RESEARCH PROJECT IN MECHATRONICS ENGINEERING

IMPROVING AN EXISITING REHABILITATION EXOSKELETON DEVICE

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ABSTRACT

The purpose of this project was to improve the gait rehabilitation process for stroke patients. This was achieved by improving an existing assist-as-needed exoskeleton device designed and built by Brian Cao, a PhD student at the University of Auckland, in order to further improve gait rehabilitation for stroke patients.

After a comprehensive literature review, two key aspects were identified as being under developed in both the exoskeleton itself and the general robotic exoskeleton field. The first aspect was adding more degrees of freedom to the exoskeleton, to improve comfort by enabling following of realistic gait patterns and to give users the option to turn corners. These added degrees of freedom were implemented into the back support and the hip joint of the exoskeleton. The second aspect was improving user feedback by making the exoskeleton a universal game controller and by adding haptics to the system to improve the tracking capability of the exoskeleton.

Despite the many issues that arose within this project, the aims of these two aspects were sufficiently met. It has been proven that both aspects are useful additions to the exoskeleton device. Additionally, both can be further developed to further improve the exoskeleton and the stroke rehabilitation process.

DECLARATION

Student

I ....BLAIR DUNCAN............ hereby declare that:

1. This report is the result of the final year project work carried out by my project partner (see cover page) and I under the guidance of our supervisor (see cover page) in the 2016 academic year at the Mechanical Engineering Department, Faculty of Engineering, the University of Auckland.
2. This report is not the outcome of work done previously.
3. This report is not the outcome of work done in collaboration, except that with a project sponsor as stated in the text.
4. This report is not the same as any report, thesis, conference article or journal paper, or any other publication or unpublished work in any format.

In the case of a continuing project: State clearly what has been developed during the project and what was available from previous years:

Signature: B. Duncan

Date: 20/09/16

Supervisor

I confirm that the project work undertaken by this student in the 2016 academic year ~~**is**~~/**is not** (*strikethrough as appropriate*) part of a continuing project, components of which have been completed previously.

Comments, if any:

Signature:

Date: 20-9-2016

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Glossary of Terms

ANSYS	A simulation software package used in this project to determine the strength of a mechanical part
Anthropometric	Population data referring to measurements of humans
CAD	Computer Aided Design
Creo Parametric	A modelling software package used to design all mechanical components in this project
Doffing	To take off
Donning	To put on
Gait	Pattern of movements an animals limbs make during walking
Haptics	A form of interaction involving touch. Frequently refers to haptics for feeling vibration in this report
HID	Human Interface Device
PCB	Printed Circuit Board
Minitec	A premade aluminium bar frequently used in this project
MPa	Mega pascals – A measurement of pressure
myRIO	A hardware package developed by National Instruments intended to be used with LabVIEW, a software package developed by the same company

1.0 Introduction

Stroke is one of the leading causes of disability; globally, 15 million people suffer strokes each year [1]. One of the main characteristics of stroke is the loss of basic motor skills and can therefore cause these people to struggle with day to day tasks such as walking. During a study in Auckland, New Zealand of 680 stroke patients, 88% suffered a hemiparesis, paralysis of one side of the body [2]. Gait rehabilitation for both patients and therapists can be time-consuming and exhausting. This project's purpose is to improve the rehabilitation process for patients and therapists through the use of a type of rehabilitation robot; an exoskeleton.

Originally this project aimed to improve gait rehabilitation by designing, building and testing a robotic exoskeleton for assist-as-needed gait rehabilitation in stroke patients. However as a result of a literature review conducted prior to beginning the design of this device, it was discovered that building a full lower limb robotic exoskeleton device would be too costly and time consuming. The literature review also informed the authors of many other similar devices already on the market or in development that would supersede a newly designed device designed. However the review revealed two aspects within the rehabilitation robot research field that had not been investigated in detail by these other devices. Therefore a decision was made to shift the focus and aims of this project to these two aspects, by applying them to an exoskeleton built by a doctorate student, Brian Cao.

The first aspect highlighted by literature as under researched in robotic exoskeletons is added degrees of freedom. Many lower limb exoskeleton devices used in gait rehabilitation only allow patients to walk in a forward direction which is unrealistic in the real world. As the back support design being used by the original exoskeleton only provided passive control over the vertical up and down motion, further development was necessary, in order to improve the comfort and support this back support provided, as well as opening up the option of allowing the patient to turn corners. This, coupled with a new hip joint that also added new degrees of freedom to the system, resulted in a more versatile device that was more comfortable to use and allowed patients to turn corners.

The second aspect involves user feedback. Although the literature showed that many devices did provide user feedback, it was usually in the form of graphs and tables. The idea behind this part of the project is to provide more stimulating and visual feedback by pairing the robotic exoskeleton with a Playstation 2 controller. This allows the user to control the speed of a character/object in a Playstation 2 game by controlling the speed at which they walk. Haptics' were also investigated as a form of feedback to improve the compliance of the system.

2.0 Literature Review

Prior to beginning the design process a literature review was performed, but due to the shift in project aim this process was carried out twice. The first literature review was focused on the previous aims of the project. Because this review was broad in nature, it provided a lot of insight into the robotic exoskeleton field of research and proved to be very useful. It also highlighted pre-existing issues with the original aims and allowed us to shift the focus of the project earlier saving both time and money. The second literature review focused more on the movement of the back and determining which were important for stroke patients.

2.1 Literature Review

The first literature review covered a wide range of aspects in the robotic exoskeleton research field as it was focused on exoskeleton devices as a whole. This review can be broken up into six different parts; existing exoskeleton systems, tests to assess gait, controller architecture, actuators, sensors and miscellaneous aspects such as comfort and safety. Despite the change in direction of the project, this literature review still contains useful information that can be transferred to the new system as well as providing a deeper understanding of the existing field of research.

2.1.1 Existing Exoskeleton Devices

Prior to starting this literature review, the authors believed robotic exoskeletons were the only type of rehabilitation robots. However it was quickly discovered that there is another major type of rehabilitation; end-effector devices. These differ to exoskeleton devices in that a robotic exoskeleton aligns to a user's joints to provide direct control over their joints, whereas the end-effector device attaches only to the user's feet. This realisation helped to clarify exactly what sort of device this project needed to focus on and allowed further research to focus on exoskeleton devices rather than rehabilitation robots as a whole. Two exoskeletons already available on the market (the H2 exoskeleton and the LOPES exoskeleton) were used as inspiration in the design of exoskeleton device [3].

2.1.2 Assessing Gait

To assess gait, metrics such as step length asymmetry (SLA) and stride length (SL) are measured while the user performs tests such as the 10 meter walk test or a timed test. Although these metrics will still be useful for measuring the success of the back support design, it is likely a user feedback form may be a better measure of the designs success. This is because back movement does not have as great of an effect to the SLA and SL metrics as knee and hip movement do. User comfort was considered an important measure for both the back support and the added degrees of freedom in the hip joint [4] [5].

2.1.3 Controller Architecture

To control the original exoskeleton device that is no longer being built, it was decided that it would use a controller area network (CAN). However since this project now involved a PhD student's exoskeleton, using the controller network that had already been set up was a sensible choice. The method used by the PhD student's exoskeleton was positional control. This involves setting up a 'tunnel' of positional coordinates that correspond to the correct location of a user's joints for their current stage through a gait cycle. If the joint is moved outside of this tunnel, the exoskeleton device guides the user's joint to a correct position. This is the same algorithm that was to be implemented in the original exoskeleton device, prior to the project shift [5] [6].

2.1.4 Actuators

Electric motors had been decided on prior to the project shift, due to their simplicity when compared to other appropriate actuators such as pneumatic air muscles (PAM) or linear actuators (both pneumatic and electric). However, as the literature review continued it became apparent that it would not be possible to design and build a successful system with the limited budget provided. Motors that were sufficiently powerful and accurate were deemed too expensive, while motors that fell within budget were either too weak or inaccurate. This was a major factor when considering the project shift [7].

2.1.5 Comfort and Safety

Comfort and safety are important factors to consider when designing a rehabilitation device, as the patient will be less inclined to use the device if they feel uncomfortable or unsafe.

To improve comfort, literature reviewed at this stage suggested the use of foam pads and designing the exoskeleton control algorithm, so that it carries its own weight and feels weightless to the user. Due to the nature of the back support and how the device attaches to the user, there was no need to implement the weightless algorithm for the back support itself. However placing straps and foam pads on the back plate (where the device is attached to the user) would be beneficial as well as relatively cheap [5].

Safety is always an important consideration when designing robotic devices. To improve safety, many of the devices investigated in literature implemented the use of mechanical stops to restrict movement past safe operating ranges. Adding to this, a device developed by S. Hussain, P. K. Jamwala, J. Parsons and S. Q. Xie utilised a safety button that can be pressed to power down the system, should the patient feel uncomfortable [7].

2.1.6 Donning Time

While investigating the various literatures referenced in this report, it was found that donning and doffing time (the time needed to attach and remove the exoskeleton) was something that needed to be accounted for when designing the device. It was found that current robotic exoskeleton devices tend to have a donning time of 10-20 minutes for the first rehabilitation session and about 10 minutes for recurring sessions [8] [9]. When compared to the length of an average rehabilitation session (between 30 to 60 minutes) this is a significant amount of time [9].

Minimising the donning time of our exoskeleton would make the session less demanding for both the patient and the therapist. To do so, the exoskeleton needed to be easily adjustable and attachable while remaining aligned to the patient’s body. Potential solutions were the straps found on roller-skates, bindings on snowboards or possibly even a strong Velcro strap.

2.1.7 User Limits

It would be near impossible to design a wearable exoskeleton that is useable by everyone. Therefore defining weight and height limits was necessary. To cover the majority of the population we looked at 95-99% anthropometric data for the U.S. population when defining these limits for our exoskeleton. Looking at current designs, a weight limit of around 120kg and a height limit of 190cm was deemed appropriate [9] [10] [11].

2.1.8 Back Movement during Gait

After the aims of the project changed to improving an exoskeleton device rather than building one, it was important to determine which motions the new back support design needed to be able to achieve. To determine what the back support needed to be provide to stroke patients as they walk, it was important to first find out how a healthy person's back moves during a standard gait cycle. Although there is a lot of information on human gait cycle, this information is focused on knee and hip joints and it was therefore difficult to obtain any information about the movement of the back and pelvis. A deeper understanding of how the back, as well as the rest of the body, moves during gait, was obtained by studying literature [12]. It outlined the key back movements used during gait and the ranges in which they move. These motions include vertical displacement, lateral displacement (pelvic sway), pelvic rotation and pelvic tilt. These motions and their relative amplitudes are shown in appendix A and the motions being controlled by the back support are described in more detail in section 3.1. A diagram showing the different planes referred to in this report is shown in Figure 1 [12] [13] [14].

