Bone Loading in the Upper Extremities

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Abstract

Over 54 million adults in the U.S. are diagnosed with low bone mineral density (BMD). This increases their chance of fractures, especially at the hip or wrist. Because bone adaptation is thought to be driven by strain-producing physical activities, surveys have been made to relate physical activity history to BMD. Current surveys focus on the lower body, but this study examines how physical activity in the upper extremities relates to upper body BMD. Subject testing of 5 basic upper body motions were used to calculate bone loading weighting factors in 34 activities. These weighting factors were used to develop a novel Bone Loading in the Upper Extremities (BLUE) score, but this score was not found to be a significant predictor of BMD ($r=0.32$, $p=0.21$).
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Authorship

All aspects of this project were contributed to equally by all three team members.

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Chapter 1 Introduction

There are over 9 million adults in the U.S. diagnosed with osteoporosis, in addition to 45 million diagnosed with low bone mineral density (BMD). These numbers equate to approximately 1 out of every 2 women and 1 out of every 4 men over the age of 50 having an osteoporosis related fracture in their lifetime (NOF Release, 2013). It is established that many factors affecting our BMD are out of our control; this includes age, sex, and family history, but a growing body of evidence is showing correlation to a controllable variable: physical activity. Bone adaptation is thought to be driven by strain-producing physical activities with strain magnitude and strain rate being key factors. The effect of bone loading physical activity has been examined in common fragility fracture sites; these include the lumbar spine and femoral neck. Consequently, there haven't been many studies focusing on other fracture sites such as the wrist. Focusing on this gap in knowledge, our team will examine how bone loading physical activity history in the upper extremities relates to upper body BMD in the upper body, focusing, specifically at the wrist.

In order to study the relationship between bone loading physical activity history and BMD, a person’s activity history must be quantified. Surveys and questionnaires have been used, assigning weighted values, based on ground reaction forces generated, to various categories of activities that were based on ground reaction force generated. An example of this can be shown from a survey called the Bone Physical Activity Questionnaire (BPAQ). In this study basic lower body exercises, such as squats and lunges, were performed on a force plate and the peak force output was noted. Peak force output was multiplied by the frequency the action was performed for a specific activity, such as gymnastics, and an effective loading rate would be assigned to that activity. These loading rates became the weighting factors used to quantify which activities provide what loads, relative to one another. An algorithm was then created using these weighting factors and how often a survey taker performed the activity associated with them. Finally, a survey was produced where participants could write their activity history in a simple fashion and a physical activity score would be produced from the algorithm. A correlation was found between these physical activity scores and a person’s BMD, specifically at the femoral neck. The aim of this project is to produce bone loading activity weighting factors in a similar fashion that focus on the upper extremities, in order to quantify the upper extremity activity history and examine the relationship with BMD.

To accomplish this goal our project will be broken down into two parts. Part I: Design of a biometric data acquisition and analysis system to measure parameters related to force and rate of force generation during strain-producing upper extremity activities. Part II: Collection and analysis of data for various upper
extremity activities in order to assign weighting factors related to how they load the bones. Using these weighting factors and data from a previous study we generated bone loading in the upper extremity (BLUE) scores and compared them to distal radius BMD.

In Part I of our project, we created various design alternatives based on methods we had found in literature to measure bone loading. These methods included the use of force transducers, strain gauges, accelerometers, force plates, and optical measurements. We down-selected a final method based on how it met our major objectives, such as being accurate and safe to use; while satisfying our constraints, like being under $400, and still able to perform necessary functions. After a selection was made we ordered parts and built a prototype. Using this prototype, we tested data acquisition for various activities and determined how to filter out unnecessary data and reduce noise and motion artifacts. After our data acquisition device and methods were refined, we tested the feasibility of upper extremity categories we selected to measure and decided on the categories to assign weighting factors to in Part II.

In Part II of our project we had volunteers perform the motions we chose to measure and acquire data. We combined data acquired to generate single motion scores for acceleration and force. Using these scores we applied them to various activities given by our client and generated our weighting factors. Using previously collected data, we calculated subjects BLUE scores with our weighting factors and compared these values to subject’s wrist BMD.

In the next chapter, we summarize our literature review and lay a foundation to emphasize the significance of low bone mineral density, the connection between activity and BMD, and what is currently known that relates the two. We conclude the background by emphasizing the state of the art for activity surveys and bone loading data acquisition devices and stress how a gap remains for upper extremity based activities. Following our Background chapter we detail our Project Strategy. This chapter begins with our initial client statement and delves into the details of our objectives for the project by showing an objective’s tree and ranking these objectives through pairwise comparisons. The constraints of these objectives are discussed next and are followed by our revised and final client statements.

The chapter following this, Alternative Designs, sets up the design process for Part I of our project. In this chapter we perform a needs analysis and define the functions our device must perform and the specifications our design must meet. We then present conceptual designs and discuss our feasibility study concluding with a design calculation used to select our final design. After, we discuss how we optimized the design and data acquisition methods based on the preliminary data we collected. The chapter following this, Design Verification, presents the raw results of our data acquisition process, including the
weighting factors generated and survey scores generated from previous data. The chapter following this is our Discussion.

In the Discussion, we discuss what the results presented in the previous chapter meant. Our initial assumptions and the results generated are compared and we discuss how our results satisfied the objectives and constraints of the project. Following this, we discuss the study's limitations and areas where problems arose. Additionally, we comment on the economic factors of our device design, ethical issues involved in data collection or survey administration, and the absence of health and safety issues in our study. In the following chapter, Final Design and Validation, we defend our experimental methods and represent our sequence of tasks. The goal for this chapter is to allow a reader to reproduce our experiment and show that our specific project aims were met. Finally, we finish with our Conclusion and Recommendations chapter, where we draw our global conclusions and describe what information we would like to pass on for future studies.
Chapter 2 Literature Review

2.1 Significance
Bone mineral density (BMD) is the measure of bone mineral mass per square centimeter. BMD increases until around age 30 and then steadily declines afterwards, declining even faster during menopause in women. Fig. 1 below shows a graph of BMD over time in women.

![Bone Mass in Women](image)

*Figure 1: Typical Bone Mass growth/loss in Women over a 90 year period.*

Osteoporosis is a disease that weakens bones over time and increases the risk of fractures. Currently, over 9 million people in the U.S. have osteoporosis and 45 million have low BMD or osteopenia (NOF, 2013). Osteoporotic patients have a BMD that is 2.5 standard deviations (SD) or more below the average value for premenopausal women. Patients with osteopenia, or low BMD, have a BMD between 1 SD and 2.5 SD below average. The increased weakness of bone due to BMD loss results in fragility fractures that are commonly seen in the lumbar spine, hip, and wrist. The prevalence of BMD loss equates to ½ of women and ¼ of men over the age of 50 having an osteoporotic related fracture in their lifetime (Kanis, 2002).

