximum symmetry value is calculated at the end of a recording from the force plates.

$$MaxSymmetry = \frac{100 * 2 * (MaxLeftvGRF - MaxRightvGRF)}{(MaxLeftvGRF + MaxRightvGRF)} \quad (6)$$

- The calculated symmetry of force between the left and right plates must be visualized in a graph. This graph will display to the clinician and the patient the distribution of their weight on their left versus their right foot.
- The clinician must be able to enter patient ID as well as their weight in kilograms prior to starting a jump trial for a given patient.
- Due to electrical noise and interference in the system, there needs to be a zeroing process within the software on the force plates. This will ensure that the data being collected is accurate and not being effected by any of the electrical noise in the system.
- The center of pressure for the left and right plates, along with the combination of the two, must be calculated. The center of pressure will tell the clinician about what area of their foot their pressure is centered on and how it changes over time throughout their jump. See formulas (7), (8), (9), (10), (11), and (12) below for how the center of pressure values are calculated for the left and right plates along with the global center of pressure for both of the force plates.

$$RightXCOP = (RightLengthX/2) * (1 + ((Channel2 + Channel1) - (Channel3 + Channel0))/RightvGRF) + RightLengthXOffset \quad (7)$$

$$LeftXCOP = (LeftLengthX/2) * (1 + ((Channel6 + Channel5) - (Channel7 + Channel4))/LeftvGRF) + LeftLengthXOffset \quad (8)$$

$$RightYCOP = (RightLengthY/2) * (1 + ((Channel0 + Channel1) - (Channel3 + Channel2))/RightvGRF) + RightLengthYOffset \quad (9)$$

$$LeftYCOP = (LeftLengthY/2) * (1 + ((Channel4 + Channel5) - (Channel7 + Channel6))/LeftvGRF) + LeftLengthYOffset \quad (10)$$

$$GlobalXCOP = \frac{(LeftvGRF * LeftXCOP + RightvGRF * RightXCOP)}{TotalvGRF} \quad (11)$$

$$GlobalYCOP = \frac{(LeftvGRF * LeftYCOP + RightvGRF * RightYCOP)}{TotalvGRF} \quad (12)$$

where:

RightLengthX is the width between the midpoint of transducers (left to right) for the right force plate

RightLengthXOffset is the width to the midline between plates for the right force plate

RightLengthY is the length between the midpoint of transducers(near to far) for the right force plate

RightLengthYOffset is the length to the nearest edge of the force plate for the right force plate

LeftLengthX is the width between the midpoint of transducers (left to right) for the left force plate

LeftLengthXOffset is the width to the midline between plates for the left force plate

LeftLengthY is the length between the midpoint of transducers (near to far) for the left force plate

LeftLengthYOffset is the length to the nearest edge of the force plate for the left force plate

- The software must provide a graph that displays the calculated center of pressure values as the data is being collected from the force plates during a jump trial.
- The software must provide a scrolling time window graph that shows how the left, right, and total vertical ground reaction forces change over time throughout a trial.
- The software must signal to a patient when it is ready for force to be applied to the plates, as well as signal when a jump was detected so only relevant data is recorded for a given jump trial.

3.2 User Stories

- As a clinician, I need to start a test data stream from the force plates to start graphing any calculated values. This is to verify the function and accuracy of the force plates prior to an actual patient trial.
- As a clinician, I need to be able to set the force plates channel gain and choose the USB camera to record from in an options menu prior to starting a patient trial.
- As a clinician, I need to be able to enter patient information prior to a trial, such as weight which is needed for calculations as well as a patient ID to keep track of recorded patient trials.

- As a clinician, I need to be able to start and execute a set of jump trials for a given patient. For each jump trial in a session, all relevant data collected and calculated must be graphed for the patient or clinician to see. This data must also be recorded into a file for the clinician to review at a later time.
- As a clinician, I need to be able to review the recorded video directly after a jump trial has taken place.
- As a clinician, I need to be able to view all of the data collected from the plates along with any calculations that took place during each jump trial in a given session.