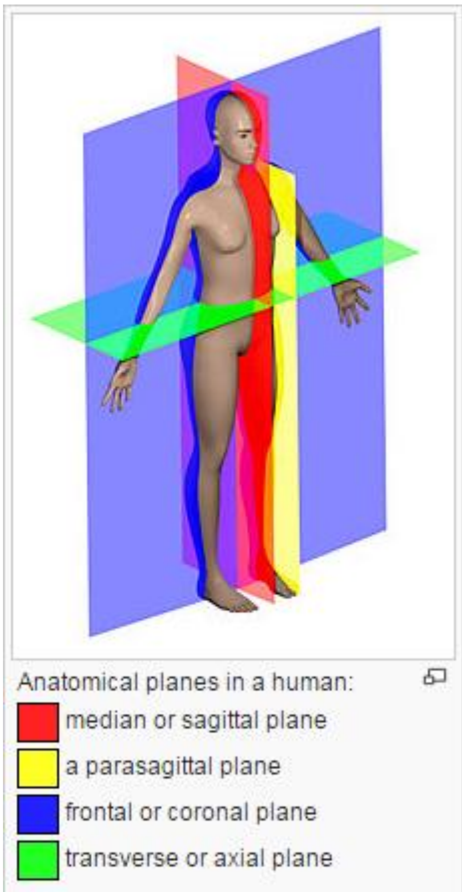

Figure 1: Diagram showing the anatomical planes of a human [15]

Once normal human gait patterns had been determined, pathological gait patterns of stroke patients needed to be established. It was found that the pathology of a stroke patient depended largely on the section or sections of the brain the affected by the stroke. This made selecting the 'correct' motions to be controlled impossible under a limited budget. However three motions; pelvic twist, hip sway and hip hiking, (see figures 2, 3 and 4) were deemed important for stroke patients after reviewing multiple literature sources [16] [17]. When designing the back support, it became apparent that it would not be possible to control the hip hiking motion due to complexity and cost. Therefore it was decided that if this motion was kept fixed it would provide satisfactory support for the user to feel comfortable when using the device.

All literature investigated dealing with the user feedback and the hip joint has been completed by project partner Luke Sawyers.

3.0 System Design

3.1 Back Support

Prior to the change in project aims, the PhD student's exoskeletons back support consisted of a simple four bar linkage and two pneumatic springs. This design allowed for passive control over linear motion in the vertical plane, while restricting all other movements. By altering the simple four bar linkage, two extra degrees of freedom could be added to further improve the exoskeleton device and the quality of the rehabilitation process.

3.1.1 Degrees of Freedom

As mentioned in the secondary literature review (section 2.2) much research was conducted in order to determine the motions the active back support design needed to control. As the pathology for stroke patients is largely determined by the location of the stroke, it was impossible to provide a 'perfect' device while still staying within the project's budget. Therefore only a few motions were selected.

The first motion to be selected was angular movement in the transverse plane, also known as axial or pelvic twist (shown in Figure 2). This motion was deemed important as stroke patients tend to favour their non-affected side more than their affected side. This results in patients spending a greater proportion of time in the stance stage on one leg than the other [17].This movement is important as it provides a driving force to transition the patient into the next stage of the gait cycle. The user's pelvis rotates $\pm 10°$ from the centre position in this direction and therefore a range of $30°$ was designed, to ensure there would be no collisions. [12]

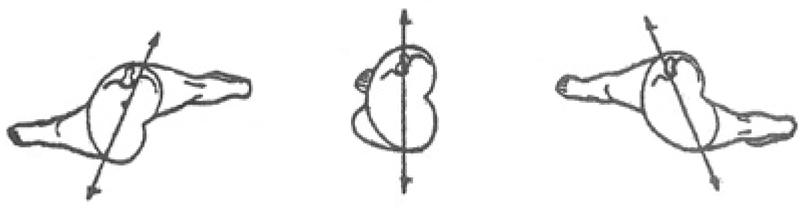

Figure 2: Birds eye view showing axial/pelvic twist [13]

The second motion selected was linear motion in the horizontal plane, also known as hip sway (shown in Figure 3). Literature suggested this was a valuable motion to control as stroke patients often lean and shift their body weight to their non-affected side. The user's pelvis moves $\pm 5cm$ from the centre position in this direction and therefore a range of $15cm$ was designed to ensure there would be no collisions. [12]

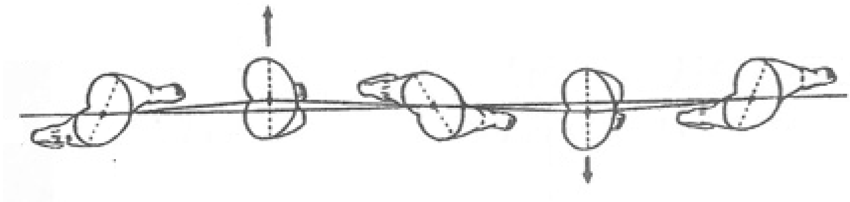

Figure 3: Birds eye view showing hip sway [13]

The third actively controlled motion was angular movement in the coronal plane, also known as hip hiking (shown in Figure 4). This motion is important to control as stroke patients tend to ‘throw’ their affected leg through the swing phase of gait due to a lack of control and strength in their hip. Although this motion was selected to be controlled, it was decided that it was too difficult to design a back support that allowed for this movement while also keeping within both the budget and time constraints. [12]

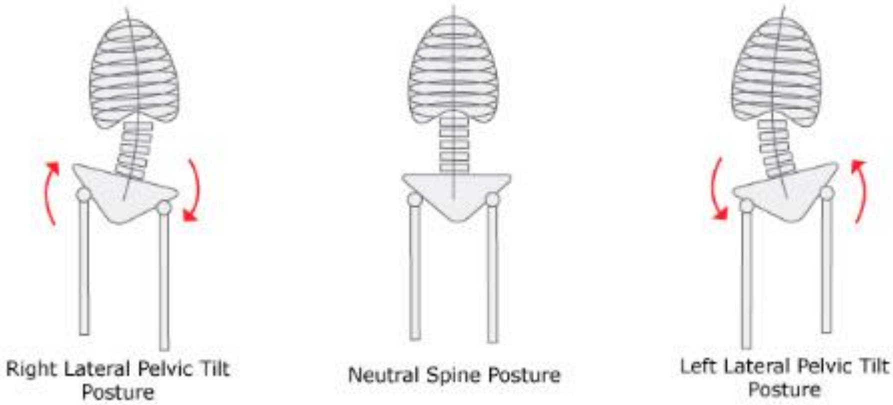

Figure 4: Diagram showing hip hiking [23]

3.1.2 Design

Shown in Figure 5 is an early concept design for the back support device. This is the concept that was chosen and further developed. The motion of the linear actuators are shown with blue arrows. These actuators provide active control over the back plate shown. Although it is not shown, this back plate will be supported by two 16mm hollow rods with two linear bearings (LM16UU) for each rod. This ensures the linear actuators do not experience any damaging lateral loads as well as restricting the back plates movement to the desired motions.

A center bar between the two plates can be seen at the bottom of this design. This center bar ensures the two linear actuators controlling the angular motion do not experience damaging lateral load. The bar is to be bolted to the fixed support (circled in red) and pin jointed to the actuated support (circled in green) to restrict movements to the motions described in section 3.1.1.

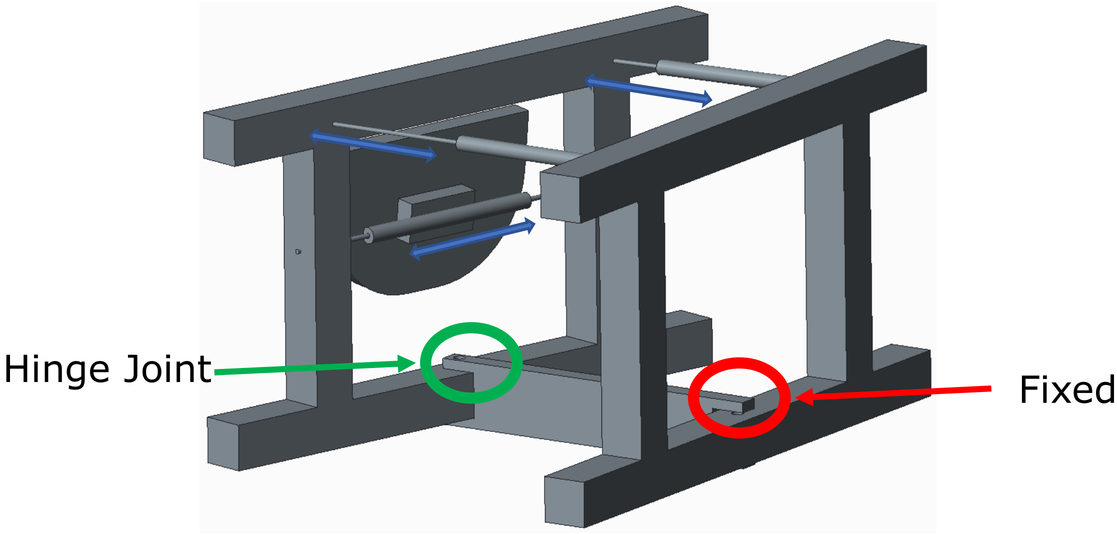

Figure 5: Back support concept design

3.1.3 Method of Actuation

A lot of time was put into deciding the method of actuation for the active back support design. As shown in Figure 5: Back support concept design, three methods of linear actuation are required to control the proposed design. This proved very difficult due to the limited budget attached to this project.

Before attempting to find suitable linear actuators, the requirement of each actuator needed to be worked out. As shown in Figure 5: Back support concept design, there are two linear actuators controlling angular motion in the transverse plane (axial twist). Using force measurements (normalised to body weight percentage) found in an article by J. P. Callaghan, A. E. Patla and S. M. McGill as well as the anthropometric data for adult body weight in the United States from 2007-2010 (taking 124.1kg as max weight) the force the two actuators needed to apply could be calculated given the setup in Figure 5: Back support concept design. This gave a required torque of $0.75 \times 124.1 = 93.075Nm$ [17] [18]. Given the actuators are 355mm apart, each linear actuator controlling the angular movement of the device needs to provide $93.075/(177.5 \times 10^{-3} \times 2) = 262N$. Using the distance between the two actuators (355mm) and the angle the support needs to be able to move through (30°), simple trigonometry can be used to determine both actuators need to be able to extend 90mm.

As shown in Figure 5: Back support concept design, there is a single linear actuator controlling motion in the linear horizontal plane. Using the force measurements from the previously mentioned source it was calculated this actuator needed to provide 38.44N [17]. However to ensure this actuator would not fail under the weight of the user if they lose balance at its extended position, another trigonometry calculation was performed. This resulted in a higher required force (101.37N) and this actuator was therefore designed for this calculation.

Originally it was decided that pneumatic air cylinders would be used to control the motion of the back support, as they are inherently compliant and relatively simple to control. However after selecting the suitable cylinders for our application, it was discovered the valves we could afford could not provide the level of control the application required. The valves made available to us by our budget could only switch at a maximum of 3 hertz and only operated as an ‘on/off’ switch. A quote from SMC Pneumatics for the three required cylinders came to $172.20. The solution was to use proportional valves which would allow positional control of the cylinder rod. However prices for these valves were outside of the allocated budget.

After ruling out pneumatic actuators, the next option was electric linear actuators. Although these actuators are not compliant, they would provide the required control for the application. However these actuators either extended and retracted too slowly or were too expensive. The next option was to repair two electric linear actuators that had been found in the university laboratory. Although this would have fallen into our budget while also providing the required control, the parts needed to repair these actuators were very specific, the original supplier could not be contacted and the lead time was too high for this to be a viable option.

The final solution investigated to actuate the back support involved driving threaded rods with electric motors. This would require three motors each with 4550 rpm and 0.03Nm torque costing $342.60 each. Two of these motors could be paired with an M12 threaded rod with a pitch of 1.25 in order to obtain the required speed and torque to control the angular motion of the back support. The remaining motor could be paired with an M12 threaded rod with a pitch of 1.75 in order to obtain the required speed and torque to control the linear motion of the back support. However if these actuators are attached directly to the frames shown in Figure 5: Back support concept design, the rod will protrude when contracted which would create safety hazards and restrict the use of the system. A solution to this is to set it up like a pneumatic cylinder rod by attaching a tube between the threaded rod and the actuated plate to hide the rod. The benefit of this solution was that it was easy to find motors with a lead time suitable for this project. However this was deemed to not be an appropriate solution due to safety hazards and high costs and therefore another project shift in terms of the back support was required.