Wrist fractures are the most common upper extremity fracture in older adults with an annual incidence of 8-10 per 1000 in the elderly populations. This is a higher incidence than hip fractures, whose annual incidence is 7 per 1000 (Madhok, 1993). In a study performed in 1993, it was shown that 15% of women over 65 had a clinically significant functional decline in the years following a wrist fracture. They also determined that the key risk factors for a wrist fracture included fall occurrence in the past 2 years, fracture occurrence before 50 and having low bone mineral density. Parameters for functional decline included reduced ability for meal preparation, heavy housekeeping, and the ability to climb 10 stairs, go shopping and get out of a car. This study did have limitations in the group size examined (6107
individuals) and infrequent patient follow up time (bi-annual), but it demonstrates the significance of wrist fractures later in life.

### 2.2 BMD Factors and Bone Adaptation

There are numerous factors that affect our ability to build and retain BMD. These factors include but are not limited to sex, race, hormonal factors, nutrition, physical activity, and lifestyle behaviors. Many factors remain unchangeable such as sex and race, however, physical activity is one factor that is controllable. Physical activity can benefit BMD in two ways; first by increasing peak BMD levels seen around age 30, and secondly by slowing the decline in BMD over time. It is accepted that physical activity leads to mechanical strains seen in bone and those strains drive bone adaptation (Turner, 1998). Studies have already taken place that demonstrates a correlation between physical activity levels and BMD (Weeks, 2008). In order to understand the connection between physical activity and bone adaptation we must examine the way bones adapt.

C.H. Turner generated three rules for bone adaptation in response to mechanical stimuli described as follows:

1. Bone adaptation is driven by dynamic rather than static loading.

2. Only a short duration of mechanical loading is necessary to initiate an adaptive response. Extending the loading duration has a diminishing effect on further bone adaptation.

3. Bone cells accommodate to a customary mechanical loading environment, making them less responsive to routine signals.

Turner used these rules and previously collected data to generate mathematical formulae describing bone adaptation (Turner, 1998). The formulae themselves have many limitations due to the assumptions made to generate them, such as the type of loading, tensile or compressive only, and bone structure involved. Yet, they do work as simple parametric models for bone adaptation and highlight a growing need to quantify certain aspects of bone adaptation.

These rules show some important facets of how bones adapt, but don’t discuss the effect of strain frequency and magnitude on bone adaptation. It is thought that large magnitude, high rate loading has the greatest effect on bone adaptation, but this hasn’t been proven yet. S. Fritton observed a power-law relationship for strain dynamics in bone suggesting that bone adaptation is driven by a continual barrage of activity with a wide span of frequency and amplitude of loading (Fritton 2000). In this study she collected strain data \textit{in vivo} for both weight-bearing and non-weight-bearing bones in three species: dog,
sheep and turkey. Her study demonstrated that lower magnitude strain (< 200 microstrain) occurred with much higher frequency than larger strains (> 1000 microstrain) in all three species and this suggests that all portions of bone strain history should be considered to play a role in bone adaptation. This study has limitations that can be seen when measuring strain events in bone. She observed numerous issues with the strain gauges being mounted directly to the bone of all three animals and a significant portion of data was not considered due to equipment malfunctions in vivo. Additionally, there were some issues with filtering out noise and still retaining all small strain events.

2.3 Derived Bone Loading and Surveys

Physical activity's effect on bone adaptation, as shown in S. Fritton’s study, is difficult to quantify through direct bone strain measurements. To negotiate this issue, a number of studies have used derived and relative loading methods to observe the relationship between physical activity and bone adaptation. In a study on the effects of leisure, physical activity in post-menopausal women in Canada, C. Hamilton et al used a questionnaire, the Minnesota Leisure Time Physical Activity Questionnaire, and from the results they generated a total activity score (TAS) to quantify physical activity history and relate it to measured participants’ BMD (Hamilton et al, 2010). They observed positive associations between BMD and TAS scores, specifically for cortical bone. Additionally, they showed positive associations for weight bearing, tibia, and non-weight bearing, ulnar, BMD. This study required quantification of survey answers based on their bone adapting effects, but without any direct measurement of bone loading. For direct measure of forces during bone loading physical activity, the main tools used have been accelerometers and force plates.

In a study done by R. Ahola et al, a daily impact score was developed through long-term and continuous acceleration measurement of exercise (Ahola, 2010). Acceleration peaks were recorded based on multiples of g (acceleration due to gravity) and from this data, twelve-month average daily loading distributions were calculated for participants. They created an algorithm based on the summation of daily impacts multiplied by their respective acceleration peak and used this to generate an exponential and logarithmic based daily impact score. The results of the study showed participants of an exercise group had much higher daily impact scores than a sedentary control group. Additionally, the BMD was measured at the mid femur and showed significantly strong correlation to daily impact scores, with the highest correlation found for the trochanter BMD (r =0.532). A major limitation of this study is that it only measured accelerations in the positive vertical direction and didn’t account for other axes of acceleration as they relate to bone loading. Although this method had promising results, it did not compare different bone loading activities and weight them against one another. A validated method that
weighted different physical activities in the lower extremities and compared total activity scores to BMD is the bone loading physical activity questionnaire (BPAQ).

In the BPAQ, activity categories were given weighted values based on an effective loading rate they derived. To assign these weighting factors, a series of basic lower body motions such as squats, lunges and walking (nineteen total movements were measured) were performed on a force plate and the peak ground reaction force output was recorded for each. Next, 48 different activities (including some sports) were given an effective loading rate based on the highest force action, from the 19 previously measured, that is seen in the activity and multiplied by the frequency it was performed. Finally the rates were normalized with gymnastics being given a score of 100 for the highest loading activity. From these weighting factors, a questionnaire was made that accounts for an individual’s past and current physical activity history, specifically for activities done and weekly frequency performed over the last 12 months. The current activity component of the BPAQ was a significant predictor of variance in femoral neck, lumbar spine and whole body BMD in men (R² = 0.36-0.68 p<0.01) and the general past activity component predicted BMD for women (R² = 0.48, p=0.001) (Weeks, 2008).

