Analysis of force distribution on upper body limbs during ambulation with crutches

by

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A thesis submitted in conformity with the requirements for the degree of Masters of Health Science
Institute of Biomaterials and Biomedical Engineering
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Abstract

Crutches provide support for various mobility impairments as well as aid during recovery of lower limbs. Resultant forces on upper limbs can cause pain and conditions such as carpal tunnel syndrome. This study aims to develop a system to accurately measure forces present on the interaction points between the upper limb and crutch, to determine if there are differences between crutch manufacturing options (spring dampening component), as well as between the environments in which crutches are used, such as up and down hills or on a rocky surfaces. Overall, it was seen that the forces at the interface are highest over the carpal tunnel region. The spring was shown to reduce the maximum rate of loading. The largest environmental effect was seen by the rocks, which increased the maximum rate of loading. Gait over rocks was also seen to increase the maximum forces seen at the interfaces, though not significantly.
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1 Background

1.1 Introduction

Forearm crutches are commonly prescribed to enable functional mobility for individuals with walking impairments. However, the resultant forces that are placed on the upper body during crutch use have been shown to cause musculoskeletal problems including pain and injury to the arms and shoulders [1]. These problems escalate over time, and can be a problem for long-term crutch users. Better crutch designs have long been sought after to lessen the ‘side-effects’ of crutch use. This includes providing shock-attenuation within the crutch system, and improving the ergonomics of the interfacing elements including the elbow rests and hand grips. However, few of these additions have been formally evaluated to determine their ability to reduce stress on the upper body. Additionally, most crutch analysis that has been performed in the past has taken place in a laboratory setting. For long-term crutch users, a laboratory setting may not provide a close enough representation to the environment that they will be using the walking aids in. For these reasons, it is beneficial to develop an ambulatory crutch analysis system that can accurately measure upper extremity forces, and compare potential crutch improvements in real-life contexts.

1.2 Background and Literature review

1.2.1 Upper Extremity Walking Aids

There are several different kinds of crutches and walking aids that can be used to provide balance or support during walking. Canes and walkers are often used by an aging population to provide stability while walking and prevent falls while crutches are associated with injury or long term disability. In the United States, canes and walkers combined are used by 6.6 million Americans, and crutch users are estimated to be used by 566,000 people [2].

Users of crutches generally fit into two categories. Short-term users often have an injury to a lower extremity and must use crutches to remove the weight bearing requirements of an injured limb. This is common with broken or sprained bones and joints of the leg, and users in this case may be required to use crutches for anywhere between a few weeks to several months. They may also be recovering from a surgical procedure and need to use crutches on a temporary basis. The
second use of crutches is for long-term users. Long-term users may require the stability that crutches provide because of pathologies such as spina bifida, lower limb amputation, or cerebral palsy that may impede movement or cause balance challenges. There are two main categories of crutches: underarm crutches and forearm crutches.

Underarm/Axillary crutches

Underarm crutches extend to just below the underarms of the user. The user places their hands on the handholds, and by locking their elbows, supports their weight on the crutches rather than an injured or weak lower limb. Underarm crutches are often adjustable by moving the handhold up and down, and extending the lower shaft to make the crutch taller. The following image, Figure 1, depicts a common set of underarm crutches.

![Figure 1: Example of underarm crutches](image-url)
Forearm Crutches

Forearm crutches are often used for their convenience; being smaller, they can be more easily packed or put aside, and the wrist cuffs allow for greater flexibility in grabbing or holding things. Forearm crutches have a handhold, as well as the wrist cuff. The shaft of the crutch may be adjustable for height. An example of a pair of forearm crutches is shown below in Figure 2.

![Figure 2: Example of forearm crutches](image)

1.2.1.1 Types of Crutch Gait

There are several methods of using crutches. These vary based on the reason for using crutches, the type of crutch or walking aid used, and personal preference. The types of crutch gait are shown below in Figure 3. If the crutches are being used supportively as might be done by a person with cerebral palsy or spina bifida, two- or four- point gait may be used as it provides support for both legs evenly, and provides support throughout the gait cycle. For someone with a fully injured limb, or an amputee, swing through or swing to gait is often used. This allows the
crutch user to extend both crutches in front of them, swing their uninjured limb through to or beyond the crutches, and shift their weight forwards to repeat. While the injured individual starts to place more weight on their injured limb, they may transition to three-point gait.

Figure 3: Types of crutch gait [5]
1.2.2 Upper Extremity Loading

Upper extremity loading has been examined in the past to determine the effects of loading on the joints and muscles of the upper limbs. Initially, these studies focused on the use of crutches and other walking aids using a force plate to determine the overall force through the aid. One such study by Goh et al. focused on axillary crutches, and used a force plate to determine the force pattern throughout the gait cycle. Additionally, force transducers were placed in the crutch tip, and in each arm of the crutch near the armpit rest. This allowed the study to determine that the palm holds 44.4% of the body weight at peak force throughout the gait cycle. As well, it was found force distribution could provide insight into improper crutch use by tracking when the participant leaned on the axillary bar under the armpit [6].

Following these studies with force plates, load cells were used to determine the overall axial and shear forces present on the walking aid. Often, this was validated using a force plate before combining with an image capture system. Using a laboratory based image capture system such as VICON, the biomechanical loads that are placed on the joints of the arm can be calculated through inverse dynamics [7]. These joint forces indicate the potential for injury to the upper extremity over the long-term use. There are several important findings from studies using load cells in the crutch. Firstly, it was determined by Slavens et al. that the forces present in the arm are higher during swing-through gait [7]. It should be noted that an additional study by Thys et al. found that swing-through gait also corresponded to an increase in energy expended by 2-3 times, as well as a mechanical work increase of 1.2-1.5 times when compared with regular walking [8]. A second study by Requeio et al. found that there was asymmetrical shoulder loading that corresponded with lower extremity strength differences [9]. These factors may be better understood when the force transmission information at the actual interfaces between the crutch and the upper extremity are determined.

In a study by Bhagchandani, the addition of a second load cell between the elbow rest and hand grip allowed the isolation of the forces present on each interface [10]. The total force through the longitudinal axis of the crutch was measured through a load cell placed below the handle, and the force through the cuff was measured through a load cell placed between the handle and wrist cuff. Through their method, the forces and moments were determined at the crutch tip, handle, cuff, wrist, elbow and shoulder [10]. The effects of the actual interface between the subject and
the crutch have yet to be explored. Additionally, these studies all remained within laboratory conditions, and may not have accurately portrayed the forces exerted during everyday activities such as going up and down stairs or ramps.

Sensors have also been mounted on crutches in order to facilitate a program of partial weight bearing [11]. Because this system focused on how to measure how much weight was being placed on the foot (or not on the crutch), and not focused on upper extremity injury, the pressure sensors were primarily organized to study ground reaction force rather than grip or forces at the interface. However, they included a grip sensor, which was used to look at where the hand was placed as a teaching tool for proper crutch usage.

1.2.3 Wrist Injury

1.2.3.1 Carpal Tunnel Syndrome

Long-term crutch users often experience pain or discomfort in the carpal tunnel region of the hand, leading to carpal tunnel syndrome. Carpal tunnel syndrome occurs when the median nerve of the hand, as depicted below in Figure 4, is compressed. This causes pain and numbness in the hand in the region affected by this nerve, depicted below in blue. In crutch walking, this pain and discomfort may be caused by an increase in force in the carpal tunnel region over many years. However, crutch modifications may be able to reduce the forces present in this region by distributing the overall force better over the handgrip and elbow rest.
Carpal tunnel syndrome can also occur as a result of overuse. By repetitively bending or flexing the wrist, friction produces swelling in the wrist, which causes a compression of the carpal tunnel nerve [13]. On a crutch that is being used by a long term crutch user, repetitive loading is necessary, and provides a potential cause of carpal tunnel syndrome. Repetitive loading without the actual force can provide a problem as well, as seen with office works, where the flexion of the wrist alone provides the same syndrome [13]. The wrist is generally flexed during crutch walking because it is needed to provide support for the body with conventional handles, and this could exacerbate any injuries forming.