It was therefore decided that the back support in this project would be a data gathering device that could also be developed further to be actuated and properly controlled. This meant the structural design of the new back support would remain unchanged but weak gas springs would be used instead of actuators to provide some support. It also meant that there had to be two centre bar arms (the second placed above the previously designed one) as the position of the top of the four bar linkage was no being controller by an actuator pair.

3.1.4 Detailed Design

Although the new main aim of the back support is to be a data gathering device, some development into actuating the pelvic sway movement was made. Using similar requirements for the pelvic sway movement, a new motor and threaded rod system was designed. This design used a cheaper brushed DC motor from RS ($123.50 before tax) that could be used with a motor controller already available for use from the University workshop. This motor is to be attached to an M20 threaded rod with a standard pitch of 2.5mm with a simple coupling that will be made in the University workshop. It will be used to drive a coupling nut that in turn drives a back plate that a patient is attached to. This coupling is to be machined out of a 45 mm section of aluminium rod that has a diameter of 30 mm. It attaches to the two shafts (motor and threaded rod) with a tight fit and uses two grub screws to be locked into place. The threaded rod will also be machined down using a lathe tool in the university workshop to remove the thread to fit its bearings and the coupling to the motor.

With the main structure of back support designed, the next step was to design the back plate that attaches to the user. This back plate also has to hold the four linear bearings to ensure smooth transmission. To achieve this, two 10 mm laser cut plates with bearing shaped sections cut out of them were placed on either side of the bearing and clamped together.

The basis of the back plate structure was to clamp and connect all four bearings which in turn produced a structure that was developed further to become the back plate shown in Figure 6. This design allows for an M20 threaded rod to pass through the centre of it and has enough room between the two middle vertical plates to house an M20 coupling nut.

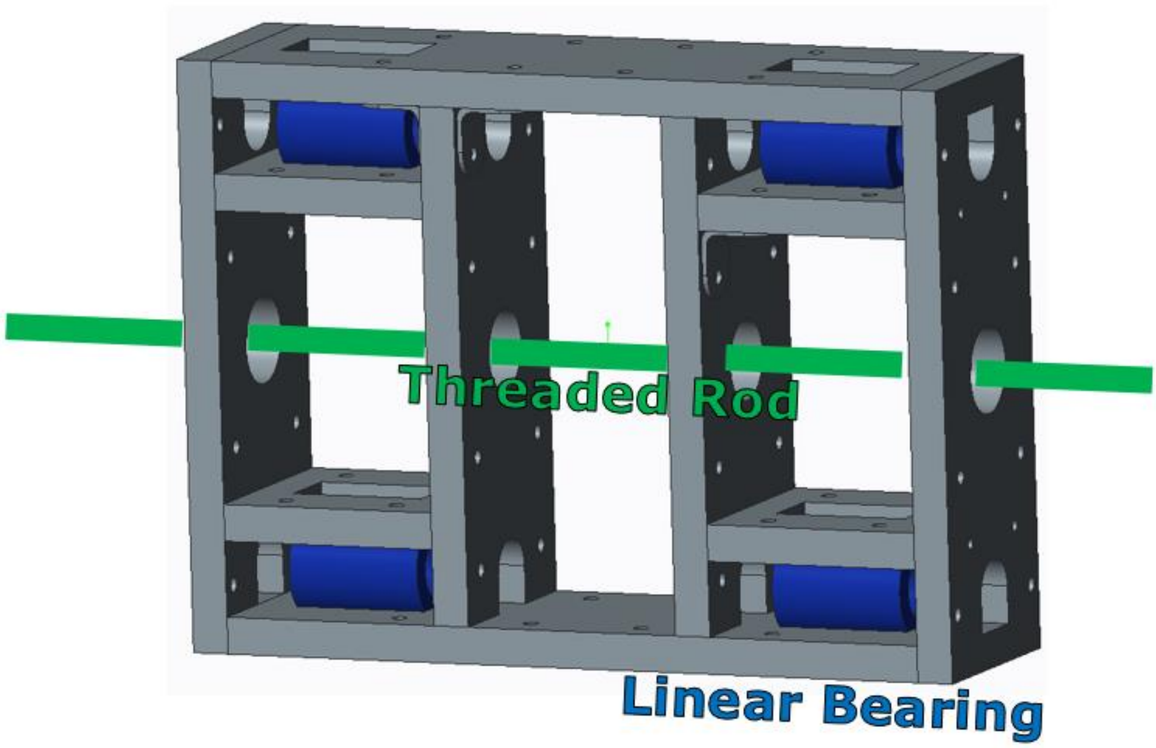

Figure 6: Final back plate design. Shows placement of threaded rod

The next stage of the design involved the centre bar arms to support and guide the movements of the four bar linkage. At this stage of the project, it was requested that the new back support design incorporate the vertical motion that was previously implemented in the original back support. At first this seemed like a redundant task as literature suggested this degree of freedom (vertical motion of the back) was not vital to gait rehabilitation. However a simple change to the centre bar arm design allowed for this movement with little or no effect on the other allowed degrees of freedom. This change involved adding two new hinge joints to the centre bar to allow movement in this axis. This new design was implemented in both the top and bottom arms and is shown implemented with the rest of the design in Figure 7.

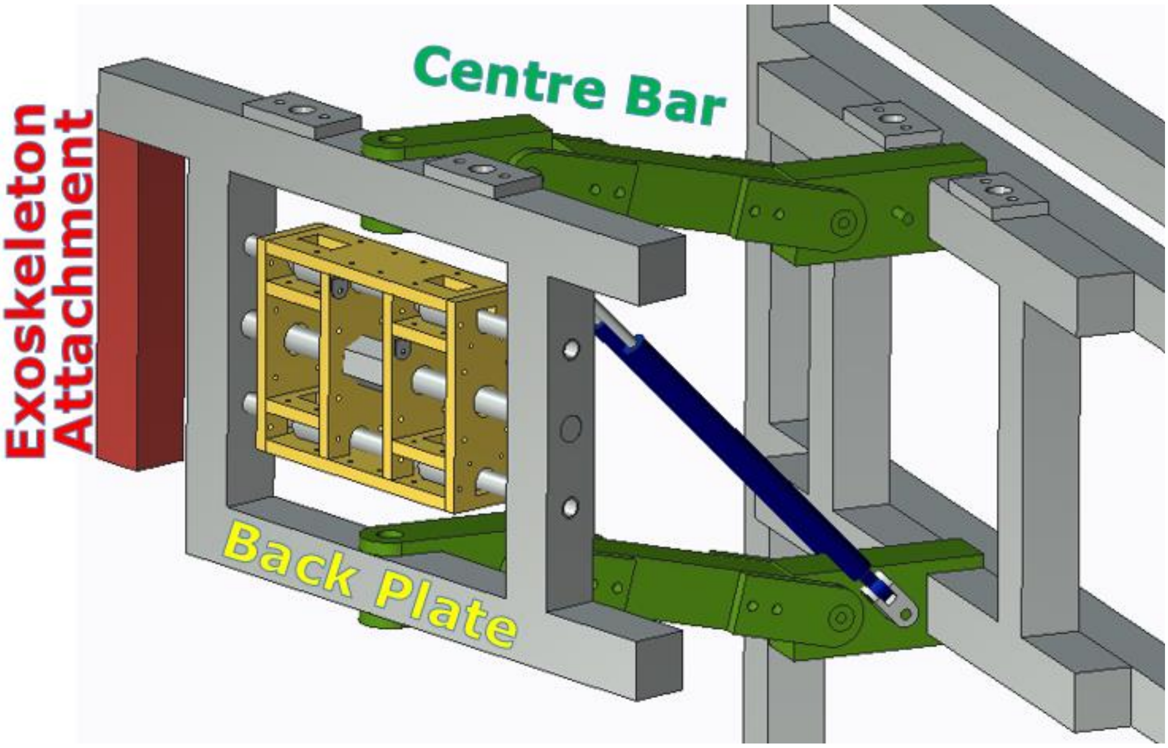

Figure 7: Final Creo assembly of the back support

As the new aim for the back support is to act as a basis for further development and data gathering, a sensor was required for each movement that is to be actuated in future work. This meant a linear potentiometer (100mm in length due to the range of movement) was needed for each joint. For the pelvic sway movement this was simple as it is a linear motion. The pelvic twist, however, is an angular movement so a small four bar linkage was used to operate the potentiometer which allowed simple trigonometry to be used to work out the angles the device moves through. This set up can be seen in Figure 8.

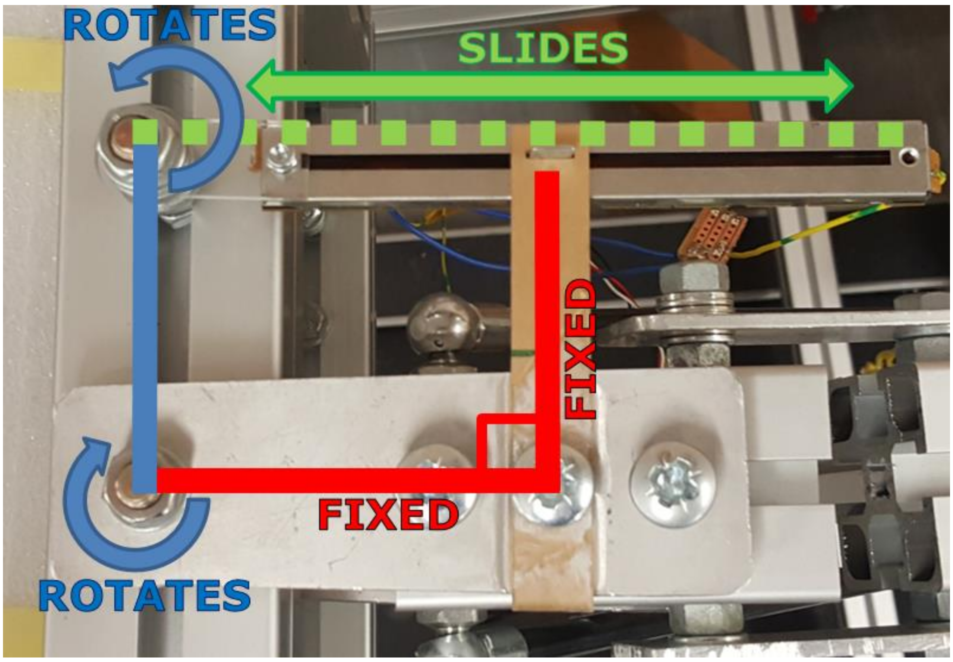

Figure 8: Linear potentiometer set up for pelvic twist

3.2 Hip Joint

3.2.1 Design

The designed hip joint (shown in Figure 9: Hip joint design to add two degrees of freedom. Designed by Luke Sawyers) has been designed by project partner Luke Sawyers. It has been designed to allow both abduction and adduction of the hip as well as axial rotation of the leg as shown with green arrows. The joint is attached between the leg (highlighted in blue) and the back support frame (highlighted in red).