In relating physical activity and BMD, the BPAQ is an example of a study that weights how different activities load bones in a subject’s physical activity history, but the study has multiple limitations that restrict it from being broadly applicable. For instance, there was a very small population examined this study, 40 men and women, and the study was focused specifically on lower body activity. Additionally the method that is used to generate loading values was via ground reaction forces seen in a force plate. This method doesn’t measure forces or accelerations locally, but rather derives them from a total produced at the ground/foot interface. These limitations make the BPAQ an inadequate tool for comparing local bone loading, especially for the upper body, to the weighting factors they had generated. In order to measure bone loading in the upper body, a device is needed that can quantify bone loading locally and is not based on ground reaction forces. Using such a device would allow for weighting factors to be applied to upper body activities, in order to measure the correlation of upper extremity bone loading physical activity and BMD, specifically at the fragility fracture site of the wrist.

To measure bone strains locally, the use of accelerometers can be employed. Compressive and tensile bone strains were predicted by peak distal axial acceleration and peak off-axis acceleration (R² 0.79 for both) in a cadaveric forearm bone model (Burkhart, 2012). The aim of this study was to relate acceleration’s and bone strain in bone injuries, but concurrently demonstrated a relationship between bone strain and acceleration at the wrist. This study’s method involved 8 fresh frozen human cadaveric radii being potted and impacted in a way to mimic conditions seen in common fall injuries. These radii were
attached with three strain gauge rosettes, a proximal off-axis accelerometer and a distal axial accelerometer attached near the radial styloid. Limitations of this study included a lack of soft tissue which could affect acceleration signal measurements as they relate to bone strain and not including a second off-axis acceleration measurement. The authors reference another previous study that found limited signal effect on surface mounted accelerations fixed to the radial styloid process and olecranon process (LaFortune, 1995). These studies validate a potential approach to measure bone strains locally, at the wrist, in a non-invasive way.
Chapter 3 Project Strategy

3.1 Initial Client Statement
The initial client statement that was given by our advisor, Dr. Karen Troy is as follows:

“Develop and test methods for assigning weighting factors based on magnitude and rate to strain-producing activities on the hands and arms. Use this information to create an upper extremity-specific survey that quantifies bone loading in the arms.”

This initial client shows that this project can be divided into two major parts. The first part of the project involves designing a device or methods that can be used to measure bone loading in the arms. The second part is to utilize data acquired from our device to create an upper extremity specific survey that quantifies physical activity history.

3.2 Objectives and Constraints

3.2.1 Objectives:
In order to achieve the goals of this project, our design team created the following list of objectives. These objectives will aide our design team in selecting design alternatives.

Accurate- It is important that the designed data acquisition system is accurate. Data collected by this system will be used to assign weighting factors to a variety of upper extremity activities and therefore accuracy of measurements related to bone loading is one of our main objectives.

Portable- The designed system should be portable in the same way that a laptop is portable. Portability of the system will ease data collection for different categories of upper extremity physical activities.

Safe- It is essential that the data collection process is safe to avoid any damage or harm to the volunteers. This includes acceleration measurements.

Comfort- Since the designed system will be used to measure bone loading during physical activities, it is important that this system is comfortable for a person to wear during one hour of these activities.

Automatic- The designed analysis system should have minimal hands-on time. It is desired to have an analysis system that will collect peak accelerations in a nearly automatic manner. This will help minimize any subjectivity by the operator.

Low Cost- The designed system of data acquisition should be relatively inexpensive. Simple and low cost design alternatives will be favored.
A pairwise comparison chart was formulated to help us rank our objectives. As shown in Table 1, accuracy is the most important objective with a score of 5 while portability of the system is least important objective with a score of 0.5.

<table>
<thead>
<tr>
<th>Objectives</th>
<th>Safe</th>
<th>Accuracy</th>
<th>Comfort</th>
<th>Portability</th>
<th>Cost</th>
<th>Automatic (minimal hands-on time)</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety</td>
<td>---</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
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<td>---</td>
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<td>1</td>
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</tr>
<tr>
<td>Comfort</td>
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<td>---</td>
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<td>0.5</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Portability</td>
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<td>0</td>
<td>0.5</td>
<td>---</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>Cost</td>
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<td>0</td>
<td>0.5</td>
<td>1</td>
<td>---</td>
<td>0</td>
<td>1.5</td>
</tr>
<tr>
<td>Automatic (minimal hands-on time)</td>
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<td>0</td>
<td>1</td>
<td>1</td>
<td>---</td>
<td>2</td>
</tr>
</tbody>
</table>

3.2.2 Constraints:
Our survey will need to meet the objectives described in the previous section, but will also have limitations to be considered at different stages of the design process. These limitations (constraints) can be listed as follows:

Non-invasive-Data collection from volunteers is limited to non-invasive methods. This will eliminate alternatives that involve invasive data collection from volunteers such as implanted force transducers or strain gauges.

IRB-approval: This research study will involve human subjects that will participate voluntarily. Because of that, data collection of physical activities must be approved by the WPI Institutional Review Board (IRB). The IRB will only approve studies that are performed under the auspices of WPI.

Mechanistic-Weighting factors are only assigned based on mechanistic measurements during various activities. This means that all of our measurements should be directly related to strain-producing signals.

Age of volunteers- All research studies at WPI that involve human subjects are limited to volunteers who are at least 18 years old. Because of this, all volunteers who will help us as subjects of the study should over 18 years old.
**Budget**- The budget for this study is approximately $400 based on the Department of Biomedical Engineering at Worcester Polytechnic Institute MQP guidelines. All expenses including the development of the system must be within this budget.

**Time**- This project must be completed during the academic year 2013-14. Based on the WPI calendar, all projects will be presented on April 24, 2013.

### 3.3 Revised Client Statement

Based on the information gathered from our client and technical research on the topic, the initial client statement was revised as follows:

**Part One:**

“Design a biometric data acquisition and analysis system to measure parameters related to force and rate of force generation during strain-producing upper extremity activities.”

**Part Two:**

“Collect and analyze data using the system designed. Use the data to assign ‘weighting factors’ to a wide variety of upper extremity activities, based on magnitude and rate of force generation.”
3.4 Project Approach

3.4.1 Technical
From our client statement, the first part of this project requires the design of a data acquisition and analysis system to quantify bone loading in the arms. Through research we’ve found multiple ways to achieve this goal. An accelerometer can be mounted on the wrist to measure local accelerations. Peak accelerations will then be analyzed to assign weighting factors to a variety of physical activities. A flexible force transducer to measure local forces, a strain gauge and an optical measurement tool are additional ways to measure bone strain. In an optical design, video game technologies such as XBOX Kinect will be used to trace acceleration of the wrist during upper body physical activities. An optical system will be the most comfortable design alternative since it does not require any physical contact with the arms.