1.2.3.2 Rate of Loading

Though the overall force present on the hand is a good indicator of wrist health, an additional factor is the rate of loading. The rate of loading consists of how quickly the force is applied. The quicker the force is applied, the higher the intensity of the compression and the worse the impact on the wrist. A study by Marklof et al. looked at the forces experienced by the wrists of gymnasts when completing maneuvers on a pommel horse [14]. They determined that the force magnitude in the wrist, as measured by a load cell implemented on a pommel horse, was measured at up to 2BW through the wrist, and the rates of loading of 219BW/s.
1.2.4 Interfacial Force Measurement

Interfacial force measurement has not been thoroughly examined in crutch use; however, it has previously been used on the lower limbs for prosthetics to determine the forces placed on the residual limb of the user. For example, in a study by Zhang et al., the pressure and shear stresses were examined to determine potential causes of pain and discomfort for trans-tibial amputees. It was determined that the pressure was not uniformly distributed on the residual limb, and that the shear stresses observed did not correspond with the pressures seen [15]. A similar process can be applied to the upper body to more accurately understand the interface between an upper extremity walking aid and the user, and determine potential points of stress. A grip sensor has been employed on a crutch in the past, however, it was used to determine hand position, and not the magnitude of the forces placed on the hand [16].

A past study by Sala et al. focused on crutch handle design and how this affected the carpal tunnel region using forearm crutches [17]. They used an F-scan interfacial force system to measure forces on both a traditional handle as well as a wider wedge shaped handle. They found that the distribution of load was very similar between the two handles, and could not recommend one over the other. The distribution seemed skewed, with the radial side of the hand (closest to the thumb) experiencing the highest forces. Additionally, it was postulated that wrist extension may contribute to the carpal tunnel symptoms found in long term crutch users. For this study, the participants used a three point gait and measured an F-scan system. The F-scan system is an interfacial force sensor system that they placed on the participants hand as shown below in Figure 5. They then segmented the information from this system into 6 regions. The F-scan system was the only force sensor used, and therefore there was no way to determine how much force was placed on the injured leg as compared to the crutch. It is therefore difficult to compare between the trials as the overall weighting may have been different.
Figure 5: Sections of the hand as segmented in the study by Sala et al. [17]

1.3 Rationale

Previously, studies have primarily focused on testing the distribution of forces in a laboratory environment. In order to better replicate the environment in which crutch users actually use their crutches, it is important to develop a system that can be used without a laboratory. It has been reported that over 40% of crutch users have inability to perform major activities due to their device [2]. Many have accessible features within their homes, however, a majority of mobility device users have to use steps to enter or exit their homes [2]. This type of movement may result in higher forces on the crutch as the user is not simply lifting the body forward, but also up to the next step. Additionally, factors such as getting on and off public transit and maneuvering in the outside environment can prove to be challenging. As most studies take place in a laboratory, and many require the participant to walk onto a force plate, an unnatural environment is created, which hopefully would be reduced by the proposed study with an ambulatory system [2]. As a result, it is important to create a system that will accurately measure the forces at the interface
between the device and the upper extremity in a way that will allow everyday activities to be measured. As stated above, reducing the forces present in the carpal tunnel region may alleviate the overall pain that the crutch user experiences over time. In order to examine this, it would be beneficial to measure the forces at the interface between the crutch and the crutch user. It is therefore important to look at the amount of force displaced during different crutch modifications, and during different environmental activities. A high peak force will indicate more force in that area, and may indicate a higher possibility of developing force if that occurs in the carpal tunnel region. Once this system is verified, it could be used in the future to compare new crutch modifications to current ones, and could also identify areas of challenging terrain for crutch users.
2 Objectives

2.1 Objective

To better understand the forces that occur between an upper extremity and a mobility assistive technology (MAT) by creating a method that accurately measures interfacial forces on a crutch in a real life environment.

2.1.1 Technical Development Objectives

1. To determine the characteristics of force sensors used in creating a force measurement system for an upper extremity mobility assistive technologies

2. Develop abovementioned force sensors into a system for analyzing the interaction between a forearm crutch and the forearm and hand of the body.

3. Use kinetic information from an axially fitted load cell on the instrumented crutch in order to assess the overall ground reaction force through the crutch shaft
2.2 Research Questions and Hypotheses

1. What is the distribution of pressures at the crutch body interfaces, and how do these relate to anatomy and potential mechanisms of injury?

It is expected that the hand will have more pressure than the forearm, and that the distribution of force will not be even across the hand. It is expected that the force will be higher across the carpal tunnel region which would increase the likelihood of injury.

Outcome Measures: Flexiforce Sensors Maximum Force

2. Is there a significant difference between different crutch modifications such as the addition of a spring component?

It is expected that the addition of a spring component will reduce the maximum force exhibited at the interface of the crutch, and reduce the rate of loading.

Outcome Measures: Flexiforce Sensors Maximum Force, Load Cell Maximum Force, Load Cell Rate of Loading

3. Do different environments such as up/down hills and over rocks have an impact on the forces at the interface between an upper extremity and an upper extremity MAT?

It is expected that ambulating in more challenging environments will increase the maximum forces on the interfaces of the crutches, and increase the rate of loading.

Outcome Measures: Flexiforce Sensors Maximum Force, Load Cell Maximum Force, Load Cell Rate of Loading
3 Methods

3.1 Overview

The following, Figure 6, represents a general overview of the process taken. The instrumentation design methodology follows first, followed by the participant requirements and trial procedure.

![Diagram of proposed methodology]

Figure 6: Diagram of proposed methodology
3.2  Technical Development

3.2.1  Flexiforce Sensors

The proposed sensors to be used in the interface between two surfaces such as the crutch and the hand are Flexiforce sensors. Flexiforce sensors are thin, flexible sensors that respond to changes in pressure by changing the resistance of the sensor. A study by Ouckama et al. used multiple Flexiforce sensors in an array to determine the forces found on the inside of a helmet during an impact [18]. The array system used allowed for the contact area to be estimated. This may relate to the proposed project if differences are seen between one side of the cuff or handle, and the other. An area with the ability to determine which side is being impacted would allow a greater understanding of how the forces may affect the hand and arm.

3.2.1.1  Sensor Characteristics

Flexiforce sensors have reported characteristics taken under ideal conditions. However, in past work, it has been found that when the sensing area itself is bent, this greatly affects the results produced by the sensor. The characteristics reported by Tekscan for the Flexiforce sensors are reported in Table 1, below. The full data sheet is available in Appendix A.

<table>
<thead>
<tr>
<th>Linearity (Error)</th>
<th>&lt; ±3%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repeatability</td>
<td>&lt; ±2.5%</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>&lt;4.5%</td>
</tr>
<tr>
<td>Drift</td>
<td>&lt;5% per logarithmic time scale</td>
</tr>
<tr>
<td>Response Time</td>
<td>&lt;5μsec</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-40°F - 140°F (-40°C - 60°C)</td>
</tr>
</tbody>
</table>

These characteristics have been reevaluated in previous work performed in the PROPEL lab. This tested for the above factors of repeatability, linearity and hysteresis, but used weights for 250g – 2000g. This weight range is more appropriate for the values expected on the crutch, and through this testing, it was determined that the sensors remain relatively accurate at this range.
Additionally, the sensors were tested with pucks placed between the weight and the sensor. It was determined that the optimal encapsulation for skin has a hard surface platform to support the sensor, with a soft puck between the application of force.

The testing then continued with testing on skin. This was to determine the sensors accuracy when used on skin, as well as if calibration was necessary on the skin surface and what encapsulation is needed for calibration. Figure 7, below, shows the method used to test the encapsulations on skin. Low weights were placed through the shaft of the tripod to rest on the skin with various encapsulations tested.

**Figure 7: Sensor testing apparatus (a) and force being applied to hand of subject (b)**

### 3.2.1.2 Sensor Pilot Testing

Continued testing on the accuracy of the sensors is continued in a separate project; however, for the purposes of this project, pilot testing was needed to determine the best method at this time for encapsulating and calibrating the sensors. Two adults were used for the pilot testing. These adults were above the age of 16, had no cognitive impairments and could speak English (to have proper verbal communications). They also did not have any skin conditions or loss of feeling in
their upper extremities. They placed their arm underneath the tripod, as depicted above, and light weights were placed through it to produce measurements.

3.2.1.3 Sensor Experimental Protocol

1. Calibrate the machine prior to participant arrival. During calibration, the sensor is placed onto a hard aluminum surface block, and a 40A polyurethane (PU) puck equivalent to the size of the sensing area is placed on top of the sensor. Calibrate the sensor with 500g, 1000g, 1500g, and 2000g.

2. Participant arrives at laboratory

3. Participant is given waiver form, and signs form. Participant is informed they may stop at any time, and that they may ask questions at any time.

4. Place participants arm under the apparatus. The weight should rest on the volar forearm on the participant’s left hand, on the anterior side of the hand. The posterior part of the hand rests on the table.