4 Software Design

This section on software design is split into 2 subsections. The first section shows a UML Class Diagram of the software design. Then, the second section talks about the UI design of the application and why it is so important for this application's domain.

4.1 UML Class Diagrams

The design of this software follows a model, view, view model architectural design pattern. The system is made up of 3 models, 5 views, and just 1 view model.

The `ChannelModel` holds the fields that pertain to the data coming in from the 8 transducer channels from the force plates. This model also holds the fields that store the various calculations that occur using the data from the force plates. The channel model also contains methods to use for calculating values that use this data from the force plates.

The `vGRFGraphModel` holds the 2 fields `ElapsedTime` and `vGRF`. This model is used along with the graphing library to map any type of data onto each axis of a graph. More specifically, the graphing library initially cannot map to the graph values of type `TimeSpan` from the `ElapsedTime` field. This model along with a mapper function built into the graphing library is used to be able to map a `TimeSpan` value to its associated graph.

The `OptionsModel` has fields that are associated with information that must be provided in the `OptionsWindow` of the program prior to streaming from the force plates and executing jump trials. The clinician must use the `OptionsWindow` to set the video capture device to use, set the save directory for files, and provide the file that contains all of the channel gain multipliers for their associated force plates being used.

Since this application shares much of the same data among all of the windows within the application, there is only one view model used. This view model is set as a static resource within the application, and each view/window that is opened during use of the software will use the same instance of the `MainViewModel` class. The `MainViewModel` contains fields that are bonded with various UI elements in the views to display and update these