A numerical evaluation matrix was formulated to help us choose among our design alternatives. Table 2 shows that optical measurements and strain gauges do not satisfy the constraints of this project. Because of that, only accelerometer and force transducers were evaluated based on our weighted objectives. Based on this table, accelerometer ranked highest among our alternatives.

<table>
<thead>
<tr>
<th>Design Constraints (C) and Objectives (O)</th>
<th>Priority</th>
<th>Accelerometer</th>
<th>Force Transducer</th>
<th>Strain gauge</th>
<th>Optical measurement tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>C: &lt; $400</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>C: Time</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>C: Mechanistic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C: Non-invasive</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>O: Accuracy</td>
<td>5</td>
<td>80</td>
<td></td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>O: Safety</td>
<td>4</td>
<td>50</td>
<td></td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>O: Comfort</td>
<td>2</td>
<td>40</td>
<td></td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>O: Automatic</td>
<td>2</td>
<td>35</td>
<td></td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>O: Low Cost</td>
<td>1.5</td>
<td>25</td>
<td></td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>O: Portability</td>
<td>0.5</td>
<td>12</td>
<td></td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Totals</td>
<td>242</td>
<td>197</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.4.2 Management
Now that we have developed an initial technical understanding of our project, we want to create management tools that can be used to keep track of time and other resources. Figure 2 shows the Gantt chart that was formulated as the primary scheduling tool for this project. Most of the work done in the fall of 2013 is directed towards the design of our system. At the beginning of the academic C-term (January), our efforts are directed towards finishing Part 1 of our client statement and then beginning the second part of the project which will involve measurements and analysis towards the end of C-term. In order to divide each part of the project into smaller and manageable tasks, we formulated a work breakdown structure (Figure 3) which includes all required subtasks for this project.

Figure 2: Our Gantt chart (Graphical representation of tasks and time frames)
Figure 3: Work Breakdown Structure for Upper Extremity Physical Activity
### 3.4.3 Financial

As it was mentioned earlier in this chapter, the total budget for our project is approximately $400. We anticipate that most, if not all, of this budget would be spent developing our data acquisition system, but device costs were lower than anticipated. The expenses related to the development of data acquisition systems include, the cost of a measurement device, mounting materials, such as wrist straps, and cabling. For the analysis part, commercial software such as MATLAB and LabView will be made available to us at no additional cost. The anticipated cost of materials to build a prototype of our system is shown in Table 3.

#### Table 3: Bill of materials for a biometric data acquisition system

<table>
<thead>
<tr>
<th>Part #</th>
<th>Materials</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Measurement Device</td>
<td>$30</td>
</tr>
<tr>
<td>2</td>
<td>Wrist Strap/Athletic Tape</td>
<td>$30</td>
</tr>
<tr>
<td>3</td>
<td>Cables</td>
<td>$30</td>
</tr>
<tr>
<td>6</td>
<td>Other</td>
<td>$30</td>
</tr>
<tr>
<td></td>
<td><strong>TOTAL</strong></td>
<td><strong>$120</strong></td>
</tr>
</tbody>
</table>

Since this data acquisition system will not be mass produced, manufacturing costs and consumer pricing will not be considered in our design process. This system is mainly utilized to assign weighting factors to physical activities related to upper extremities.
In the following chapter we will address the design alternatives for our data acquisition device. In order to do this, a Needs Analysis was first conducted with our client. The results of which were used to generate functions and specifications for our device which we then used to guide our alternative design generation. We created four alternative designs and using specific design calculations we came to our design decision. After this selection, we created a conceptual final design and made a prototype to begin our preliminary data collection.

4.1 Needs Analysis

As was discussed in the previous chapters, the data acquisition system must be capable of recording the parameters related to force and rate of force generation during upper extremity activities. Our client requested that our device was able to measure upper extremity activities between 14-20Hz. Because of this, the sampling rate of the device should be greater than 40Hz to accommodate all activities. Since the device is mounted onto the wrist, the total weight of the device and the mounting strap should be less than 0.4kg.

Since these data are constantly recorded by the data acquisition system, it is important to filter data allowing only forces caused by each activity to be considered while creating the weighting factors. Motion artifacts in the muscles should be taken into account as one source of noise generation. The analysis system should also be capable of peak detection within the frequency range of upper extremity activities. Most of the analysis is done in MATLAB where signals generated by the accelerometer are used as an input.

4.2 Functions and Specifications

4.2.1 Data acquisition

- **Sampling Frequency** - Based on the Nyquist Sampling Theorem, the sampling frequency of the data acquisition device should be greater than 40 Hz. This allows for the detection of bone loading for all strain-producing activities. Most bone loadings occur within a frequency of 14- 20 Hz.

- **Force** – The data acquisition device should be able to detect all forces acting on the bones that are less than or equal to 400N to accurately measure bone loading in the arms.
• **Size**- The size and shape of the device should allow comfortable movement of the arms during upper extremity activities.

• **Weight**- The combination of the measurement tools and the mounting strap should weigh no more than 0.4 kg. Additional weight of the device will disturb the motion of arms in some activities.

• **On/Off Switch**- It is important for the device to have an On/Off switch. The device should not be reset or turned off during activities due to motion artifacts.

• **Recording time**- The device should be able to record up to 5 minutes of non-stop data acquisition.

### 4.3 Analysis System

• **Peak detection**- Peak forces acting on the bone have the greatest impact. Because of that, the analysis system should be capable of detecting peak forces during each activity. For measurements with more than one peak value, the average of all peak values should be considered while creating the weighting factors.

• **Rate analysis**- The analysis system should quantify the rate of force generation for different activities. This includes an algorithm that calculates the time in which loading in the bone reaches its maximum value.

### 4.4 Alternative Designs

Design alternatives were generated through a collection of meetings with our client, literature reviews, brainstorming and currently available product research. Multiple iterations of design alternatives were generated in this process and are listed below. These design alternatives focus on the data acquisition side of the project, previously recognized as “Part 1” of our client statement. The first design, Extech VB300 Datalogger, was initially chosen and data acquisition began. Soon after starting the initial testing we recognized that the device sampling rate was 1/10th of that which the manufacturer published. Then we had to generate numerous alternatives and start the decision process over. A design selection matrix was used afterwards to select a final data acquisition device. Additionally, mounting design alternatives were generated for some of the devices and are shown in the Appendix A.
4.4.1 Design 1 (Previous Final Design Selection): EXTECH VB300 Datalogger

In this design an EXTECH VB300 Datalogger would be used as the data acquisition device mounted on top of the wrist (See the mounting design alternatives for details in Appendix A). This device measures accelerations of +/- 18g, measures accelerations in three axes and comes with a set of analysis software. The major benefit to this design is the software that is included as it allows for easy visualization of acceleration events and will export all data to EXCEL for further analysis. The design's small size was an additional benefit. The sampling rate for this device was listed at 200Hz, as shown in the Appendix D. After preliminary testing, the device was shown to sample at 20Hz. We inquired with the company and found out that the 200Hz was published in error and 20Hz was in fact the true limit.