5. The test to be completed is the linearity test, as follows, repeated for weights 500g, 1000g, 1500g, and 2000g.

   a. Place the weight through the tripod tube gently onto the participant’s arm, and allow it to rest for 30 seconds.

   b. Record the reading.

   c. Repeat the test 10 times

6. Apply different lining and puck combinations, and repeat the linearity test as completed above 500, 1000 and 1500. The lining and puck combinations are as follows:

   a. Prosthetic Lining with diameters of: 7/16 inch, 11/16 inch, and 15/16 inch. The diameter represents the surface over which the force will be displaced, and the pressure sensor is smaller than the prosthetic lining diameter.
b. Shore 40A PU puck between the weight and sensor, and 90A PU platform between sensor and hand

c. 40 A PU puck between weight and sensor

d. 90 A PU platform between sensor and hand

e. Just sensor then hand directly

f. Just sensor then aluminum directly

g. 40 A PU puck between weight and sensor, with sensor resting on aluminum.

3.2.1.4 Encapsulation Method

From the testing performed, it was determined that the optimal encapsulation method at this time consisted of two discs of material. A polyurethane puck the same diameter as the Flexiforce sensing area was placed on the crutch side of the sensor. This is to provide the hard backing so that the sensor does not bend if placed on an uneven surface on the crutch. On the hand side of the sensor, a piece of prosthetic lining was placed. This is to ensure that the force is properly transmitted from the crutch to the hand where the sensors are. It also provides some comfort so that the participant does not have their hand directly on the sensors.

The testing also determined that the most important factor in calibration of the Flexiforce system is to ensure that the same encapsulation method is used for calibration as used during the trial. The surface on which the sensor is calibrated (i.e. a metal block or a wrist) is much less significant. The sensors can therefore be calibrated on a metal block and then used on the crutch with both systems encapsulated as described above.

3.2.2 Flexiforce Hardware

3.2.2.1 Hardware Overview

The hardware of the Flexiforce system consists of nine medium force sensors (maximum 25 lb. unadjusted), and four low force sensors (maximum 1 lb. unadjusted). There is a main sensor board based on an Arduino that is used to collect and transmit the data from the sensors. The crutch has sensors in two locations: the forearm rest, and the handle. To accommodate this, the
seven medium sensors feed into one sensor bank on the board, while the four low sensors feed into another. The board itself has the ability to connect to up to sixteen sensors total (eight in each bank) for future use. The banks are also adjustable independently to adjust for the range of the sensors required, by increasing or decreasing a potentiometer in the circuit. The board has an X-bee system on it that connects to a dongle plugged into the USB port on a computer. This transmits any data collected wirelessly from the board to the laptop where it can be read in real-time through a LabVIEW program as described below. The data can also be stored on an SD card on the circuit board itself.

3.2.2.2 LabVIEW Program

The software used to collect the Flexiforce data is LabVIEW. The LabVIEW program was edited from a previous program used within the PROPEL laboratory. The program that is used uses a visa based system to collect data from each sensor individually. Within the program the things such as the sampling rate can be modified. The LabVIEW program also contains screens to view the system in real time as it operates. It allows either an instantaneous read of each sensor’s value, or shows sensors grouped according to location over time. The full LabVIEW program is included in Appendix B. The Flexiforce system was sampled at 50Hz

3.2.3 Load Cell

3.2.3.1 Load Cell Specifications

The load cell was mounted axially in order to determine the overall force through the length of the crutch. The load cell used was from AMTI, and was a MC1.75 model. The model was fit with customized brackets to allow it to be fitted axially into the shaft of the crutch. The load cell is a six axis model, which allows it to sense force and moment in the x, y and z axis.

The load cell data was recorded using a CRONOS-PL from IMC. The load cell itself was connected to this system, which was powered by a rechargeable battery. It then connected to a router to wirelessly transmit the data from the CRONOS module to the laptop computer. All equipment required to operate the load cell was housed in a backpack worn by an assistant walking beside the crutch participant.
3.2.3.2 Load Cell Program

The load cell was used with imc Devices to record the data from the imc CRONOS. The settings used included a sampling rate of 10ms with the following y-factors used as calibration, as seen in Table 2.

Table 2: imc Devices calibration settings for load cell

<table>
<thead>
<tr>
<th>Channel</th>
<th>Y-Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fx</td>
<td>1467 N</td>
</tr>
<tr>
<td>Fy</td>
<td>1490.5 N</td>
</tr>
<tr>
<td>Fz</td>
<td>6142.5 N</td>
</tr>
<tr>
<td>Mx</td>
<td>25.265 Nm</td>
</tr>
<tr>
<td>My</td>
<td>25.335 Nm</td>
</tr>
<tr>
<td>Mz</td>
<td>35.355 Nm</td>
</tr>
</tbody>
</table>

Full screen captures of the program for future use are included in Appendix C.

The load cell was sampled at 100Hz.

3.2.4 Overall Crutch Design

The crutch was implemented with both the Flexiforce system, and the load cell system. The load cell was placed axially in the shaft of the crutch. It was fitted nearer to the handle in order to reduce the weight at the crutch tip so that as close to normal gait can be achieved. The additional equipment needed to operate the load cell was housed in a backpack. The backpack was worn by an assistant walking beside the participant, tethered by a cord that goes to the load cell.

The Flexiforce system was mounted directly to the crutch itself. The circuit board was placed on the shaft above the load cell, with ribbon wires connecting out to two smaller boards that the sensors were attached to. Four low force sensors were placed on the forearm of the crutch, six medium force sensors were placed on the top of the handle of the crutch, and one medium sensor was placed underneath the handle of the crutch.
The crutches used are Sidestix crutches, which have an optional spring damped component. During experimental trials, this may be modified to disable or enable the spring component at will. The crutch is shown below with all additional instrumentation in Figure 8 and 9.

**Figure 8: Crutch with instrumentation**
Figure 9: Sensor positions on crutch
The following image, Figure 10, shows the locations of the hand sensors as they sit on the hand itself.

Figure 10: Approximate locations of Flexiforce sensors as positioned on the right hand
3.2.5 Experimental Trials

3.2.6 Participant Information

The participants for this study included 12 able-bodied individuals. These individuals were instructed to walk with crutches in a swing-through gait pattern at three speeds on flat ground. They also completed several tasks, by then walking up and down hills and over uneven rocky ground. The specific trials are noted below in Crutch Experimental Protocol. All participants gave consent, and the consent form and all other appendices from the Research and Ethics Board submission are included in Appendix D.

General Inclusion Criteria

1. Participant age must be greater than 16.
2. Have no cognitive impairments (to ensure proper verbal communication)
3. Be able to speak English (to have proper verbal communication)

Exclusion Criteria

1. The participant may not currently have an upper extremity injury that would prohibit walking on crutches for a period of 2 hours.
2. Participants must not have lower limb or neurological impairments impacting gait or balance
3. Participants must not currently be using a mobility aid.

3.2.7 Crutch Experimental Protocol

1. Calibrates all equipment on the crutch prior to participant arrival. Calibration was performed between each participant due to unreliability of Flexiforce sensors. Used method as defined below, which was determined from previous sensor testing in past chapters
2. Participant arrived at laboratory wearing comfortable clothing
3. Participant was given waiver form, and signs form. Participant was informed they may stop at any time, and that they may ask questions at any time. Recorded pertinent participant information including age and weight.

4. Adjusted crutches to the appropriate height for the participant.

5. Placed instrumented crutch under right arm of participant

6. Participants were instructed on how to use the crutches by me. First, showed the participants the proper way to hold the crutches. Then, instructed the participant on how to walk with a swing through gait. Told the participant to hold the crutches close to their body, place the crutches down in front of the body, and slightly to the sides. Told the participant to shift the weight onto the hands, push off with both feet together, and swing the feet through to land in front of the crutches. Allowed the participant to walk back and forth until they become comfortable with the crutches.

7. Had participant walk across flat ground of a known distance in the laboratory setting with swing through gait. Start the data recording, and use a stopwatch with the distance walked to get an assessment of the speed of the participant. Repeat this trial three times.

8. Had participant walk as fast as they were comfortable, and repeat the same procedure as in step 7.

9. Had participant walk as slowly as they could comfortably, and repeat the same procedure as in step 7.

10. Repeated step 7-9, with the spring damped component disabled by placing a stopper such that the spring cannot compress.

11. Environmental trials were completed outside, and all trials were repeated with both the spring system enabled and disabled as before. Additionally, a stopwatch was used to assess speed for all trials, though the participant was to choose a self-selected walking speed. Each trial was completed three times. The different environments were as follows:

    a. The participant walked over uneven ground of small rocks
b. The participant walked up an outdoor ramp

c. The participant walked down the same outdoor ramp.