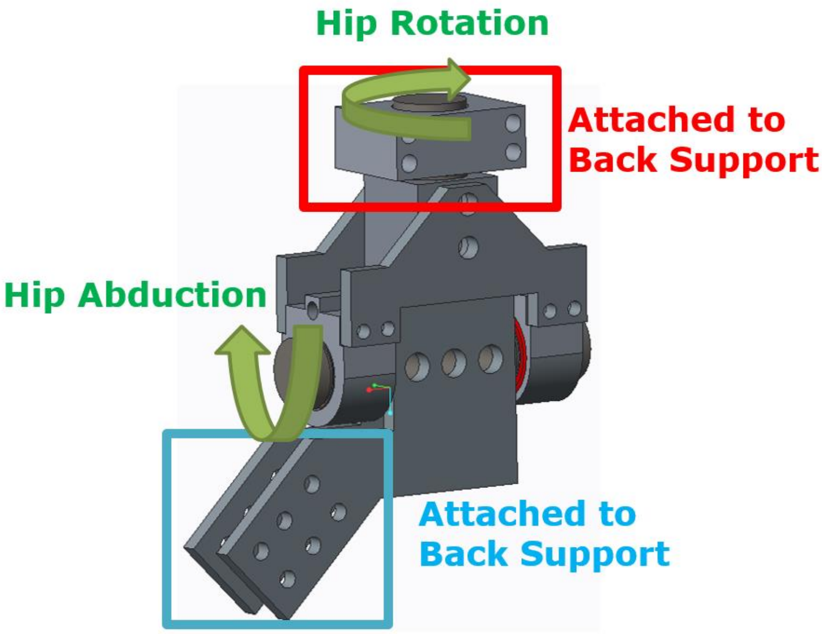

Figure 9: Hip joint design to add two degrees of freedom. Designed by Luke Sawyers

3.2.2 ANSYS Analysis

To ensure this hip joint could withstand the required load, ANSYS was used to perform static analysis. Although the hip joint will be moving dynamically, this would have been more difficult to model in ANSYS. Therefore it was decided static analysis would be sufficient, as long as the stresses were sufficiently below the material's yield stress. The CAD model (designed by project partner Luke Sawyers) was easily imported into ANSYS from Creo Parametric.

To set this analysis up, forces needed to be correctly placed and a fixed support had to be selected. The fixed support was located on the block at the top of the part (as shown in Figure 9: Hip joint design to add two degrees of freedom. Designed by Luke Sawyers) as this is the part that would be attached to the upper frame of the exoskeleton. The hip joint needed to be able to hold the weight of the lower exoskeleton frame (everything below the joint) which weighs 11kg. However at the time of analysis it was believed to weigh 12kg and after applying a safety factor of 2, the tested weight was 24kg. This was applied to the ANSYS model through the twelve holes (six on each plate) at the bottom of the part as shown in Figure 9: Hip joint design to add two degrees of freedom. Designed by Luke Sawyers. The force applied to each hole in a downwards direction is 19.62N.

Both principal and shear stress analysis has been performed. In Figure 10: Ansys analysis showing the principal stresses on the loaded hip joint it can be seen that there are two points on the model that experience high principal stresses in relation to the rest of the model, as circled in red. It can be seen that the highest principal stress experienced by this part is 53.318 MPa. This is much lower than the yield stress of aluminium (276 MPa) allowing the assumption that the part's integrity will not fail in the principal plane when dynamically loaded. Furthermore, the high stress on the lower plates is due to a sharp corner. During manufacturing this corner will naturally become slightly curved, reducing stress in this area.

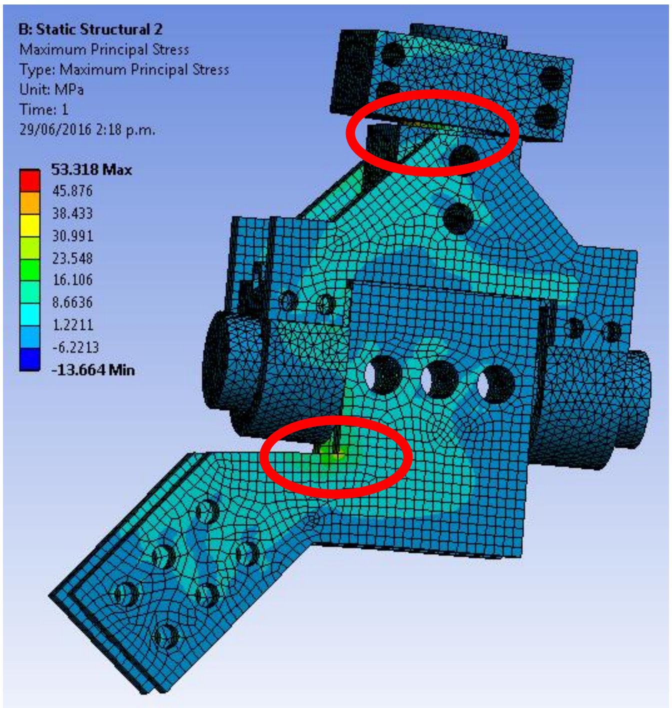

Figure 10: Ansys analysis showing the principal stresses on the loaded hip joint

In Figure 11: Ansys analysis showing the shear stresses on the loaded hip joint it can be seen that, as with principal stress, there are two points on the model that experience high shear stress in relation to the rest of the model, as circled in red. The highest shear stress experienced by this part is 22.255 MPa. This is much lower than the shear strength of aluminium (approximately 150 MPa), allowing for the assumption that the part's integrity will not fail due to shear forces when dynamically loaded. Both of these results suggest that the hip joint is able to withstand the forces it is likely to experience.

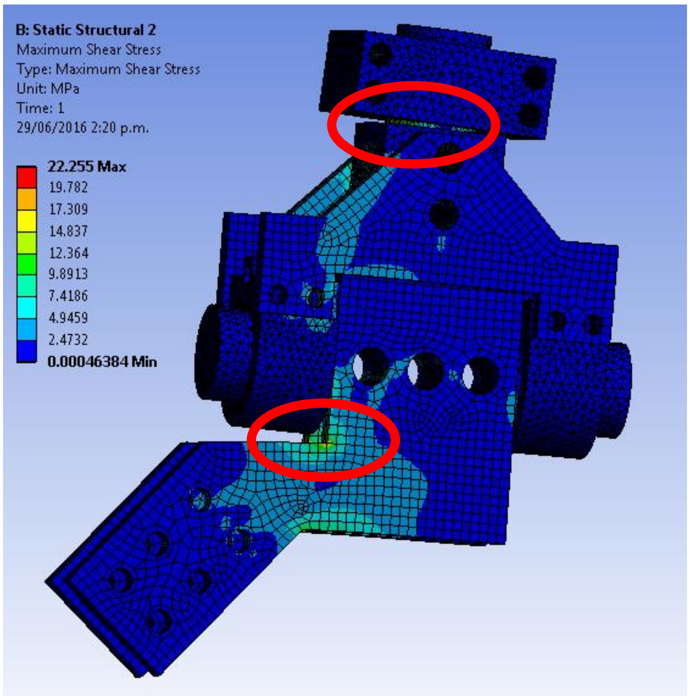

Figure 11: Ansys analysis showing the shear stresses on the loaded hip joint

3.3 User Feedback

One of the key aims of the user feedback system was to meet the requirements while remaining as low cost as possible. This lead to the system using an Arduino Leonardo as it has a native USB support that can be made human interface device (HID) compliant. A PCB was also designed and integrated by project partner Luke Sawyers that acts as an Arduino shield (sits on top of the Arduino Leonardo). This meant the system was able to be easily deployed, compatible with most versions of Windows and remain cheap (approximately $50.00).

3.3.1 Pairing to a Playstation Controller

In literature and previous final year projects completed at the University of Auckland, rehabilitation devices have been used to control games as a means of further engaging patients in the rehabilitation process. This idea suggests that the exoskeleton could be used to control a character's actions by the player controlling their walking speed or rotating their hips. However it was found in literature that these devices were unable to be used with normal games and some of devices needed software such as LabVIEW. This seemed counter intuitive as the gaming market has a huge range of games and therefore suggested that this device should find a way to be able to interface with as many games as possible. To do this the exoskeleton needed to be made HID compliant. This was done by utilising the native USB support on the Arduino Leonardo as this was a simple, low cost solution.

3.3.2 Haptic Feedback

Another simple and low-cost way in which the exoskeleton can provide user feedback is through haptic feedback. To achieve this haptic drivers were placed on the Arduino shield to drive four motors with eccentric masses attached. Two of these motors were positioned on the exoskeleton to target both the front and back of thigh and another two were positioned to target the front and back of the lower leg. These motors were used to provide feedback in the form of vibrations when the user moves their leg to an incorrect position.

4.0 System Implementation

4.1 Back Support

The design for the back support was intentionally done in such a way that would allow for simple manufacturing. This is because getting parts manufactured at university would have taken a long time, due to queuing. As a lot of time was lost due to the project shift at the beginning of the year and the time spent on choosing actuators, there was insufficient time for this to be an option. Instead, the design utilised the two laser cutters and minitec beams that were readily available for use.

4.1.1 Back Plate

The back plate was laser cut using sections of 10mm acrylic and small brackets purchased from a local hardware store. This proved to be more time consuming than expected, as the quality of the brackets varied significantly and therefore time had to be taken to sort them into matching pairs to ensure they correctly fit into acrylic. As this device was not actuated in this project, the holes left for the threaded rod were available to be used for the back strap. The final back plate can be seen in Figure 12.

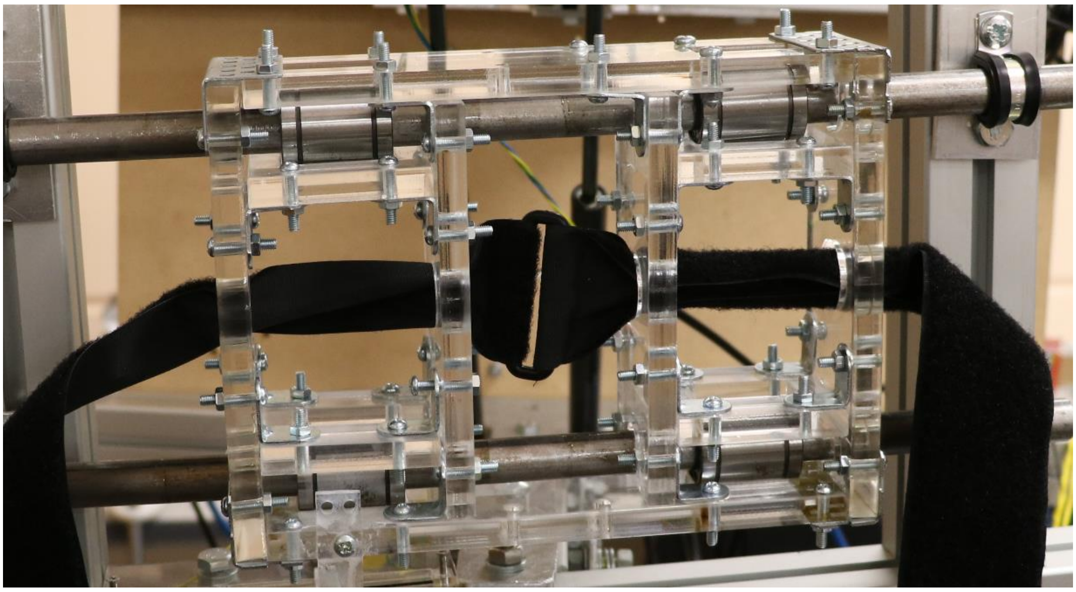

Figure 12: Implementation of the back plate design with 10mm acrylic

4.1.2 Centre Bar Arms

As previously mentioned, two centre bar arms were required in this design to allow and restrict certain motions. These arms were designed to use three 45mm square minitec bars as a base and aluminium plates ranging from 3mm to 5mm in thickness as hinge joints. Various fixings were also used to allow smooth motion of these hinge joints. These hinge joints were made in the university workshop using the various drills, saws and files available. The final assembly of these arms can be seen in Figure 13.