Figure 4: The VB300 datalogger, without its cap.


4.4.2 Design 2: GENEActiv Raw Data Accelerometer

The GENEActiv Raw Data Accelerometer is a three axis accelerometer that has been used in previous physical activity research. It can sample at a rate up to 100Hz, measures accelerations in the +/- 8g range, and comes with signal analysis software. The device is rechargeable and comes with a wrist strap for mounting. Analysis software can export raw data in a csv format and also has multiple native visualization graphics. A set back of this device is the lead time and price as it’s not mass produced and made in the UK.
4.4.3 Design 3: Texas Instruments Chronos EZ430

The Chronos EZ430 is a programmable watch with a built in CMA3000 three axis accelerometer. A major benefit of this device is that it comes with a wireless RF USB access point for live data logging. This device can sample up to 400Hz and measures accelerations in the +/- 8g range. The device comes with a programmable software package and basic serial monitors. The EZ430 also comes with a wrist strap for mounting.
4.4.4 Design 4: ADXL326

The final two designs utilize the same component accelerometer, Analog Devices ADXL326, but interface with the computer in different ways. This accelerometer can measure accelerations of +/- 16g in three axes and has various sampling rates (1-500Hz) based on capacitors used (4.7-0.01μF). A benefit of this device is its small size and light weight. A setback of these designs is that they would need to remain wired to the computer during testing. The full data sheet for this component can be found at http://www.analog.com/static/imported-files/data_sheets/ADXL326.pdf

![Image of the ADXL326 accelerometer on an Adafruit board.](image)


4.4.5 Design 4A: Arduino + ADXL326

In this design we would utilize an Arduino Uno microcontroller board as our interface between the device and a computer. This design would require we program an Arduino Sketch and interface the device with MATLAB or LabView software for analysis.

![Arduino Uno Rev3 microcontroller](image)

4.4.6 Design 4B: USB-6008 and ADXL326

This design will include a USB6008 data acquisition device (DAQ) attached to the ADXL326 accelerometer. This device has 8 analog inputs, 2 analog outputs and is compatible with both LabView and MATLAB. A major benefit of this device is that it is simple to transmit data with and requires no additional programming.

![USB 6008 DAQ from National Instruments](image)

Figure 9: A USB 6008 DAQ from National Instruments

4.5 Decisions

This final selection matrix was created to evaluate all the alternative designs generated. Our alternative designs were compared to our design objectives to show the best match. The design objectives were first ranked in order of their importance to the final design. A numerical evaluation was computed for each alternative design. Table 4 demonstrates that the best designs were The DAQ device, Arduino-component, GENEActive raw data, and wrist cuff with v-tech pocket. The DAQ device scored highest, 130/150, and was selected as the final design.

Table 4: A design selection matrix listing numerical evaluations for various designs. W.S.: weighted score and is based on weights from our Pairwise Comparison Chart.

<table>
<thead>
<tr>
<th>Design Objectives</th>
<th>Weights from PCC</th>
<th>Mounting Designs based on USB Accelerometer</th>
<th>Arduino-component design</th>
<th>Chronos design</th>
<th>GENEActive raw data</th>
<th>DAQ device design</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weight</td>
<td>Score</td>
<td>W.S.</td>
<td>Score</td>
<td>W.S.</td>
<td>Score</td>
</tr>
<tr>
<td>Accurate</td>
<td>5</td>
<td>7</td>
<td>35</td>
<td>6</td>
<td>30</td>
<td>4</td>
</tr>
<tr>
<td>Portable</td>
<td>0.5</td>
<td>9</td>
<td>4.5</td>
<td>7</td>
<td>3.5</td>
<td>7</td>
</tr>
<tr>
<td>Safe</td>
<td>4</td>
<td>9</td>
<td>36</td>
<td>7</td>
<td>28</td>
<td>7</td>
</tr>
<tr>
<td>Comfort</td>
<td>2</td>
<td>9</td>
<td>18</td>
<td>5</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>Automatic</td>
<td>2</td>
<td>6</td>
<td>12</td>
<td>7</td>
<td>14</td>
<td>7</td>
</tr>
<tr>
<td>Low cost</td>
<td>1.5</td>
<td>5</td>
<td>7.5</td>
<td>5</td>
<td>7.5</td>
<td>5</td>
</tr>
</tbody>
</table>

Total | 15 | 45 | 113 | 37 | 93 | 34 | 81 | 32 | 76 | 42 | 106 | 39 | 101 | 43 | 116 | 50 | 130
4.6 Design Calculations

Based on our client’s feedback and the design selection matrix, we chose the data acquisition (DAQ) accelerometer based device to quantify bone loading in the upper extremities, specifically at the wrist. We used the Nyquist sampling theorem to determine the limitations of the accelerometer. We found that our accelerometer must be able to record a signal at a minimum rate of 40Hz. We chose to use the ADXL326 - 5V ready triple-axis accelerometer with a +/- 16 g analog output. Based on the capacitors used in the blue board in our accelerometer we have a sampling rate of 50Hz. We have selected 16 upper extremity activities for our testing and based on these activities we determined that we would need excess wire, approximately 10 ft., to meet the functional requirements of our device. After determining that these requirements were met with the accelerometer that was selected, we began brainstorming how we could analyze our data. LabView was our initial choice for analyzing all of our data. We created a virtual instrument with a DAQ assistant and wave chart to read the signals produced by our accelerometer and were able to view the serial data monitor and locate the peak accelerations generated at the wrist. This can be seen in Figure 10 below. Data collection and analysis was tedious and required several steps, so we decided to create a MATLAB program that would identify the peak accelerations automatically, fulfilling an objective of this project. EXCEL was also used to generate a correlation between the peak force and acceleration of each upper extremity activity performed. The DAQ device imported our data into MATLAB and we were able to export data from MATLAB into EXCEL and create a vector sum column and graph that against time to view these correlations.