The uneven ground portion was done in one location at Holland Bloorview, and the ramp was in another location. Thus, all rock trials were completed together, and the outdoor ramp trials were completed together.

12. All trials were completed with the distance of 10m.

13. Each participant was then thanked for their time and offered a gift card for participating.

3.2.7.1 Flexiforce Calibration

The Flexiforce calibration was based on what was determined by past testing to be the most accurate method for the given situation. Because there are two different forces to be analyzed, the low force sensors were calibrated with the weights 0g, 100g, 250g, 500g, 1000g, and the medium force sensors were calibrated with the weights 0g, 500g, 1000g, 1500g, 2000g.

1. Removed sensors from crutch
2. Placed sensor 1 underneath testing apparatus
3. Started LabVIEW, and ensured file save name and location. Started recording
4. Placed weight gently onto sensor (started with lightest value). Allowed weight to remain in place for 30s.
5. Removed weight, and placed second weight
6. Continued for full listing for either low or medium force weights as needed.
7. Stopped recording once all weights complete
8. Repeated for all sensors.
9. Compiled all sensors into one data file
10. Averaged 1000 data points from each data piece collected (did not include the first 250 values as the sensor had not yet stabilized)
11. Created a chart, with the sensor value on the x axis, and the known force applied on the y axis (including 0).
12. Added trend lines. Formatted the trend line to include the y-intercept of (0,0), and included the equation. Recorded values from the equation to use in the crutch trial data.
3.3 Crutch Analysis

Analysis was completed in Excel for all measurable variables. The variables measured by the study are grouped into three primary categories of walking speed, Flexiforce force sensors, and load cell.

3.3.1 Walking Speed

Walking speed was analyzed to provide a general understanding of how self-selected walking speed may be affected by the addition of a spring component, and to determine which speed to compare each environmental trial to. It is known that as walking speed increases, the force applied generally increases [20]. Therefore, by looking at what the walking speed was for the various trials, appropriate comparisons can be made.

To analyze walking speed, the speed was calculated for each of the three iterations of each different trial scenario, and averaged to provide a data set for each participant. The overall average was then calculated for all 10 participants.

3.3.2 Flexiforce Sensors

The Flexiforce sensor data was compiled into Excel sheets for each participant. It was then charted against time to determine and extract the middle three steps from each data set. The maximum value was then found for each step, and multiplied by the calibration factor to determine the force. This was calculated for each of the 11 sensors that were placed on the crutch, and compiled for all 10 participants. The forces were then normalized using body weight.

An average force was found for the hand as well as the forearm segments of the crutch. The hand segment was found by compiling sensors 1,3,4,5 and 6 on the hand. Hand sensor 2 was removed because it had an unacceptably high standard deviation from participant to participant due to the location on the crutch. The forearm segment was found by compiling sensors 3 and 4 on the forearm. Forearm sensors 1 and 2 were removed because the sensors fluctuated and accurate maximum forces could not be calculated. Two individual sensors were also analyzed. Sensor 4 on the hand was looked at because it had the highest force of any of the individual sensors. The grip sensor was also looked at individually.
3.3.3 Load Cell

The load cell data was combined into Excel sheets for each participant. Initially, force through the crutch Fz, and overall force determined by combining Fx, Fy, and Fz were both analyzed. However, it was determined that the difference was negligible between the two values, and Fz was the only value analyzed for the entire set. It was then charted against time to determine and extract the middle three steps from each data set. The maximum value was then found for each step. This was calculated for all 10 participants. The forces were then normalized using body weight.

The load cell data was also analyzed for maximum rate of loading. For each time step, the rate of loading was found by subtracting the previous value, and diving by the time step. The maximum value was found, and compiled for all 10 participants.

3.3.4 Comparisons

Comparisons were drawn to answer the three research questions. The first was to compare the maximum forces found for the load cell segment to the maximum forces from the Flexiforce sensors. This is to respond to research question 1.

To respond to research question 2 and 3, a repeated measures ANOVA was used to compare the spring trials to the no spring trials in each of the different environments. This was done for both the Flexiforce sensors, as well as the load cell for the maximum forces, and for the load cell for the maximum rate of loading. The repeated measures ANOVA was run for a 0.05 confidence interval. From the ANOVA, it was determined which, if any, differences were deemed to be statistically significant.
4 Results

4.1 Participant and Trial Information

In order to account for potential order effect, and drift of the sensor over time, the trials were arranged such that the two different characteristics affecting the trials were alternated. For the environmental effects, the indoor portion of the trial (walking with different speeds) was alternated with the outdoor portion of the trial (walking on different terrain of rocks, and up/down a hill). For the crutch component effects, whether the spring was tested first or the ‘not spring’ condition was tested first was alternated for each participant. This was maintained in each location.

Table 3, below, shows which participant completed which portion of the trial first, as well as participants’ weights which were used in calculating percentage body weight. It also includes any additional notes from the trial.
<table>
<thead>
<tr>
<th>Participant Number</th>
<th>Trial Order</th>
<th>Weight (kg)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Indoor</td>
<td>86.2</td>
<td>Participant completed indoor and outdoor portions of trial on separate days, additionally load cell data for indoor trials was unable to be calculated</td>
</tr>
<tr>
<td></td>
<td>Spring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Indoor</td>
<td>74.8</td>
<td>Participant’s load cell data failed for trial Rock Spring</td>
</tr>
<tr>
<td></td>
<td>No Spring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Outdoor</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Spring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Outdoor</td>
<td>67.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>No Spring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Indoor</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Spring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Indoor</td>
<td>98.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>No Spring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Outdoor</td>
<td>77.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Spring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Outdoor</td>
<td>96</td>
<td></td>
</tr>
<tr>
<td></td>
<td>No Spring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Indoor</td>
<td>68</td>
<td>Participant was unable to complete ramp portion of trial, including Up Ramp and Down Ramp for Spring and Not Spring</td>
</tr>
<tr>
<td></td>
<td>Spring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Outdoor</td>
<td>84</td>
<td></td>
</tr>
<tr>
<td></td>
<td>No Spring</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.2 Walking Speed Data

The participants were encouraged to walk at a self-selected pace for the indoor “Normal” speed walking trial. They were then instructed to walk faster, and slower, for the respective “Faster” and “Slower” trials, and this was intended to provide a 10% faster and 10% slower speed as a reference for forces at those speeds. The participants were instructed to walk at whichever self-selected pace they found comfortable for the outdoor environmental trials. The following chart, Table 4, shows overall walking speeds and standard deviation.

Table 4: Average walking speed for all conditions (m/s)

<table>
<thead>
<tr>
<th></th>
<th>Spring</th>
<th>No Spring</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal</td>
<td>Fast</td>
</tr>
<tr>
<td>Average</td>
<td>0.97</td>
<td>1.54</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.24</td>
<td>0.29</td>
</tr>
</tbody>
</table>

Figure 11, below, depicts the differences in walking speed for the different environments, as well as the speeds seen when the participants walked with and without the spring damped crutch.
4.3 Raw Data Sample

The following graphs, Figures 12 and 13, show a sample of the raw data in Newtons. This shows one step from a normal, spring trial. The first graph, Figure 12, shows the load cell data. It was initially calculated for both overall force and for Fz through the crutch. As can be seen below, the difference in force is negligible, and therefore only Fz was calculated after this. In the Flexiforce graph, Figure 13, it shows that hand sensor 4 is significantly higher than the other sensors. All of the Flexiforce sensors show the same general pattern of loading, except for the grip sensor, which is not loaded according to the gait cycle directly. For both graphs, there was no significant spike in data near the maximum force, which allows for the maximum force to be used as a measure.
Figure 12: Raw load cell data for one step, one participant for Normal Spring condition

Figure 13: Raw Flexiforce data for one step, one participant for Normal Spring condition
4.4 Flexiforce Sensor Data

4.4.1 Flexiforce Maximum Force Table

Maximum force as averaged for all 10 participants is included below in Table 5. Four major areas were considered. Firstly, the hand data was determined by combining sensors 1, 3, 4, 5, and 6 on the hand. Sensor 2 was omitted due to the standard deviation from participant to participant averaged 110% of the mean, due to the sensor being located in a position that was not always in contact with the hand. The forearm data was determined by combining sensors 3 and 4 on the forearm. Sensors 1 and 2 were found to have inconsistencies within the sensors themselves, and were removed on that basis. Hand sensor 4 was deemed to be the most important due to magnitude of force and importance of location, and therefore was included as a separate sensor. The grip sensor from the bottom of the crutch handle was also considered. The four combined sensor locations are summarized below in Figure 14.