Figure 13: Implementation of the centre bar arm using minitec and aluminium plates

4.1.3 Assembly

Assembly of this device proved to be more difficult than anticipated. This is due to the nature of minitec bars and the order in which it was assembled proved to be important. Therefore some parts had to be disassembled in preparation of assembly. The final back support assembly can be seen attached to the rest of the exoskeleton device in Figure 14.

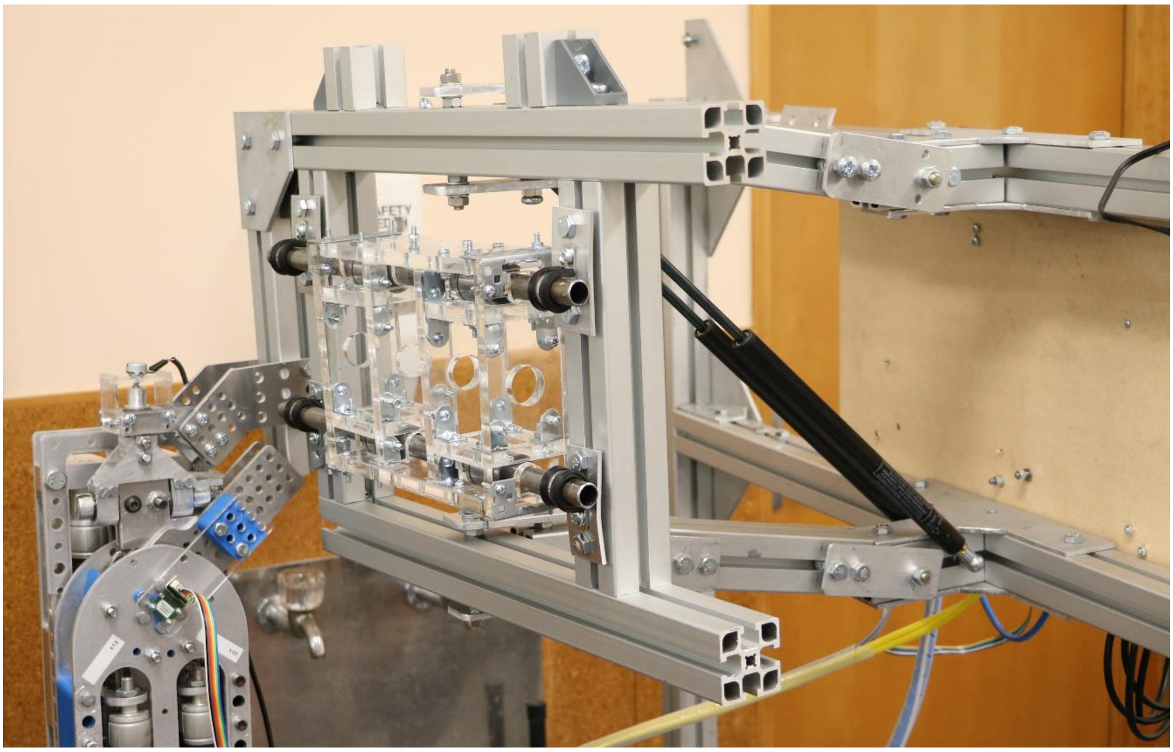

Figure 14: Final assembly of the back support device

4.2 Hip Joint and User Feedback System

Both the hip joint and user feedback system were designed and built by project partner Luke Sawyers and in depth stages of building these aspects of the system will not be covered.

5.0 Testing Procedure

As this project involves working on a robotic device that interacts with humans, ethics approval was needed. However the PhD student, Brian Cao, had already obtained ethics approval for the exoskeleton system to be used with healthy subjects only (ref 014970) and therefore it was not necessary for us to get approval too. However this meant that Brian had to be present when testing this device to keep in line with the ethics approval. It also meant that only healthy subjects could be used to test the system.

5.1 Back Support and Hip Joint

The aim of testing the back support was to determine whether the design is suitable to actuate in the future and to act as a data gathering device, to compare how the back moves at different speeds for varying gaits. It was also intended to be used in conjunction with the new hip joint to provide more degrees of freedom to the exoskeleton to further improve the overall device.

Testing the back support was done in two parts. For the first test, the subject was asked to walk normally on a treadmill at 2, 2.3, 2.6 and 3 miles per hour (treadmill measured speed in miles per hour) while only being attached to the back support (the exoskeleton leg was removed for this test). During this time, the subject's pelvic twist and pelvic sway movements were recorded for at least 10 steps to ensure enough data to determine a trend was collected. Four subjects carried out this first test.

The second test involved the subject walking normally on a treadmill at 2, 2.3 and 2.6 miles per hour (3 miles per hour felt too fast while wearing the exoskeleton leg) while being attached to both the back support and the exoskeleton leg. This allowed the back support to be tested along with the hip joint to see how they work in conjunction with each other. During this test the subject's pelvic twist, pelvic sway, hip rotation and hip abduction/adduction movements were recorded for at least 10 steps to obtain a sufficient amount of data. Unfortunately only two subjects were able to complete this test due to availability issues.

While preparing the device for testing it was discovered the gas springs providing passive control over the pelvic twist motion were too stiff (even after being deflated) and therefore it was decided the device would function better without them. During this stage foam was also placed on the back plate where the user is attached too. This was to both make the device more comfortable to use as well as ensuring a better fit to a patient's body, reducing slip between their back and the device. It was also found that the base of the exoskeleton supporting everything was rotating as a subject walked and therefore weights had to be placed on either side of each wheel to ensure they remained as still as possible.

5.2 User Feedback

The aim of the user feedback system was to both improve compliance with the existing exoskeleton device and to further engage the user in order to enhance the rehabilitation process. As this part includes both using the exoskeleton as a game controller as well as haptic feedback as a form of improving user compliance, a multitude of tests were performed.

5.2.1 Game Controller

Tests with the game controller were performed with the back support and the Arduino shield PCB designed by project partner Luke Sawyers. The system was set up so that the user could turn a character in the game in the horizontal plane by rotating their hips and using the standard controller for all other in game actions. Three games were selected for these tests; Spyro: The Year of the Dragon, Halo and Crash Team Racing. This aspect of the project was tested by having subjects use the system first while the treadmill was off and then while the treadmill was on and moving at a comfortable walking speed determined by the subject. This was to see whether subjects found it easier to play while walking and also to gauge user enjoyment and engagement.

5.2.2 Haptic Feedback

Testing the haptic feedback included two main tests; the first involves walking on the treadmill and measuring the compliance of the subject’s movements to the exoskeleton’s movements. The second test was identical except this time the haptic system was turned on. This was repeated five times while increasing pressure being sent to the exoskeleton leg from 180 kPa in 45 kPa intervals up to 360 kPa.

6.0 Results

6.1 Back Support and Hip Joint

As the exoskeleton leg was not attached while performing these tests, the data obtained could not accurately be positioned on the gait cycle. Also, as both linear and angular motions are being plotted on the same graph, the vertical has been left in ohms. These values can converted into millimetres for the pelvic sway motion by dividing by 100. To convert these values from ohms to degrees for the pelvic rotation motion the following equation needs to be used.

$$\theta = \sin^{-1}\frac{75 - \frac{\Omega}{100}}{60}$$

Where θ is the position in degrees or radians in a clockwise direction, from where the back support is at right angles to the centre bar. However neither these conversions nor the x axis are required to draw conclusions as the general motions and relation between each graph are what was important in this project.

The first test for the added degrees of freedom provided insights into the success of the back support device. However as the exoskeleton leg was not attached for this test, data was not received from the hip joint. Subjects One and Two showed consistent (periodic sine wave following a straight line) pelvic sway at all speeds. Subjects Three and Four, however, showed more consistent pelvic sway movements for higher speeds when compared to low speeds. Subject Four only showed consistent at the highest speed tested. For this test all four subjects showed virtually no pelvic twist movement for all speeds. Figure 15 shows the results obtained while subject one walked at 2.3 miles/hr for 20 steps and shows the general motions all four subjects achieved.

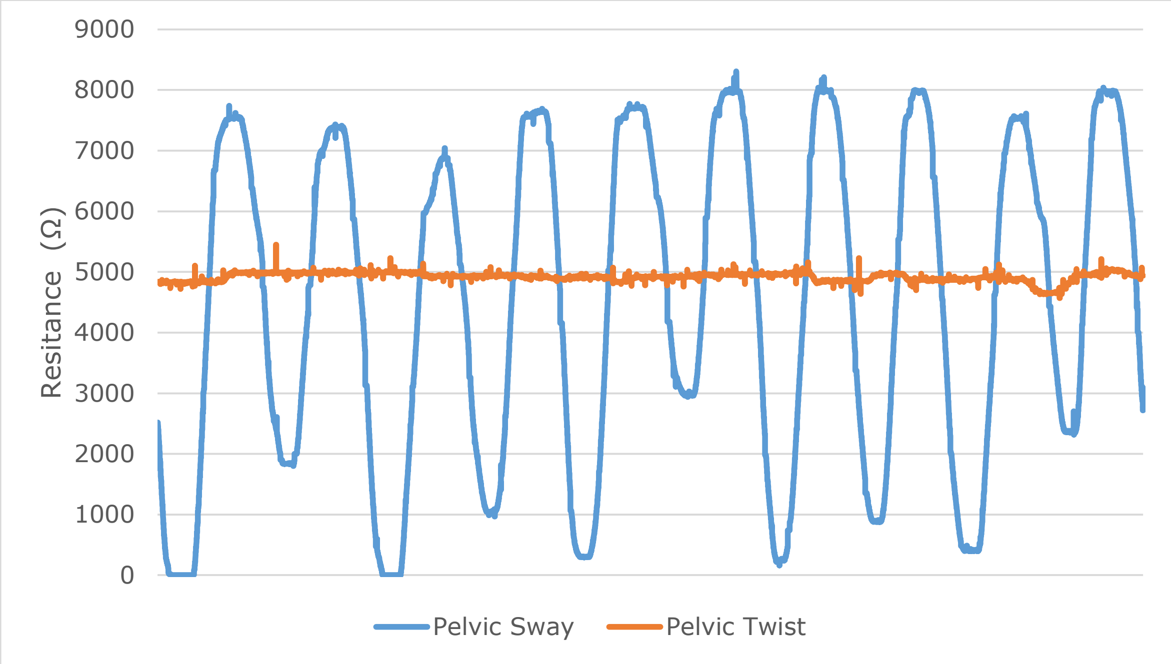

Figure 15: Subject One walking at 2.3 miles/hr with back support only

As the second test (where the exoskeleton leg is attached) only had two participants, it is difficult to comment on the effectiveness of the hip joint. While Subject One showed periodic abduction/adduction and hip rotation movements (as shown in figure ???), Subject Two showed very minimal movement of the hip in this directions but showed less pelvic sway compared to Subject One. Both subjects showed very similar ranges for pelvic rotation in all three of these tests. All four of these movements (pelvic sway, pelvic twist, abduction/adduction and hip rotation) occurred at very similar frequencies during this test for Subject One. For Subject Two, pelvic sway and pelvic twist occurred at very similar frequencies however it is difficult to comment on the frequency of the hip movements as the amplitudes were too small. Figure 16 shows the results obtained while subject one walked at 2.3 miles/hr with the exoskeleton attached and shows engagement in all four motions.