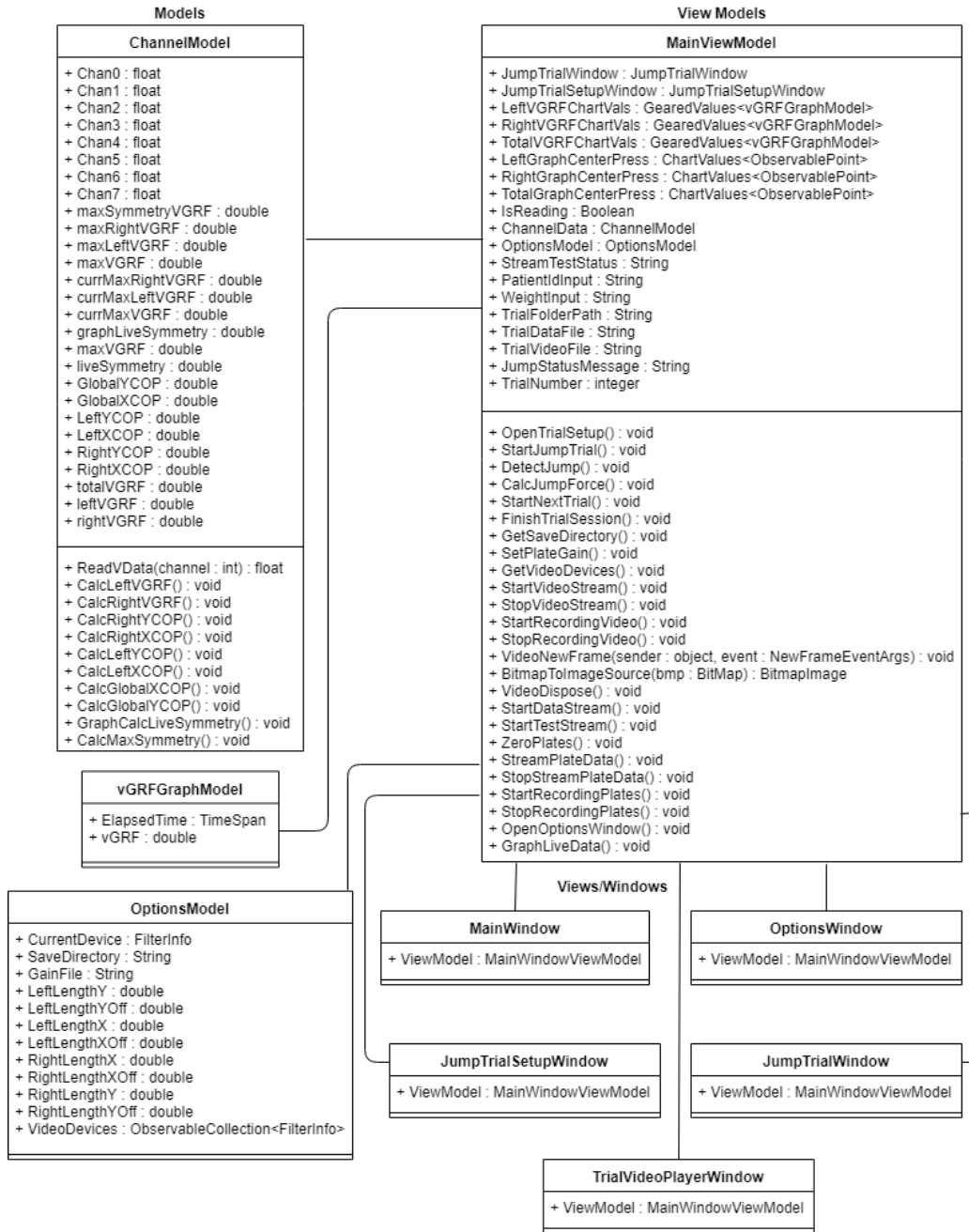


Figure 2: UML Class Diagram for Rehabilitation Trainer Software

values. It also has many methods that pertain to the various functionalities that need to be performed within the application.

4.2 UI Design

Since this application was designed to be used in a clinic setting, it was important that the UI design was kept as simple as possible. For this application, the goal was to make the

application very user friendly so that setup and starting to collect data from patients is just a few clicks away.

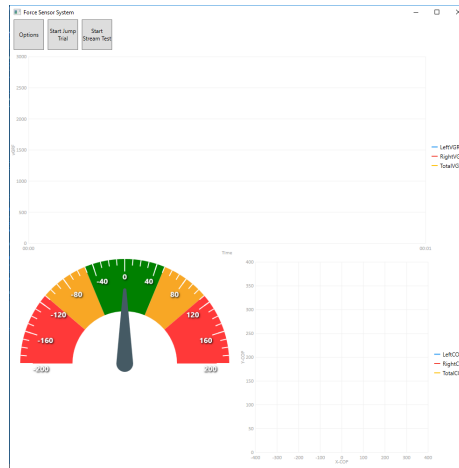


Figure 3: The main window of the application

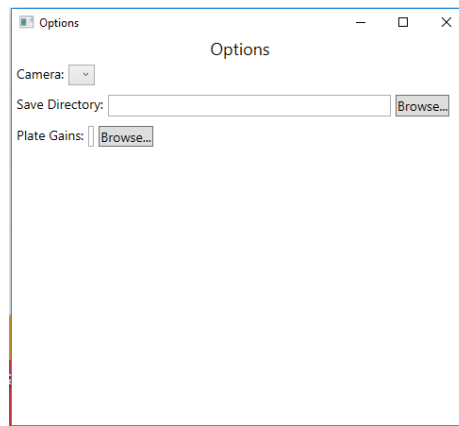


Figure 4: The window to set the options for the software and force plates.

Figure 3 shows the main window of the application when it is first started. The main window of the application contains 3 graphs. The graph on the top is the scrolling time graph that will show the left, right, and total vertical ground reaction force values over time. The gauge on the bottom left is what is used for showing the patients live weight symmetry. The last graph on the bottom right shows the live feed of the patients center of pressure during a stream test or jump trial. The graphs displayed on this window will be used during a stream test to verify that the force plates are working correctly. They will also be used to show the clinician these values while a patient is performing jump trials. This main window only has 3 buttons to interact with. The options button will open up the options window to set up the camera device, set the save directory for files, and the gain file to read the gain multiplier values from. Figure 4 shows the options window that gets displayed to the user for entering in this information. All of the options in the options window must be set, otherwise it is

not possible to start a stream test or a session of jump trials. The start stream test button will start streaming data from the force plates and displaying it on this window's graphs for the clinician to verify. Lastly, the start jump trial button will begin the setup to start patient trials.