Figure 14: Locations of 4 major areas of focus for Flexiforce sensors
<table>
<thead>
<tr>
<th></th>
<th>Spring</th>
<th>No Spring</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal</td>
<td>Fast</td>
</tr>
<tr>
<td>Overall Hand</td>
<td>Mean</td>
<td>5.59</td>
</tr>
<tr>
<td></td>
<td>St. Deviation</td>
<td>3.07</td>
</tr>
<tr>
<td>Overall Forearm</td>
<td>Mean</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>St. Deviation</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>St. Deviation</td>
<td>5.18</td>
</tr>
<tr>
<td>Grip</td>
<td>Mean</td>
<td>1.55</td>
</tr>
<tr>
<td></td>
<td>St. Deviation</td>
<td>0.62</td>
</tr>
</tbody>
</table>

Table 5: Average force for hand, forearm, hand sensor 4 and grip sensor for all conditions (%Body Weight)
4.4.2 Flexiforce Sensor Comparison

The Flexiforce sensors were grouped according to the four categories as seen in Table 5, and Figure 14, above. The following 6 graphs, Figures 15-20 show this comparison in each of the environments, for spring and no spring.

Figure 15: Flexiforce sensor values according to position for normal speed trials

Figure 16: Flexiforce sensor values according to position for fast speed trials
Figure 17: Flexiforce sensor values according to position for slow speed trials

Figure 18: Flexiforce sensor values according to position for rock environmental trials
Figure 19: Flexiforce sensor values according to position for up environmental trials

Figure 20: Flexiforce sensor values according to position for down environmental trials
4.4.3 Flexiforce Maximum Forces by Sensor Location

The maximum forces are summarized below in Figures 21 through 24.

**Figure 21:** Maximum forces observed on the overall hand by body weight

**Figure 22:** Maximum forces observed on the overall forearm by body weight
Figure 23: Maximum forces observed on sensor 4 on the hand by body weight

Figure 24: Maximum forces observed on the grip sensor by body weight

4.5 Load Cell Data

4.5.1 Load Cell Data Tables

The load cell maximum forces were averaged for all 10 participants and are displayed below in Table 6. Additionally, the maximum rate of loading was calculated and is included below in Table 7.
Table 6: Load cell forces by maximum force in Newtons and % body weight for all conditions

<table>
<thead>
<tr>
<th></th>
<th>Spring</th>
<th></th>
<th>Spring</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal</td>
<td>Fast</td>
<td>Slow</td>
<td>Rock</td>
</tr>
<tr>
<td>Maximum Force (N)</td>
<td>346.81</td>
<td>340.17</td>
<td>343.35</td>
<td>384.28</td>
</tr>
<tr>
<td>%Body Weight</td>
<td>49.82</td>
<td>48.78</td>
<td>49.13</td>
<td>49.15</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>3.21</td>
<td>3.99</td>
<td>2.44</td>
<td>5.12</td>
</tr>
</tbody>
</table>

Table 7: Load cell maximum rate of loading in N/s for all conditions

<table>
<thead>
<tr>
<th></th>
<th>Spring</th>
<th></th>
<th>Spring</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal</td>
<td>Fast</td>
<td>Slow</td>
<td>Rock</td>
</tr>
<tr>
<td>Loading Speed</td>
<td>2950</td>
<td>5375</td>
<td>2125</td>
<td>4744</td>
</tr>
<tr>
<td>(N/s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>1456</td>
<td>2217</td>
<td>877</td>
<td>1275</td>
</tr>
</tbody>
</table>
4.5.2 Load Cell Maximum Force and Rate of Loading

Figure 25, below, represents force as a percentage of the subject’s body weight across all conditions. Additionally, Figure 26 shows the rate of change of the force in N/s, showing maximum values.

![Force as % Body Weight](image1)

**Figure 25:** Maximum forces observed on the load cell by body weight

![Rate of Loading](image2)

**Figure 26:** Maximum rate of loading observed on the load cell in N/s
4.6 Research Questions

For the following questions, the speed trials were analyzed to determine which trial to statistically compare the environmental trials to. After performing a repeated measures two way ANOVA in SPSS, it was found that there was no significant differences due to the spring condition (p=0.428) and spring*environment (p=0.0225), however, it was deemed that the environment played a significant part in modifying walking speeds (p=0.006). From pairwise comparisons, it was confirmed that the timed trials of slow, normal, and fast, were all significantly different than each other (p=0.000). The rock trial was considered significantly different from the normal and fast trial, but not significantly different than the slow trial (p=1.000). For the force investigations, this means it is most appropriate to compare the future rock trials to the slow trials. The up and down trials were shown to be significantly different than the slow trials (p=0.004 and 0.001, respectively) and the fast trials (p=0.000 and 0.001, respectively). They were both however not significantly different than normal speed (p=1.000) and so up and down trials are compared to normal speed trials for force analysis.

4.6.1 Research Question 1: Interfacial Force Distribution

The comparisons made between the individual sensors can be seen above in the Flexiforce section, Figures 14-19. The location of the Flexiforce sensors on the hand is in the Methodology section, Overall Crutch Design, Figure 10.
4.6.2 Research Question 2: Spring Crutch Modification

4.6.2.1 Flexiforce

The comparisons between the spring and not spring scenarios can be seen above, in section 4.3 Flexiforce Sensor Data. Additionally, a repeated measures two way ANOVA in SPSS was performed on the four different Flexiforce sensor measures to determine if any of the spring differences were statistically significant. It was determined that in terms of spring vs no spring, the grip sensor (p=0.766), overall hand (p=0.709), overall forearm (p=0.619), and hand sensor 4 (p=0.582) were all not determined to have statistically significant changes in spring compared to no spring.

4.6.2.2 Load Cell

The comparisons between the spring and not spring scenarios can be seen above, in section 4.4 Load Cell Data. Additionally, a repeated measures two-way ANOVA in SPSS was performed on the load cell force data, and the load cell rate of loading data, to determine if the spring in the crutch design was statistically significant. For the load cell force data, the differences in forces were not deemed to be statistically significant (p=0.270). For the load cell rate of loading data, there was a significant difference for the differences between spring and not spring (p=0.012). Because for this measure there was only one comparison, it was determined that spring was deemed to have a significantly lower rate of loading.

4.6.3 Research Question 3: Environmental Modifications

4.6.3.1 Flexiforce

The comparisons between the environmental modification scenarios can be seen above, in section 4.3 Flexiforce Sensor Data. Additionally, a repeated measures two way ANOVA in SPSS was performed on the four different Flexiforce sensor measures to determine if any of the environmental differences were statistically significant. It was determined that in terms of environmental modifications, the grip sensor was not affected (p=0.161), overall hand (p=0.269), overall forearm (p=0.081), and hand sensor 4 (p=0.487) were all not determined to have statistically significant changes.
Additional figures were drawn which show visually the difference between the different environments. As no significance was reached for the crutch modifications, this portion was completed on the no spring trials only, and is shown below in Figures 27-30.

**Hand Force vs Speed**

![Graph showing hand force vs speed](image)

- Linear (No Spring Flat): \( y = 0.6925x + 4.7745 \)

**Forearm Force vs Speed**

![Graph showing forearm force vs speed](image)

- Linear (No Spring Flat): \( y = 0.2166x + 0.7126 \)

**Figure 27:** Spring-less crutch hand force compared to speed, with environmental conditions

**Figure 28:** Spring-less crutch forearm force compared to speed, with environmental conditions
Figure 29: Spring-less crutch hand sensor 4 force compared to speed, with environmental conditions

Figure 30: Spring-less crutch grip force compared to speed, with environmental conditions
4.6.3.2 Load Cell

The comparisons between the environmental modification scenarios can be seen above, in section 4.4 Load Cell Data. Additionally, a repeated measures two-way ANOVA in SPSS was performed on the load cell force data, and the load cell rate of loading data, to determine if any of the environmental differences were statistically significant. For the load cell force data, the differences in forces were not deemed to be statistically significant (p=0.255). For the load cell rate of loading data, there was a significant difference for the differences between spring and not spring (p=0.018). For this measure, there were multiple comparisons being made. The comparisons that hold significance are as follows: between medium and fast (p=0.008), and slow and fast (p=0.004). Additionally, for environmental trials, between rocks and slow was statistically significant, (p=0.008), while the difference between normal and up (p=0.164) and normal and down (p=0.147) was not.
5 Discussion

5.1 Research Questions

5.1.1 Research Question 1: Interfacial Force Distribution

What is the distribution of pressures at the crutch body interfaces, and how do these relate to anatomy and potential mechanisms of injury?