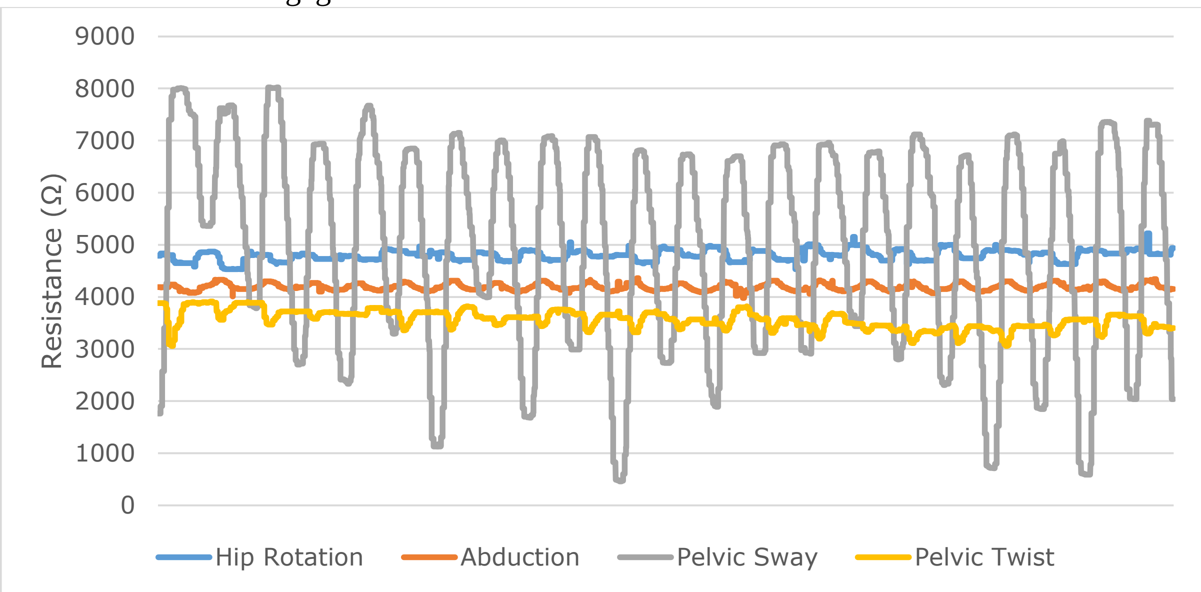

Figure 16: Subject One walking at 2.3 miles/hr with the exoskeleton

Between tests, subjects showed much larger ranges in pelvic rotation with the exoskeleton leg attached compared to when only the back support was being used. Both subjects appeared to show less pelvic sway with the exoskeleton attached however this was only by a small amount. Both subjects also showed more engagement and evenness (not favouring one side) of all movements while walking at higher speeds. More results can be seen in appendix C

6.2 User Feedback System

As the results for the game controller were mainly from observation and feedback, they were limited. However they were still useful for drawing conclusions. It was observed that all three subjects who participated in the game controller tests struggled to control the system to begin with. It was commonly seen that they would forget they had to control player rotation using the back support as they would attempt to do it with the joy stick. However the longer they played the game, the better they performed. It was found that 5 to 10 minutes was sufficient time for the subjects to get used to controlling the system correctly.

After both tests were complete and subjects had spent a sufficient amount of time playing the games both while the treadmill was on and off, all three subjects mentioned it was easier and felt more natural to play the game while walking. Subject One also mentioned they almost forgot they were walking as they were too engrossed in the game.

The results from the haptic feedback showed increased compliance when used in conjunction with the exoskeleton leg when compared to the compliance experienced with the exoskeleton leg by itself. This means that having the haptic system present improved user tracking when used with the exoskeleton leg.

7.0 Discussion

7.1 Back Support and Hip Joint

7.1.1 Back Support

Overall, the data obtained by the back support showed periodic movement in all motions monitored as suggested by the investigated literature. However while the exoskeleton was left unattached, there was virtually no pelvic twist movement in all four subjects. This suggests that the back support was too stiff and was unintentionally restricting this motion. This motion could be made less stiff by using lubrication or thrust bearing on the hinge joints. It is also possible that the potentiometer was not sensitive enough to small rotations. This is because the way it has been set up does not move the potentiometer slider for small rotations, suggesting that an angular potentiometer or a second linear potentiometer oriented in a different way is needed to accurately measure these rotations.

Another reason for virtually no movement recorded for the pelvic rotation motion is due to the location of the devices pivot point. This pivot point is located on the device itself rather than the subject's spine. However to effectively achieve a pivot point located within a subjects spine, a more complicated design would be needed. However once actuated, this is possible with the back support designed in this project. For this to be achievable, a complicated control algorithm would need to be designed that uses both the pelvic sway and pelvic rotation motions to place the effective pivot point in the subjects spine. A diagram of how this can be achieved is shown in Figure 17. Note the relative position of the back plate with the rotation of the back support.

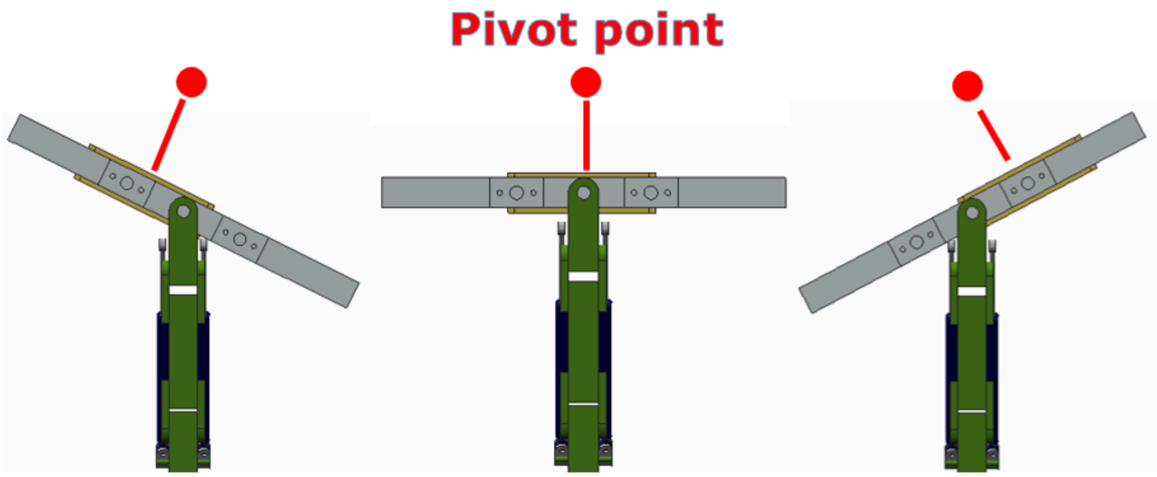

Figure 17: Control method to place the pivot point in a subject's spine

As mentioned in section 6.1, subjects Three and Four seemed to have more consistent (periodic sine wave following a straight line) pelvic sway for higher walking speeds while subjects One and Two had consistent pelvic sway for all speeds. As subjects One and Two both had prior experience with using the device before these tests it could be possible that the inconsistent motions measured in subjects Three and Four at low speeds could have been because they were still getting used to the device.

Subject Four's tests provided the most inconsistent results out of all the participants. This is likely to be because Subject Four was significantly shorter than the other three participants and due to time constraints, minimal adjustment was performed to account for this. This meant that the device was attached to the subject's upper back, which has a lot more freedom compared to the lower back when walking.

In the second test, with the leg attached, there is a clear increase in the pelvic twist motion compared to the first test without the exoskeleton leg. A possible reason for this is due to the exoskeleton leg being unactuated during these tests. This meant it is effectively dead weight that the subject had to walk with. Due to this extra weight on their leg, subjects were forced to use the larger muscles in their hips and abdomen to rotate their hips to assist in moving their leg forward.

An issue with these results is that in some cases it can be seen that the pelvic sway data becomes saturated (at 0 and 800) during testing. Although this does not happen too regularly and only occurs close to the amplitude of the movements, it's likely it had an effect on the subject's gait. This occurred despite designing for a range of 100mm as the back plate proved to be too unstable during the building stage. This meant two extra plates had to be added to either side to hold the device together, adding 20mm to its width and reducing the range of movement in the pelvic sway direction to 80mm.

An addition one subject suggested for the back support, was to provide more linear movement in the walking direction. This is likely to be because at present, the back support restricts the pelvic tilt motion (shown in figure that occurs during walking. This motion is relatively small in magnitude, however allowing some passive control over it will provide more comfort for patient. It is unlikely that this motion will need to be actuated in the future.

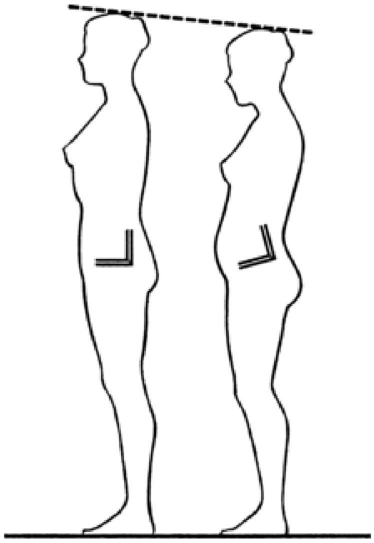

Figure 18: Pelvic tilt motion [19]

7.1.2 Hip Joint

Despite minimal testing of the hip joint, a few conclusions can be gathered. Although only one subject (Subject One) significantly used the degrees of freedom added by the hip joint, it is likely this subject would have found the test more difficult or uncomfortable if these degrees of freedom were not there. Although there is not enough data to claim it is a statistically useful addition, it is likely that if more trials were carried out, more subjects would also find this device useful when walking on the treadmill.

Another benefit of the hip joint is that it would allow the user to comfortably turn a corner. Although this is not useful on a standard treadmill, this function could be utilised with an omnidirectional treadmill to further improve the rehabilitation process.

7.2 User Feedback System

The game controller built was demonstrated to be a successful proof of concept. It was y kept low cost while also being as useable with a large range of games. It was successfully implemented with three games and was proven to make the device more engaging. However the device was never tested with unhealthy patients. As the exoskeleton only replaces a few of the controls in the game, a game controller is still required. This means the patient’s hands are not available to hold onto a support bar or a safety button. An unhealthy patients is much more likely to need to hold onto a bar as they struggle to balance. This could make the device dangerous to use and only suitable for patients nearing the end of the rehabilitation stages.

Additionally, it was concluded that the back support could be used as a game controller. This is because as shown in the data collected, there was minimal pelvic rotation occurring during walking without the exoskeleton leg and for some subjects, with the exoskeleton leg. This means that in many cases, this motion is ‘free’ to be used for the game controller.

8.0 Conclusions

Despite the shift in the projects aims, two useful additions have been added to the existing exoskeleton device. It has been proven that the addition of four degrees of freedom; two in the back and two in the hip can be useful to the rehabilitation process. It has also been proven that user feedback can also be useful for both keeping a patient engaged and improving the compliance with the system.

Although the back support design was not successfully actuated, a versatile base has been completed. Significant work has also been done towards effectively actuating it for both pelvic sway and pelvic rotation. Further work to the back support should include ordering the remaining parts required for actuation, integrating them into the current system and using the data gathered in this project, implement a control program using the myRIO available. The designed hip joint has been completed with only 'quality of life' improvements needed such as designing better headers for the potentiometers used on it.

The user feedback system successfully built can be customised to be used with many games. However this was a proof of concept and the device has not been designed to handle more recently developed games due to the complexity of their controls. The haptic feedback component has also been proven to be a viable opportunity to improve the rehabilitation process.