Figure 5 shows the setup window that is shown to the clinician prior to starting a set of jump trials for a patient. The clinician must enter in the ID of the patient along with their weight in kilograms before they can continue with their trials. The get weight button is currently not in use on this window. It is planned in the future to have this button get the patients weight while they are standing still on the plates. Once this data is entered, the clinician can press the start trial button on this window to open the jump trial window and begin collecting data.

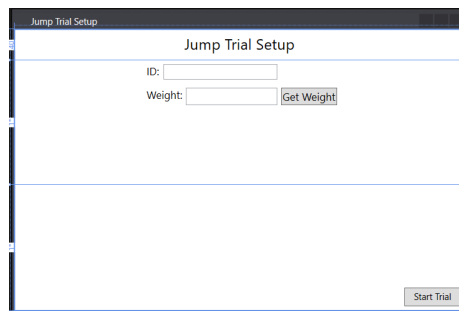


Figure 5: The window to enter patient information prior to starting a set of jump trials.

Figure 6 shows the jump trial window that will be opened upon finishing the jump trial setup. This window has one gauge that is located on the top of the screen. This gauge is mapped to a value that is calculated at the end of every jump trial. This value is the max symmetry vertical ground reaction force. This value will visualize to the patient what their weight symmetry was like at the time of maximum force being applied to the plates. Below the gauge there is a label setup with the name $vGRF$. This label will also receive a value to display to the patient after each jump. This value will essentially be the multiple of their body weight that was applied to the force plates. The bottom right portion of the screen is reserved for a jump status message. This informs the patient whether or not the system is ready for them to jump on the plates for a given trial. It will also inform the user when a jump has been detected in this area. The larger portion in the middle of the screen on the bottom displays the live video feed from the web camera. Lastly, the bottom has a counter to keep track of what trial number you are on along with buttons for various controls. The 3 buttons in the bottom right can be used to advance to the next trial, finish the trial session, or to open the video from the previously recorded jump trial.

At the end of each jump trial, the values on the jump trial window will be displayed to the patient, all of the recorded data will be saved into a CSV file, and the video file will also be saved. After all of the data is done processing for a trial, a video player window will open with the recorded video from the previous trial. From here, the clinician and patient can

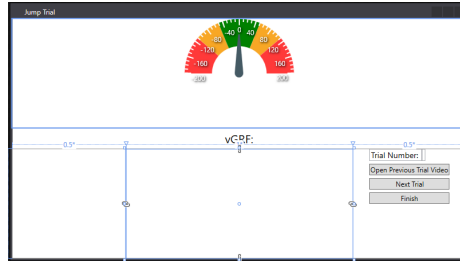


Figure 6: The window shown to the patient and clinician while performing jump trials.

review the video from the previous trial before moving on to the next jump trial. Figure 7 shows the video player window that is shown after each of the jump trials performed in a session. This window only has 3 controls to interact with, a play button, a stop button, and a time-seeking slider.

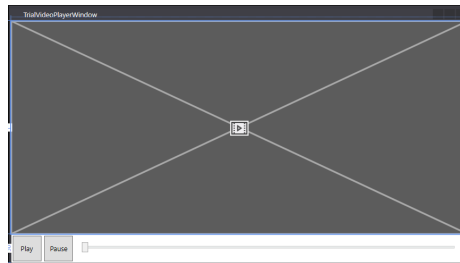


Figure 7: The video player window shown to the patient and clinician after each jump trial.

5 Conclusion

In this paper we describe a collaborative software project between the Health Professions and Computer Science departments of the University of Wisconsin-La Crosse. The project implements a visualization tool for video and force sensor measurements from a rehabilitation platform. We outlined the rationale for the project – having the two main goals that the software should be easy-to-use by non-technical clinicians, while also being cheaper than existing data acquisition software tools. We also describe the software engineering aspects unique to this project.

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