5.1.1.1 Carpal Tunnel Region

The most valuable information gained from this study is from the Flexiforce sensors seen at the interface. From Figures 15-20 in the results section above, it can be clearly seen that the different regions of the crutch experience different amounts of loading. The most important sensor was found to be sensor 4 on the hand. This sensor was seen to have about 10% of the body weight on average. This sensor was also located directly on the carpal tunnel region, which is not optimal loading as the added force could lead to compression of the nerves in the wrist over time. Conversely, the sensors surrounding this one had about 4% of the body weight, to average at 6% for the overall hand when including sensor 4. If these forces were placed more evenly over the hand, it’s possible that long term pain would be diminished because the carpal tunnel region would have a reduced load.

5.1.1.2 Flexiforce Sensor System

Overall, it was seen that the forearm sensors had about 1% body weight each, and the hand sensors had at average 6% each. This means that the forearm rest is essentially being used mostly has a balance mechanism, and isn’t actually taking much of the force off of the hand to reduce the load. It may be interesting to look at different angles or lengths of the forearm tube to see if further weight can be displaced to the forearm. The grip sensor was seen to have about 2% of the body weight on average. This implies that the participants were gripping upwards, which may imply that some of the force directed downwards on the top of the crutch handle could be due to the participant squeezing the handle. It is possible that if this amount was reduced, the likelihood of injury may reduce as well because the overall forces may decrease.

The Flexiforce sensors in general, as anticipated, were useful in determining where on the hand and arm the force is placed. It was determined that the force isn’t displaced evenly over the crutch.
handle and forearm rest, and this kind of discovery would not be possible without using a system that can analyze directly at the interface. However, the Flexiforce sensors were less accurate, and couldn’t be verified that the entire force placed on the crutch handle went onto the sensors, as it is likely that the hand impacted the handle directly in some places. This is evident by examining the overall load seen by the Flexiforce sensors. As can be seen in Figure 17, the overall force through the crutch hovers around 46-50% of the body weight, which makes sense because the entire body weight would be supported on the two crutches. The Flexiforce interfaces however, hold an average of about 6% for each sensor on the hand, and about 1% for each sensor on the forearm, as previously stated. This would add up to about 40% of the body weight total for the 6 sensors on the hand, and the 4 on the forearm. The residual not measured by the Flexiforce sensors is likely explained by the hand contacting the crutch on areas besides the sensors.

5.1.2 Research Question 2: Spring Crutch Modification

Is there a significant difference between different crutch modifications such as the addition of a spring component?

From the Flexiforce data, no significant changes were seen between the different crutch modifications. The overall force seen on the various parts of the hand remained consistent from trial to trial. This would imply that the spring would not add any significant benefit from a force-based injury perspective such as carpal tunnel syndrome. However, the load cell data showed that for the rate of loading, there was a significant decrease in maximum rate from the addition of the spring. It is not clear how this may directly affect the rate of forces at the interface due to the inability to analyze rate of loading on the Flexiforce sensors at this time, but it is expected that because it decreased through the crutch, it would decrease at the interface as well.

The fact that the spring reduces the maximum rate of loading is likely beneficial because it allows the force to more gradually impact the hand. High rates of loading have been seen in sports such as gymnastics, which are known to have wrist injuries similar to crutches [14]. In a pommel horse study, it was seen that loading rates averaged 129BW/s with maximums of 219BW/s. Though the maximum loading rates in this study are much lower, by decreasing the loading rates with the inclusion of a spring dampener, the likelihood of injury is reduced.
In the future, if an additional load cell could be placed in the forearm shaft and that rate of loading was measured at that point, it may be easier to speculate if the rate is consistent throughout the crutch. This would imply that the loading pattern seen in the crutch would likely follow the same pattern seen with the maximum forces, and that the rate of loading on the carpal tunnel sensor would be similarly high.

5.1.3 Research Question 3: Environmental Modifications

Do different environments such as up/down hills and over rocks have an impact on the forces at the interface between an upper extremity and an upper extremity MAT?

It was clearly determined in the rate of loading trials that different environments have an impact on the forces at the interface. The most obvious case was the rock trials. When compared to the similar speed slow trials, the rock trials were statistically significantly higher. This trend was continued with all of the Flexiforce sensor trials, though they did not achieve statistical significance. It is speculated that the increase in rate of loading is partially due to the instability, as well as the possibility for the crutch to slip and land harder than anticipated on the ground. This would rapidly increase the force through the crutch, and cause a spike in the rate of loading.

Generally, up and down did not differ very much from the normal speed trials for the Flexiforce sensors, and there was no trend with either the up and down trials being higher or lower forces. The trials that showed the largest differences were the forearm sensor when travelling down the ramp, and the grip sensor when travelling up the ramp. This implies that while travelling downwards, one leans back on the crutch more, causing a displacement to the forearms, and when travelling upwards, one pulls up on the crutch, and flexes the muscles needed to pull the body up the hill. The rate of loading also increased, though not statistically significantly.

In general, the sensor that showed the least change over the different environments was the hand sensor 4. This is promising, because it means that if it is able to reduce the force for sensor 4 on a standard flat ground trial, it is likely to apply to all environments. The overall load itself on the crutch also did not show change from environment to environment. This is likely because the maximum load through both crutches would need to reach 100% total, and therefore any major changes would have to result from a transfer from one crutch to the other or vice versa.
5.2 Study Limitations

One of the key limitations to this study is in the sensitivity and reliability of the Flexiforce sensors. The standard deviation from participant to participant is significantly higher with the Flexiforce sensors (averaging 52.8% of the mean) than with the load cell (averaging 11.5% of the mean). Additionally, some of the sensors were unable to measure the forces reliably at the forces in use, and so were unable to be used. One way to limit the effects is to use the same sensor in the same place for all trials, which was done during this trial. Additionally, comparisons can be made between the sensors, but the overall accuracy of the sensors limits their use as an overall measure of the force on the hand. Improvements in encapsulation could also allow for better accuracy in the future.

Another limitation is that the instrumentation was only placed on one of the two crutches. Because of this, it was challenging to determine how accurately the load cell was measuring the force through the crutch. If a load cell was placed in each crutch, the entire force would need to be placed through the two crutches, and any discrepancies could be considered error. Due to the crutch instrumentation in general, the actual manner in which participants walked with the crutches could have been modified from how they would walk with no instrumentation. This could be due to the weight in the crutch, though the location of the load cell was placed closer to the handle in order to reduce the moment arm caused by the weight.

There were also several limitations due to the locations of the Flexiforce sensors. The first is that because the sensors did not cover the entire area of the hand, there were portions of the hand that made contact with the crutch itself. This means that the entire weight going through the crutch was not accounted for by the sensors themselves. Additionally, the size of the participants’ hands would exacerbate this effect, with the larger hands placing more weight on the crutch, and the smaller hands not fully compressing all of the sensors.

5.3 Future Work

The most valuable factor studied from the load cell in this study was the rate of loading. Therefore, one major area of investigation would be to look at the rate of loading for the Flexiforce sensors, and determine through that if the same changes occur at the interface. This
could be done for the current conditions with changing environments and the addition of a spring damped component, as well as any additional conditions outlined below.

In the future, there are several possible additions and modifications to this study that could allow for improvements to crutch manufacturing processes and crutch technique. Primarily, this study was conducted with just 10 participants, and a larger or more indicative sample group may provide a better result statistically. Additional studies with various crutch user groups would be highly beneficial to determine how crutches are actually used within the populations. Ideally, several populations would be considered in separate groups such as amputees, participants with spina bifida or cerebral palsy, or participants with short term injuries such as broken legs. A way to test this without using population groups may be to have able bodied users perform different crutch gaits, or walk the same gait with modifications like keeping the crutch tips close or far from the body. These gait modifications may indicate a more appropriate gait for certain users to employ, or may determine that a certain crutch placement has a higher likelihood of causing upper extremity injury.