9.0 Further Work

9.1 Back Support

At the conclusion of this project, the base for the active back support has been completed as well as the majority of the design. Some data has also been obtained that show how the back moves in both the pelvic sway and pelvic twist motions. Anyone working on this device in the future should first trial the device themselves before making any changes.

It is suggested that the back support structure could be further developed by working out how to incorporate the hip hiking movement. However, as this is a key motion that stroke patients have trouble with, it should not be passively controlled. It should only be implemented if the designer is sure the motion can be controlled or restricted appropriately as it would likely become a hindrance to the rehabilitation process if left unfinished.

As previously mentioned and intended in this project, further work could be done into actuating both the pelvic sway and the pelvic twist motions. For the pelvic sway motion the motor, motor controller and any required connectors have already been purchased. Although the PCB created by Luke Sawyers in this project has hardware to control the pelvic sway motion, it is recommended that a National Instruments myRIO is used instead. This is because further development will involve actuating the pelvic twist motion as well and the PCB designed is not capable of controlling both motions.

To control the pelvic twist motion it is suggested that a pair of electric linear actuators are used. It is uncommon for these actuators to have the capability to extend and retract with the required speeds of this device so care should be taken when selecting one. An example of a suitable electric linear actuator that could be used is the SKF CAHB-21 actuator (RS number 885-5319) with 102mm stroke length. However these actuators will need to be placed no more than 240mm away from each other if the desired angular speed is to be obtained.

9.2 Hip Joint

The hip joint has been completed and has been successfully integrated into the system. Only small quality of life changes need to be made such as providing it with a smoother finish. Further work into making the device easier to manufacture could also be done.

9.3 User Feedback

As both components of the user feedback system were proof of concepts, further development can be done in both the game controller and the haptic feedback. However it is likely that these two systems will need to be separated for further development as more computational power and PCB space will be needed.

10.0 Acknowledgements

I would firstly like to thank Brian Cao, a post graduate student, for allowing his exoskeleton to be used for various parts of this project. Also thanks for the guidance you provided throughout the year. The effort you put into fixing various components of it during our testing stages was outstanding.

Also thank you to my supervisor Shane Xie for your guidance throughout this project and many tips for this report.

Thanks to the lab technician Rizwan Mustafa for your help resolving a lot of the technical issues I have had throughout this project.

Thanks to the lab technician Anesh Pratap who showed me how to use the various tools in the workshop and helped resolve problems I had with my mechanical design.

Also thanks to all that participated in testing the design – Luke Sawyers, Sam Wrait and Laura Sawyers.

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Appendices

Appendix A

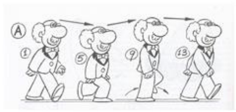
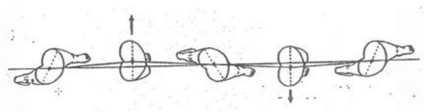
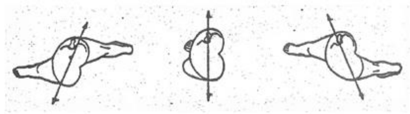
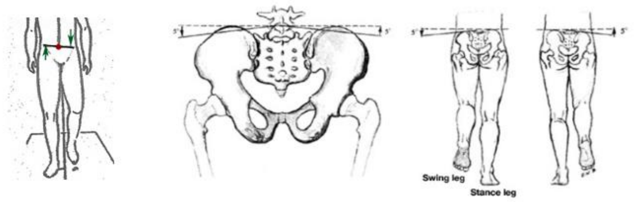
Recurring pelvic moment		Local Control's attribute to key
Vertical displacement of pelvis		Translate Y
Lateral displacement of pelvis		Translate X
Pelvic rotation		Rotate Y
Pelvic tilt		Rotate Z

Figure 19: Normal pelvic movements that occur during gait [13]

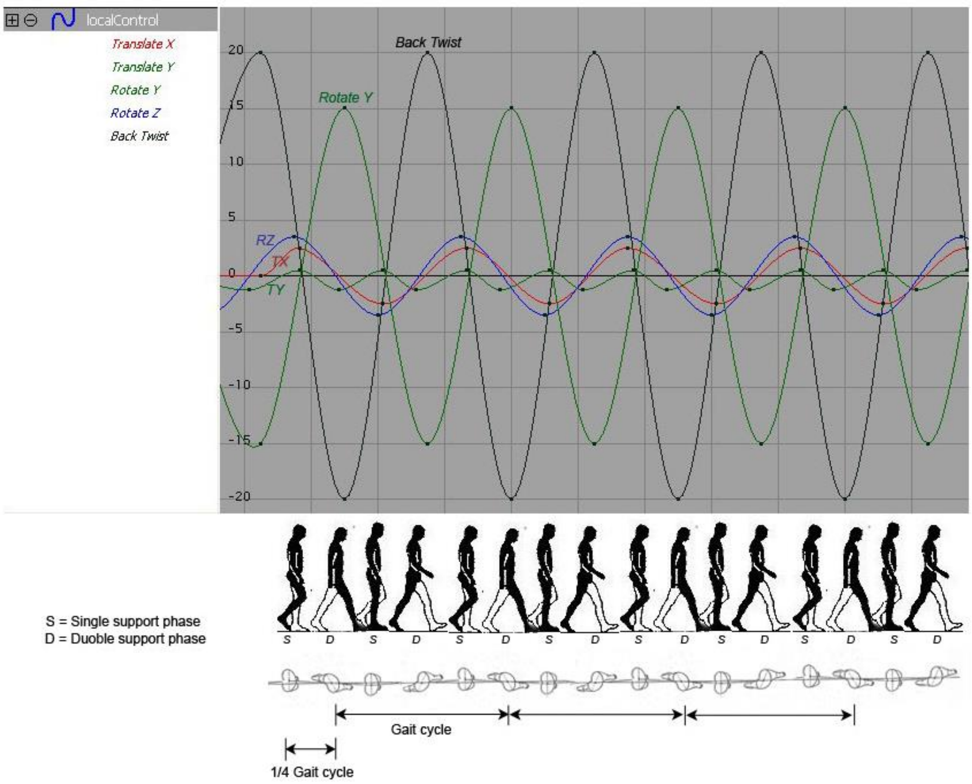


Figure 20: Relationship between normal pelvic movements and their relative magnitudes [13]

Appendix B

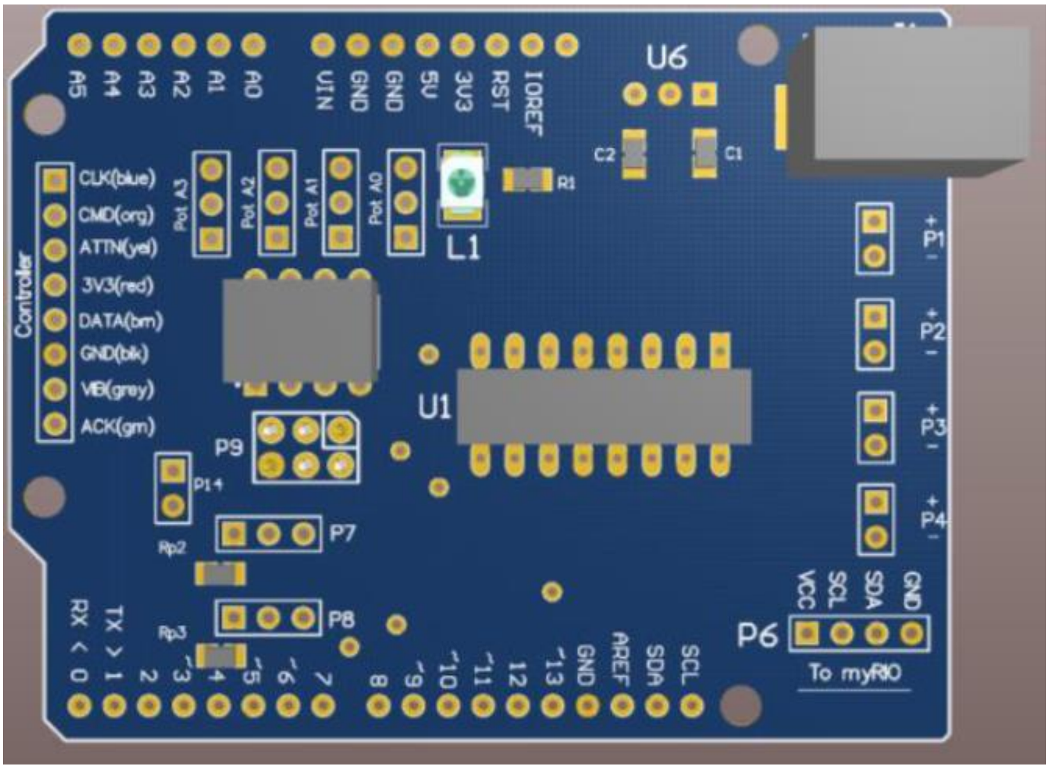


Figure 21: Arduino shield for the user feedback component of this project. Developed by Luke Sawyers

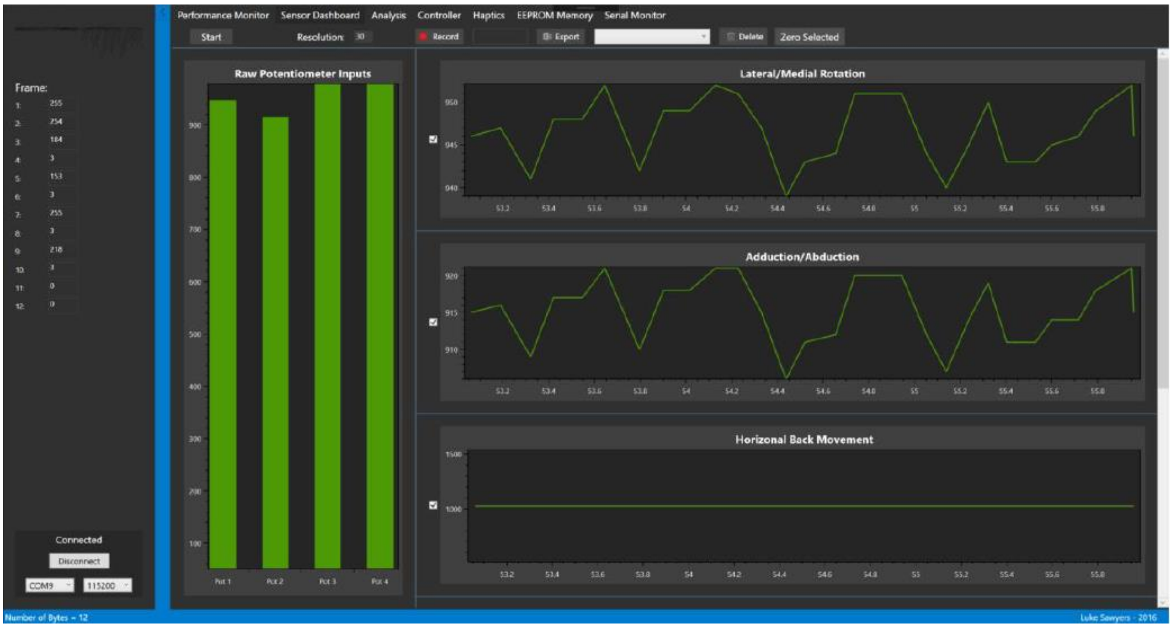


Figure 22: User interface for the program developed by Luke Sawyers for this project