![Figure 10: A view of our LabView VI front panel. There is an unfiltered chart of all three axes below and a filtered chart for each axis above.](image-url)
4.7 Conceptual Design

The DAQ device design is made to connect to the accelerometer, which is housed in a wrist cuff that fits many different wrist sizes, or directly attached to the wrist. The accelerometer is connected to a National Instruments DAQ assistant USB6008. This device is able to acquire accelerations that impact the wrist during physical activity. The DAQ will be attached to the accelerometer using wires. We will use a 10 foot CAT 5 cable to consolidate all the output wires and connect to the DAQ, and using a USB cable that comes with the DAQ we will attach to a computer for data acquisition and analysis. In order to analyze the data we obtain we will use MATLAB. A program was created to read the signals output by the accelerometer. As shown in Figure 11, the cuff design can be slipped over the hand to fit the wrist and contains a small pocket for insertion of the accelerometer. Once the device is placed on the wrist, the accelerometer can be inserted into the pocket and turned on to record accelerations at the wrist. Following this, different physical activities can be performed and the data can be collected from the accelerometer. Alternatively, the accelerometer can be directly taped to the ulnar styloid process of the wrist.

![Pocket for Accelerometer](image)

Figure 11: Conceptual Design of Wrist Cuff Mount for Accelerometer

4.8 Preliminary Data

The following preliminary data were conducted to analyze the functionality of our device. First, the conversion factors were calculated to find acceleration data in each axis. After that, the sensitivity of the device was tested in each axis to estimate the signal to noise ratio and also ensure that small accelerations could also be detected. An image of the device prototype can be seen in Appendix B. Lastly, a peak detection algorithm was tested for different activities to estimate the threshold values.
4.8.1 Conversion Factors

In order to estimate the acceleration data in each axis, six conversion factors were calculated using a simple calibration method. An initial set of measurements were conducted when the accelerometer was placed on a flat surface in a way that the gravitational acceleration acts on its z-axis (into the page). On this axis, acceleration in the other two axes (x and y) were expected to be zero. Because of this, the following equations must be true for the conversion factors $a_1, b_1, a_2, b_2, a_3, b_3$.

$$0 = a_1 S_{1x} + b_1 \quad \text{Equation 1}$$

$$0 = a_2 S_{1y} + b_2 \quad \text{Equation 2}$$

$$-1 = a_3 S_{1z} + b_3 \quad \text{Equation 3}$$

To generate the second set of equations, the accelerometer was rotated 90 degrees in such a way that the gravitational acceleration acts on its y-axis. The following equations must be true for the conversion factors $a_1, b_1, a_2, b_2, a_3, b_3$.

$$1 = a_2 S_{2y} + b_2 \quad \text{Equation 4}$$

$$0 = a_3 S_{2z} + b_3 \quad \text{Equation 5}$$

The sixth equation was generated when the gravitational acceleration acts on the x-axis:

$$1 = a_1 S_{3x} + b_1 \quad \text{Equation 6}$$

The following conversion factors were obtained from equations 1 through 6:

X-axis conversion factors: $a_1 = 20.16$ and $b_1 = 4.20$
4.8.1 Conversion Factors

In order to estimate the acceleration data in each axis, six conversion factors were calculated using a simple calibration method. An initial set of measurements were conducted when the accelerometer was placed on a flat surface in a way that the gravitational acceleration acts on its z-axis (into the page). On this axis, acceleration in the other two axes (x and y) were expected to be zero. Because of this, the following equations must be true for the conversion factors \(a_1, b_1, a_2, b_2, a_3,\) and \(b_3\).

\[
0 = a_1 S_{1x} + b_1 \quad \text{Equation 1}
\]
\[
0 = a_2 S_{1y} + b_2 \quad \text{Equation 2}
\]
\[
-1 = a_3 S_{1z} + b_3 \quad \text{Equation 3}
\]

To generate the second set of equations, the accelerometer was rotated 90 degrees in such a way that the gravitational acceleration acts on its y-axis. The following equations must be true for the conversion factors \(a_1, b_1, a_2, b_2, a_3,\) and \(b_3\).

\[
1 = a_2 S_{2y} + b_2 \quad \text{Equation 4}
\]
\[
0 = a_3 S_{2z} + b_3 \quad \text{Equation 5}
\]

The sixth equation was generated when the gravitational acceleration acts on the x-axis:

\[
1 = a_1 S_{3x} + b_1 \quad \text{Equation 6}
\]

The following conversion factors were obtained from equations 1 through 6:

X-axis conversion factors: \(a_1 = 20.16\) and \(b_1 = 4.20\)
Y-axis conversion factors: \( a_2 = 10.71 \) and \( b_2 = -0.52 \)

Z-axis conversion factors: \( a_3 = 19.57 \) and \( b_3 = -31.52 \)

### 4.8.2 Signal-to-noise ratio

To visualize the signal-to-noise ratio of the device, the accelerometer was placed on a flat surface where we expect the acceleration to be zero in the x and y axis and 1g in the z-axis. After that, non-zero acceleration was manually generated to confirm the sensitivity of the device. Figure 13 shows the acceleration data in the absence of non-gravitational accelerations.

![3-axis Acceleration data](image)

**Figure 13:** Acceleration data when the device was placed on a flat surface. Noise in the x and y-axes is higher than noise in z-axis.

Figure 14 shows acceleration data when the device was gently moved in the direction of its x-axis to manually generate accelerations for a period of 10 seconds.
4.8.3 Peak detection

Since the analysis system should be capable of detecting peak accelerations during upper-extremity activities, preliminary data of falling motions were analyzed to ensure that the device would detect all the peaks without any errors. Figure 4.12 shows the graph of acceleration during 30 seconds of data collection. Peak accelerations are shown in red.
Figure 15: Acceleration during 30 seconds of data collection. Falling motion was repeated nine times and peak accelerations (shown as asterisks in red) were detected each time.
Chapter 5 Design Verification

5.1 Overview
This chapter presents data that were obtained to verify the final design. First, validation of our device was necessary and was achieved by correlating the acceleration and force data. These data were collected through the testing of group members, obtaining peak accelerations and forces at the wrist during punching, hammering and falling motions. Afterwards, a study protocol was formulated and submitted to the WPI Institutional Review Board to allow human subject testing for multiple categories of upper extremity physical activities. Using our data processing algorithm, we computed average peak and rate of peak generation for each of these categories. Utilizing research and our data, we created weighting factors for our tested categories. From these weighting factors, we were able to give a bone loading in the upper extremity (BLUE) score to various activities; based on the percentage that each tested category was involved. The BLUE scores were then applied to a previous study’s subject data to show the relation between the BLUE scores and measured BMD values.