If a crutch user group is chosen, it should be considered that the current results may not apply due to differences in gait and posture. Therefore, current assumptions should be reevaluated, and changes may need to be made to the crutch instrumentation for the crutch users. Specifically, the crutch users may find the weight to be too much. If this is the case, it may be necessary to find a lower weight load cell. It may be possible to use a single axis method that measures the force through the longitudinal axis, but it should be noted that different crutch user groups may use the crutches in unexpected ways, and if the additional axes are necessary this will not be possible. Other measures that could be included could be the acceleration of the crutch, or an accelerometer to look at the position of the torso to determine if that has an effect on the forces. It may be valuable to visually compare walking methods with the crutch with and without the instrumentation, to ensure no major changes have occurred from the addition of the instrumentation.

One possibility for crutch modifications is to test future grip designs against current ones to determine if the force is better displaced over the hand, and less localized in the carpal tunnel region. A design that better supports the hand on the thumb side, where the sensors had the least force placed on them, may be an option to look into. When looking at this, something to consider
would be to change the location of the sensors dependent on the size of the hands of the individual participants. One method may be to use anatomical landmarks on the hand to place the sensors, to ensure they act on the same place for each participant.

The grip angle itself likely has an effect on force, wherein a reduced angle such that the wrist is held relatively straight may help displace weight better. In past studies, wrist flexion has been shown to increase the pressure in the carpal tunnel region, and therefore cause pain and stress [21]. A handle design that holds the hand in the most neutral position possible would likely reduce pain, and may correspond to lower forces as well. This could be tested by looking at the interface forces at various angles. It could also be tested by looking at the orientation of the wrist through use of an accelerometer.

Crutch modifications may also be made to the forearm shaft to attempt to place more weight on the forearm which may be better able to displace the weight. One such crutch modification that could be tested would be the length of the forearm shaft, and therefore, where the forearm rest sits on the forearm itself. Additional comfort may come in placing the forearm rest on a soft or muscled part of the arm rather than bone. Additionally, the angle of the forearm shaft to the main shaft of the crutch may have an effect on the forces on the arm. One way to assess this might be to add an additional load cell into the forearm shaft of the crutch to determine how much force is continued up that part of the shaft to the forearm interface.

In the future, it is likely that the environment plays some role on the forces on the arms, and therefore should be considered in any future work. The factor that seems the most important is walking over small rocks or uneven ground due to the instability of the surface. Further environments that would be useful to test if a safe way to test is available is force when slippage occurs, such as on ice or water.

In many studies on crutch injury, it is stated that repetitive motions can compound leading to stress fractures or other wrist injuries [22, 23]. It would therefore be highly beneficial to perform a longer trial in order to replicate the loading pattern over time. It is possible that either the forces remain consistent and the repetitive motion occurs in the wrist entirely, but it is also possible that as time progresses, the loading pattern itself shifts from one part of the hand to a more vulnerable area, causing pain and discomfort for long term users.
6 Conclusions

The overall goal of the study was to determine how the forces from a crutch are transferred to the upper body during ambulation with crutches. This was done primarily because crutch users are prone to wrist injuries such as carpal tunnel syndrome. In order to reduce the risk of injury, it is optimal to reduce the forces seen both in the hand in general, and the carpal tunnel region specifically. Additionally, it is important to recreate situations closer to what a crutch user may experience in everyday life, rather than laboratory conditions, in order to get a better idea of what the forces would actually be day to day. Once this information is obtained, and a system is in place, it can be used to test new developments in crutches and see if improvements are made.

With this in mind, this study had three technical developments and three research questions. The technical developments included determining the characteristics of thin flexible bend sensors, creating a system for those sensors to be used on a crutch wirelessly, and fitting a load cell onto the crutch for overall data. Through this, it was intended to discover the relationship between the load cell and the interface sensors, the effect of a spring damped crutch component on the forces seen on the crutch, and the effect of different environments on the forces seen on the crutch.

The study was completed with 10 participants who walked at three different speeds on flat ground, and three environmental trials over rocks, up, and down a hill. It was found that the load cell maintained about 50% of the body weight for all trials. The Flexiforce sensors were grouped into four categories: average hand, average forearm, grip sensor, and hand Sensor 4. Hand sensor 4 was looked at individually because it maintained about 10% of the body weight, and was situated on the carpal tunnel region. The average hand values were around 6%, average forearm around 1% body weight, and the grip sensor around 2%. No major correlations were seen between the maximums seen from the Flexiforce sensors and the load cell.

The effect of the spring was not seen on the maximum forces observed in either the Flexiforce sensors or the load cell. However, a significant decrease ($p=0.018$) in the load cell’s rate of loading was seen when the spring was placed on the crutch. This is likely because the spring slows down the force’s transmission through the crutch as gait occurs.
The effect of the environment was not seen in the maximum forces observed in the load cell. For the Flexiforce sensors, significant differences were not observed, but a trend was seen that the rocks trial was higher than the slow trial for all areas (hand, forearm, grip, and hand sensor 4). For the load cell rate of loading, a significant difference (p=0.008) was seen between the rock trials and the slow walking speed trials (to which the rock trials corresponded in speed). Changes were seen between the normal speed trial and the uphill and downhill trials, but they were not deemed significant (p= 0.164 and 0.147, respectively). The rock trial likely placed the participants in the most unstable position, and caused the crutch tip to slip and force more pressure through the shaft of the crutch more quickly.
7 References


Appendix A: LabVIEW Code for Flexiforce Sensors

Figure 31: LabVIEW ‘Config’ tab

Figure 32: LabVIEW ‘History’ tab
Figure 33: LabVIEW ‘Full View’ tab
Figure 34: LabVIEW ‘Quick View’ tab
Figure 35: LabVIEW block diagram
Appendix B: Load Cell Settings

Figure 36: imc Devices home screen

Figure 37: imc Devices measurement settings
Figure 38: imcDevices amplifier settings

Figure 39: imcDevices storage settings
Appendix C: Flexiforce Data Sheet

FlexiForce®
Standard Force & Load Sensors Model # A201

Physical Properties

- Thickness: 0.208 mm (0.008 in.)
- Length: 197 mm (7.75 in.)
- Optional trimmed lengths: 152 mm (6 in.), 102 mm (4 in.), 51 mm (2 in.)
- Width: 14 mm (0.55 in.)
- Sensing Area: 9.53 mm (0.375 in.) diameter
- Connector: 3-pin Male Square Pin (center pin is inactive)
- Substrate: Polyester (ex. Mylar)
- Pin Spacing: 2.54 mm (0.1 in.)

✓ ROHS Compliant

* Length does not include pin, please add 31.75 mm (0.25 in.) for pin length to equal a total length of 203.2 mm (8 in.).

Standard Force Ranges (as tested with circuit shown below)

<table>
<thead>
<tr>
<th>Range</th>
<th>Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 1 lb</td>
<td>4.4 N</td>
</tr>
<tr>
<td>0 - 25 lb</td>
<td>110 N</td>
</tr>
<tr>
<td>0 - 100 lb</td>
<td>440 N</td>
</tr>
</tbody>
</table>

In order to measure forces above 100 lb (up to 1000 lb), apply a lower drive voltage (-0.5 V, -0.10 V, etc.) and reduce the resistance of the feedback resistor (1kΩ min.) Conversely, the sensitivity can be increased for measurement of lower forces by increasing the drive voltage or resistance of the feedback resistor.

![Recommended Circuit]

- Supply voltages should be constant
- Reference Resistance Rf is 1kΩ to 100kΩ
- Sensor resistance R_s at no load is >3MΩ
- Max recommended current is 2.2mA

Typical Performance

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linearity (Error)</td>
<td>&lt; ±3%</td>
</tr>
<tr>
<td>Repeatability</td>
<td>&lt; ±2.5% of full scale</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>&lt; 4.5% of full scale</td>
</tr>
<tr>
<td>Drift</td>
<td>&lt; 5% per logarithmic time scale</td>
</tr>
<tr>
<td>Response Time</td>
<td>&lt; 5 sec</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-40°F - 140°F (-40°C - 60°C)</td>
</tr>
</tbody>
</table>

Evaluation Conditions

- Line drawn from 0 to 50% load
- Conditioned sensor, 80% of full force applied
- Conditioned sensor, 80% of full force applied
- Constant load of 25 lb (111 N)
- Impact load, output recorded on oscilloscope
- Time required for the sensor to respond to an input force
Appendix D: Research and Ethics Board Appendices

Budget

This study involves the pursuits of one Master’s student at the University of Toronto who is funded by other agencies (through University of Toronto Fellowships, Research Assistantships). Other costs associated with the study, described below, will be covered by discretionary funds held by Dr. Andrysek.