Appendix C

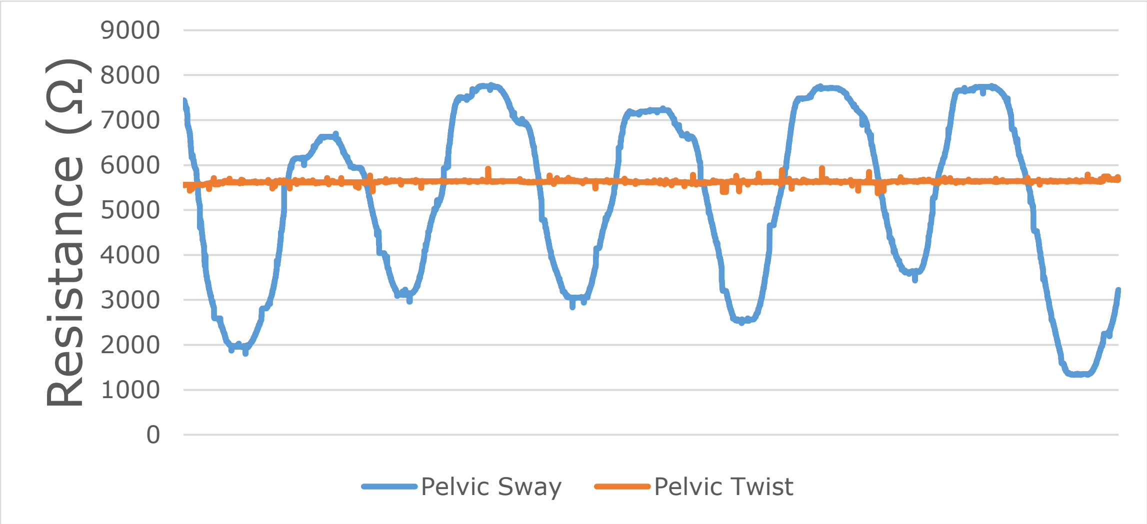


Figure 23: Subject Two walking at 3.0 miles/hr with back support only

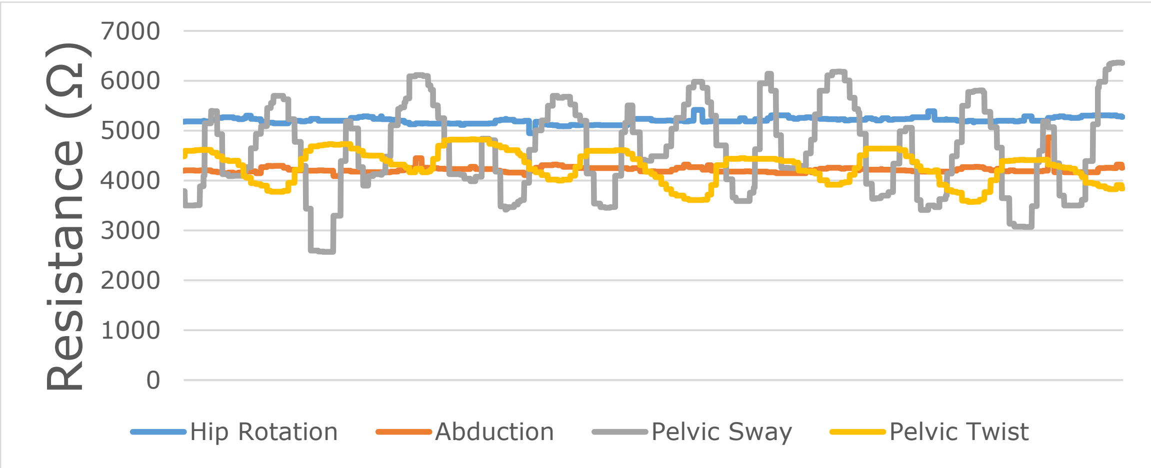


Figure 24: Subject Two walking 2.6 miles/hr with full exoskeleton

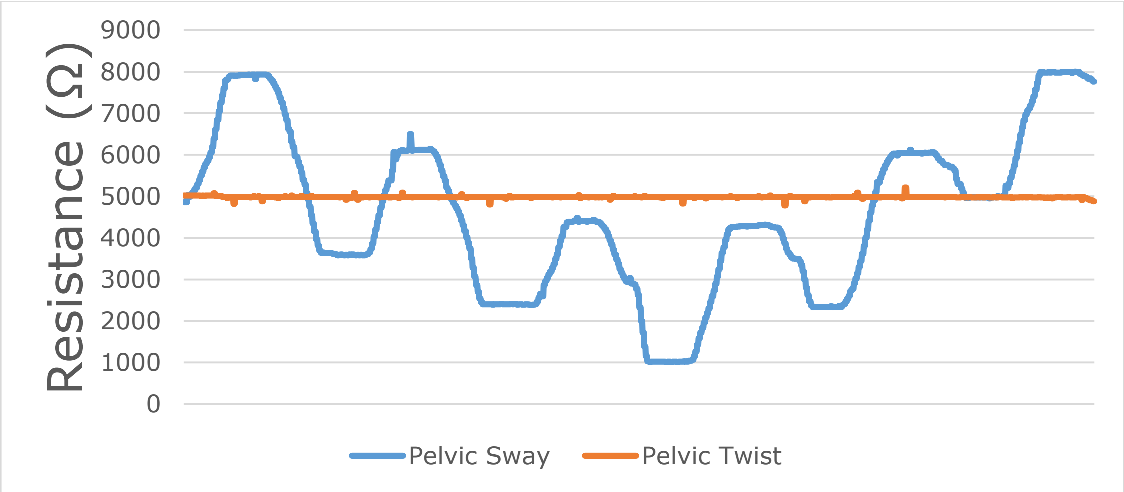


Figure 25: Subject Three walking at 2.0 miles/hr with back support only

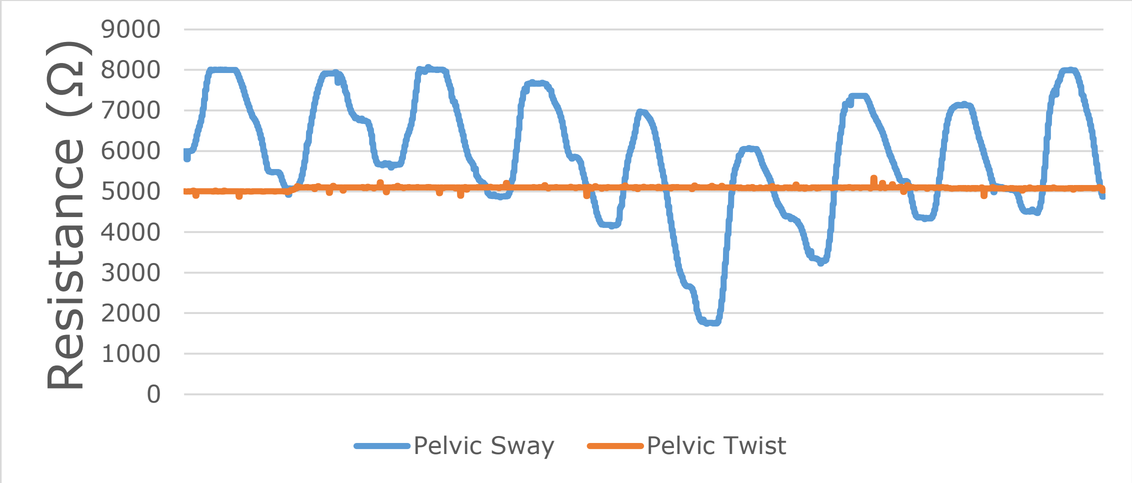


Figure 26: Subject Three walking at 3.0miles/hr with back support only

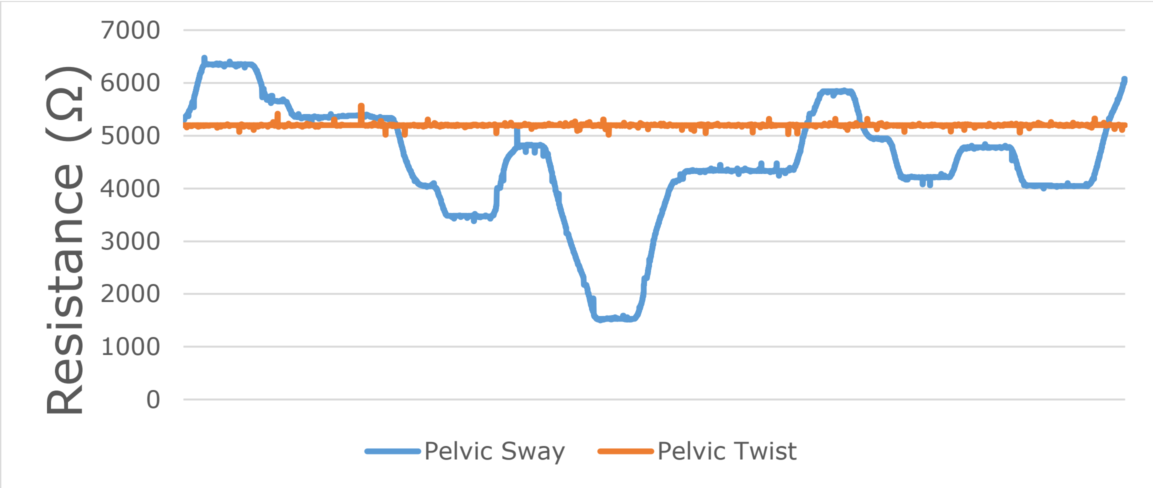


Figure 27: Subject Four walking at 2.0 miles/hr with back support only

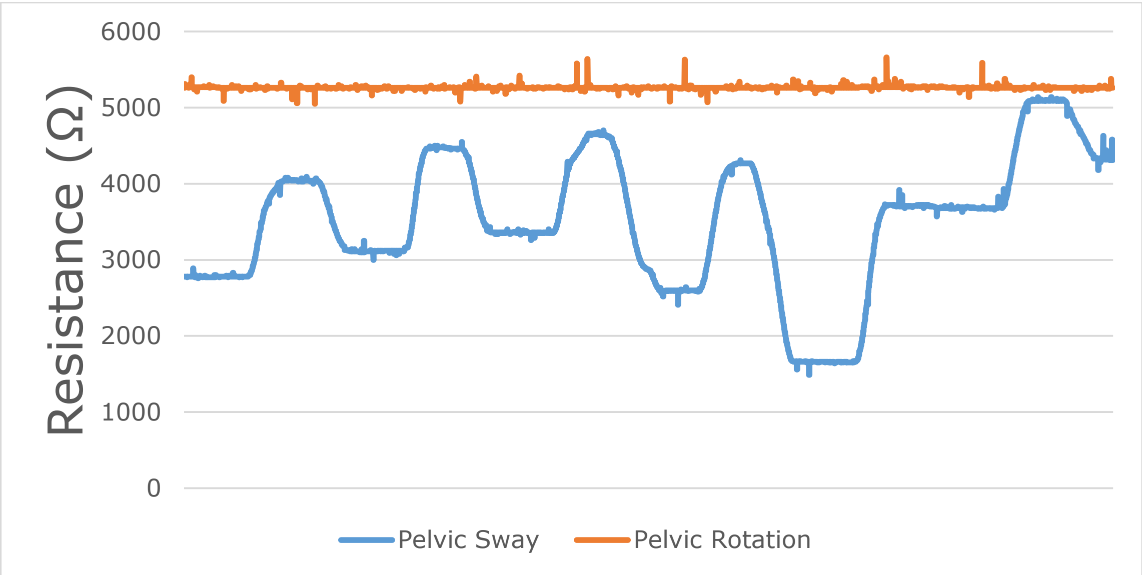


Figure 28: Subject Four walking at 3.0 miles/hr with back support only