5.2 Preliminary Testing
To validate raw data obtained from the accelerometer, ground reaction forces and accelerations were measured during three impacting motions: hammering, punching and falling. Hammering involved hitting the bottom of the fist on the force plate while rotating the forearm at the elbow. The elbow was to remain fixed during this motion. Punching involved a straight arm extension with a closed fist at the force plate while the subject was kneeling over the plate and positioned as to have full extension of the arm meet the plate. Falling occurred from the knees and had the subject fall forward onto their hands, with a cushion placed on the force plate. Impact was absorbed into their arms to their chest at the plate and after falling the subject was instructed to push up from the ground at the sides of the force plate when returning to the starting position. This was done to restrict peak force occurrence to free fall impact. Force data were collected at 100 Hz using an ATMI force plate. Our device was previously calibrated and set to collect accelerations at the same frequency as the force plate. Testing was repeated three times for each of the motions and each time, 30 seconds of data were collected. Impact motions were repeated 5-10 times per test which resulted in 30-40 peaks for each motion. Figure 16 shows the relation between peak resultant force and peak acceleration data during the punching motion, $R^2$ value of 0.871 indicates the relation between accelerometer raw data and forces measured by the force plate. Peaks shown on this figure were detected manually in Microsoft ® EXCEL.
5.3 Design Validation

To further verify that the designed data acquisition system is capable of quantifying bone loading in the arms, we analyzed raw data obtained from the accelerometer and compared them with resultant force plate data. Figure 17 shows raw data collected at 100 Hz before and after a single impact peak during hammering. Please note that a data acquisition time offset was taken into account to align force and acceleration data.

Figure 16: Device Validation with Force Plate during punching

Figure 17: Hammering impact data, Forces and accelerations obtained at 100 Hz
Upon alignment of peak acceleration and force curves, we used distance between peaks to verify peak events occurred concurrently. Figure 18 below shows the peak resultant forces during the entire hammering motion analyzed in Figure 17. This figure also shows the corresponding acceleration values measured by the device. As shown below, the trend of the peak forces matches that of the accelerations and the time between peaks are identical. Therefore, higher accelerations (or decelerations) result in higher impact forces and lower accelerations result in lower impact forces.

![Peak Forces Generated During Hammering and the Corresponding Accelerations](image)

**Figure 18- Peak forces generated during hammering and the corresponding accelerations**

5.4 Subject Testing

After validating the accuracy of raw data obtained by the device, a study protocol was formulated and submitted to a WPI Institutional Review Board (IRB) for their approval of human subject testing (approval letter in Appendix C). According to the study protocol, individual subjects were asked to perform 16 different categories of upper extremity activities, which were first demonstrated to the subjects including an overhand throw, underhand throw, vertical arm swing, front arm raise, lateral arm raise, overhead arm extension, catching a ball, punching, falling, hammering, side dragging, front dragging, shovel heave, reverse curling and a horizontal arm swing. Data collection time was
approximately one hour for each subject (including setup time). After following this protocol for the first 4 subjects, it was concluded that activity weighting factors can be estimated based on percentages of 5 major categories involved if we include and consider an inertial force contribution in bone loading. Because of this, testing categories were refined to the following list:

- Punching- a straight arm extension with a closed fist at the force plate while the subject knelt over the plate and was positioned as to have full extension of the arm meet the plate. A cushion was placed on the force plate to prevent injury.
- Hammering- impacting the force plate with a dowel in the subject’s hand while rotating the forearm at the elbow. The elbow was to remain fixed during this motion. A cushion was placed on the force plate to prevent injury.
- Falling- the subject falls forward, starting from their knees, onto their hands. Impact was absorbed into their arms, to their chest at the plate and after falling the subject was instructed to push up from the ground at the sides of the force plate when returning to the starting position. This was done to restrict peak force occurrence to free fall impact. A cushion was placed on the force plate to prevent injury.
- Catching- the subject lied on their back on the force plate with their dominant arm extended and caught a 2.2lb ball dropped from approx. 5ft. The subject was instructed to catch the ball and allow their arm to compress and the ball to fall out of their hand after their arm fully compressed.
- Rowing- the subject pulled a rope that was adhered to the bottom edge of the force plate while positioned directly over the force plate, with their torso parallel to the plate. This motion was nearly opposite to that of punching in motion.

Each of the 8 subjects who voluntarily participated in this study signed an informed consent form (Appendix C). Individuals’ weight (kg), height (cm) and sex were recorded before testing for future analysis of the recorded data.
5.5 Data Analysis

To make the device automatic, we used MATLAB for data analysis. In the peak detection algorithm, a threshold was defined for each testing category (i.e. 2 g for hammering and 3.5 g for falling). After that, maximum accelerations and the corresponding times were detected when the total acceleration (3 Dimensional) passes this threshold value. Peak detection is done similarly for the force data using different thresholds for each category. Figure 19 was used to validate the peak detection algorithm. For each of the testing categories, averages of peak values were calculated as one of the outputs of analysis system.

Figure 19- Peak detection of existing falling data in MATLAB where threshold is defined to be 3.5 g.

In addition to average peak loading, force and acceleration data were also analyzed for average rate of loading or the slope of force/accelerometer curve right before their peaks. The following equations were used to calculate the average rate of loading for each of the testing categories:

\[
\text{Average Rate of force generation} \quad \left[ \frac{N}{s} \right] = \sum_{1}^{\# \text{of peaks}} \frac{F_{\text{peak}}[N] - F_{\text{peak}-0.20s}[N]}{0.20s} \\
\text{Average Rate of acceleration (Jerk)} \quad \left[ \frac{g}{s} \right] = \sum_{1}^{\# \text{of peaks}} \frac{a_{\text{peak}}[g] - a_{\text{peak}-0.20s}[g]}{0.20s}
\]

Equation 7
5.6 Weighting Factors

In order to assign bone loading scores to upper extremity activities, we first needed to create weighting factors for major categories chosen for subject testing: catching, falling, hammering, punching and rowing. To achieve this goal, all subject testing data were analyzed for peak loading force, rate of force generation, peak loading acceleration (or deceleration) and rate of acceleration (or deceleration). Force data were then normalized based on subjects’ body weight (BW). Tables 5-9 summarize testing data obtained from all 8 subjects.

In next step, we used the following equations to calculate the effective loading stimulus and effective accelerative stimulus for each of these motions.

**Effective Loading Stimulus (ELS)** \( \left( \frac{N \cdot s}{kg} \right) = \text{Avg. peak force} \times \text{Avg. rate of force} \)  \hspace{1cm} \text{Equation 8}

**Effective Accelerative Stimulus (EAS)** \( \left( \frac{m \cdot s^2}{kg} \right) = \text{Avg. peak accel.} \times \text{Avg. rate of accel.} \) \hspace{1cm} \text{Equation 10}

A summary of average loading measurements, ELS and EAS values are presented in Table 9.