<table>
<thead>
<tr>
<th>Item Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexiforce Sensors (25 lbs) x 10</td>
<td>$200</td>
</tr>
<tr>
<td>Flexiforce Sensors (1 lb.) x 5</td>
<td>$100</td>
</tr>
<tr>
<td>Renumeration for Subject Participation (Part 2)</td>
<td>$120</td>
</tr>
<tr>
<td>Parking for Subject Participation (Part 2)</td>
<td>$120</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$540</strong></td>
</tr>
</tbody>
</table>
Analysis of force distribution on upper body limbs during ambulation with crutches

Data Collection Form

Date of collection: __________
Consent/Assent obtained? □
Age: __________
Sex: F or M
Height (cm): __________
Weight (kg): __________

Allergy / associated conditions (eg: asthma):
__________________________________________
__________________________________________

Things to do if these conditions occur:
__________________________________________
__________________________________________

Comments:
__________________________________________
__________________________________________
Dear Participant,

My name is Emma Rogers. I am part of a research team at Holland Bloorview that is developing a way of measuring forces on crutches by testing a new device. We would like to invite you to take part in this study. Before agreeing to take part in this study, it is important that you understand how you will be involved.

**What is the study about?**

We are testing how force is placed on crutches when people walk. To test this, we are using flat sensors on the crutches, and measuring how much force is placed on different areas. There are two parts. The first part is testing how accurately the sensors measure force, and the second will use crutches to test how crutch types and environment affect force. You are being invited to participate in the second part of the study.

While walking with crutches, some long-term users experience pain and discomfort in the upper limbs. In particular, carpal tunnel syndrome may be developed in the wrists, and shoulder problems may develop as well. The forces that are placed from the upper limbs onto crutches have been analyzed before, but the participants were never able to use the crutches in their natural environment. This test will first see how accurate the system that has been developed is, and then test whether there are differences between different crutch types, and different environments. The results of this study will help determine how to make better crutches in the future by showing what forces exist at the hand and elbow rest of the crutch.

We’re not sure how the forces at the hand and forearm relate to the overall force through the crutch. We are also not sure whether there will be improvements with a spring damped crutch, and if there are any differences in the natural environment. In this study, 12 participants will help us test this system on the crutches. We want to invite you to be one of the subjects who will try it.

**How will I be involved in this study?**

We will fit the crutches to you, and show you how to walk with them. You will then be asked to complete a series of walking trials with different modifications. You may be asked to remove one shoe to facilitate one of the gait styles we will be using. You will be asked to walk up and down a ramp, and across uneven ground.

This session at Holland Bloorview will last about 3 hours.
**Will anyone know what I say?**

We will ask for basic personal information such as your weight, name, height, and age. All the information we collect about you will be kept confidential. We will not make public anything that might identify you, unless legally required to do so.

If the results of the study are published, your name will not be used and no information that discloses your identity will be released or published without your prior agreement. We must keep the research data we collect for 7 years as required by Holland Bloorview.

**Do I have to do this?**

You do not need to do this study. It’s okay if you decide not to take part. If you decide to take part, you can change your mind at any time. Whatever you decide will not affect the services you get from Holland Bloorview.

**What are the risks and benefits?**

There are no major risks associated with the crutches you are using for the duration of the study. They are similar to crutches you may receive if you were to be injured. They are known as forearm crutches, and may seem different than crutches you may have seen or used before. You may experience some discomfort in your arms, and can take breaks between trials to rest your arms. Most risks associated with crutches happen over long term use. There is a low risk of you slipping or falling. We will make sure that you are comfortable walking with them prior to starting the study by training you on how to use the crutches. You will have full use of both legs during all trials, and when walking across uneven ground, we will have a spotter beside you to ensure you are safe.

By participating in this study you will be providing valuable information about the forces that are at the crutch interfaces. This will allow us to further our research, and ultimately allow us to improve crutches and reduce injury.

You will not waive your legal rights in the event of research-related harm if you decide to take part in this study.

**What if I have questions?**

Please ask me to explain anything you don’t understand before signing the consent form. My phone number 416-425-6220 x3367. If you leave a message, I will return your call within 48 hours.

We will pay for your parking expenses when you visit Holland Bloorview for this study. You will receive a $10 gift certificate for participating in this study.

If you have any questions about your rights as a research participant, please contact the Holland Bloorview Research Ethics Board at 416-425-6220 ext. 3507.

Thank you for thinking about helping us with this project.

Yours truly,

*Emma Rogers*

Clinical Engineering Graduate Student  
Holland Bloorview Kids Rehabilitation Hospital  
Phone: 416-425-6220 x3367
CONSENT FORM
HOLLAND BLOORVIEW KIDS REHABILITATION HOSPITAL

1. Re: Analysis of force distribution on upper body limbs during ambulation with crutches

Please complete this form below and return it to the researcher. You will receive a signed copy of this form.

Emma Rogers explained this study to me. I read the attached Information Letter and understand what this study is about.

I understand that I may drop out of the study at any time.

I agree to participate in this study.

______________________________  _______________________________  ________
Participant’s Name (please print)   Signature                   Date

I have explained this study to the above participant/parent and have answered all their questions.

______________________________  _______________________________  ________
Name of Person Obtaining Consent   Signature                   Date
Hello,

We are looking for volunteers to participate in a research study to investigate the forces that are placed on the upper arm while walking with crutches. We hope that this work will lead to better crutch design and use in the future, helping to improve how people with mobility problems walk and get around.

As part of the study, you will attend one session lasting roughly 2-3 hours. You will use the crutches to walk in a laboratory setting, as well as complete some functional mobility tasks using crutches.

During the session, we will size the instrumented crutches to fit you, and allow you time to familiarize yourself with walking with them. We will then perform simple experiments by modifying the crutch, and then asking you to complete simple tasks. These may include walking up or down stairs or a ramp, or across uneven ground.

You are eligible to participate in this study if you: are older than 16 years, can communicate, read and write in English, can put weight onto your arms to walk with crutches to simulate an injury

You are ineligible to participate in this study if you: have a lower limb or neurological impairment that may impact gait or balance, currently use a mobility aid

Please note that your participation is completely voluntary and the decision to participate will not affect your status at Holland Bloorview or the University of Toronto. If you are interested in learning more about this study, or have any questions or concerns, please contact me.

Thank you for your time and support.

Best regards,

Emma Rogers
Room 4W254
Bloorview Research Institute
150 Kilgour Road
Toronto, Ontario, M4G 1R8
Tel: 416-425-6220 x3367
Email: erogers@hollandbloorview.ca
Email Script

Hello ______________________,

My name is ______________________ from Holland Bloorview Kids Rehabilitation Hospital and I’m a researcher involved with a study that will test how force is placed on crutches. Recently, I received your response to my advertisement that you would had agreed to be contacted to hear more.

If you are still interested in this project, please let me know. If not, that’s fine, and I will not contact you again, and thank you for your time.

Here is some general information about the part of the study you will be involved in:

For this study we will be testing how force is placed on crutches. We will teach you with how to walk with crutches, and then have you walk with them on a flat surface, up and down a ramp, and over an uneven surface, as outlined in the information letter. We will have a spotter available for the ramp trials, and you will be allowed to walk normally whenever you wish.

If you are still interested in participating in this study, please send me a time at which you would be able to come to Holland Bloorview for 3 hours.

Consent forms will be available to sign before first visit starts. If you think of any other questions or would like to speak to me about this at anytime, please feel free to call me at 416-425-6220 extension 3367.

Thank you,

Emma Rogers
Telephone Call Narrative

Hello. May I please speak with ____________________?

My name is ____________________ from Holland Bloorview Kids Rehabilitation Hospital and I’m a researcher involved with a study that will test how force is placed on crutches. Recently, I received your response to my advertisement that you would had agreed to be contacted to hear more.

Are you still interested in hearing about this project?

- **If NO,**
  That’s fine, we won’t contact you again. Thanks for your time!

- **If YES,**
  Great. Let me tell you more about this study. Please interrupt me at any time if you have a question.
  
  For this study we will be testing how force is placed on crutches. We will teach you with how to walk with crutches, and then have you walk with them on a flat surface, up and down a ramp, and over an uneven surface, as outlined in the information letter. We will have a spotter available for the ramp trials, and you will be allowed to walk normally whenever you wish.

Do you have any questions relating to the information sheet or study in general?

Are you still interested in participating in this study?

- **If NO,**
  “That’s fine, we won’t contact you again. Thanks for your time!

- **If YES,**
  proceed to set up time for one visit (3 hours)

Consent forms will be available to sign before first visit starts. If you think of any other questions or would like to speak to me about this at anytime, please feel free to call me at 416-425-6220 extension 3367.

Thank you.