### Table 5- Peak loading forces normalized based on Subjects’ body weight (BW)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.08</td>
<td>1.18</td>
<td>Not available</td>
<td>0.12</td>
<td>0.11</td>
</tr>
<tr>
<td>2</td>
<td>0.08</td>
<td>1.19</td>
<td>0.11</td>
<td>0.75</td>
<td>0.12</td>
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<tr>
<td>3</td>
<td>0.17</td>
<td>1.28</td>
<td>0.13</td>
<td>0.48</td>
<td>0.13</td>
</tr>
<tr>
<td>4</td>
<td>0.11</td>
<td>0.78</td>
<td>0.13</td>
<td>0.63</td>
<td>0.12</td>
</tr>
<tr>
<td>5</td>
<td>0.20</td>
<td>0.71</td>
<td>0.25</td>
<td>0.91</td>
<td>0.07</td>
</tr>
<tr>
<td>6</td>
<td>0.26</td>
<td>0.60</td>
<td>0.36</td>
<td>0.34</td>
<td>0.14</td>
</tr>
<tr>
<td>7</td>
<td>0.33</td>
<td>0.78</td>
<td>0.23</td>
<td>0.91</td>
<td>0.14</td>
</tr>
<tr>
<td>8</td>
<td>0.24</td>
<td>0.62</td>
<td>0.39</td>
<td>0.99</td>
<td>0.21</td>
</tr>
</tbody>
</table>
### Table 6- Rate of force generation normalized based on subjects' body weight (BW)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.59</td>
<td>2.60</td>
<td>Not available</td>
<td>2.32</td>
<td>2.07</td>
</tr>
<tr>
<td>2</td>
<td>0.46</td>
<td>16.19</td>
<td>2.24</td>
<td>15.80</td>
<td>1.94</td>
</tr>
<tr>
<td>3</td>
<td>2.74</td>
<td>6.90</td>
<td>2.55</td>
<td>9.56</td>
<td>0.97</td>
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<tr>
<td>4</td>
<td>1.99</td>
<td>14.58</td>
<td>2.69</td>
<td>12.50</td>
<td>2.23</td>
</tr>
<tr>
<td>6</td>
<td>3.12</td>
<td>4.70</td>
<td>3.61</td>
<td>3.41</td>
<td>1.28</td>
</tr>
<tr>
<td>7</td>
<td>6.89</td>
<td>3.70</td>
<td>4.30</td>
<td>18.79</td>
<td>1.79</td>
</tr>
<tr>
<td>8</td>
<td>3.57</td>
<td>7.64</td>
<td>7.45</td>
<td>20.03</td>
<td>3.56</td>
</tr>
</tbody>
</table>

### Table 7- Peak loading accelerations

<table>
<thead>
<tr>
<th>Subject #</th>
<th>Catching [g]</th>
<th>Falling [g]</th>
<th>Hammering [g]</th>
<th>Punching [g]</th>
<th>Rowing [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.32</td>
<td>7.81</td>
<td>4.55</td>
<td>5.22</td>
<td>Not available</td>
</tr>
<tr>
<td>2</td>
<td>4.25</td>
<td>4.17</td>
<td>4.71</td>
<td>4.93</td>
<td>2.47</td>
</tr>
<tr>
<td>3</td>
<td>2.67</td>
<td>3.70</td>
<td>5.62</td>
<td>4.61</td>
<td>2.93</td>
</tr>
<tr>
<td>4</td>
<td>3.33</td>
<td>4.60</td>
<td>5.34</td>
<td>4.71</td>
<td>3.17</td>
</tr>
<tr>
<td>5</td>
<td>2.74</td>
<td>3.15</td>
<td>4.89</td>
<td>4.91</td>
<td>3.45</td>
</tr>
<tr>
<td>6</td>
<td>3.62</td>
<td>4.12</td>
<td>4.96</td>
<td>4.65</td>
<td>3.30</td>
</tr>
<tr>
<td>7</td>
<td>3.92</td>
<td>5.47</td>
<td>4.04</td>
<td>4.63</td>
<td>3.19</td>
</tr>
<tr>
<td>8</td>
<td>2.83</td>
<td>4.08</td>
<td>4.26</td>
<td>4.73</td>
<td>3.91</td>
</tr>
</tbody>
</table>

### Table 8- Rate of Acceleration (Jerk)

<table>
<thead>
<tr>
<th>Subject #</th>
<th>Catching [g/s]</th>
<th>Falling [g/s]</th>
<th>Hammering [g/s]</th>
<th>Punching [g/s]</th>
<th>Rowing [g/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>52.11</td>
<td>Not available</td>
<td>77.67</td>
<td>73.56</td>
<td>Not available</td>
</tr>
<tr>
<td>2</td>
<td>65.03</td>
<td>72.24</td>
<td>81.05</td>
<td>91.18</td>
<td>17.15</td>
</tr>
<tr>
<td>3</td>
<td>36.45</td>
<td>54.00</td>
<td>88.45</td>
<td>74.41</td>
<td>20.21</td>
</tr>
<tr>
<td>4</td>
<td>53.38</td>
<td>75.95</td>
<td>90.40</td>
<td>63.52</td>
<td>26.01</td>
</tr>
<tr>
<td>5</td>
<td>26.75</td>
<td>43.87</td>
<td>82.91</td>
<td>90.35</td>
<td>34.45</td>
</tr>
<tr>
<td>6</td>
<td>41.11</td>
<td>60.33</td>
<td>90.86</td>
<td>81.87</td>
<td>34.94</td>
</tr>
<tr>
<td>7</td>
<td>59.46</td>
<td>92.88</td>
<td>75.99</td>
<td>83.65</td>
<td>34.16</td>
</tr>
<tr>
<td>8</td>
<td>34.08</td>
<td>67.48</td>
<td>79.28</td>
<td>75.66</td>
<td>46.10</td>
</tr>
</tbody>
</table>
Table 9- Average loading measurements, ELS and EAS values, and the assigned BLUE scores for five major categories: catching, falling, hammering, punching and rowing

<table>
<thead>
<tr>
<th>Activity</th>
<th>Catching</th>
<th>Falling</th>
<th>Hammering</th>
<th>Punching</th>
<th>Rowing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Peak Force [BW]</td>
<td>0.18</td>
<td>0.89</td>
<td>0.23</td>
<td>0.64</td>
<td>0.13</td>
</tr>
<tr>
<td>Average Rate of Force Generation [BW/s]</td>
<td>2.76</td>
<td>8.04</td>
<td>3.81</td>
<td>11.77</td>
<td>1.98</td>
</tr>
<tr>
<td>ELS [BW²/s]</td>
<td>0.51</td>
<td>7.17</td>
<td>0.87</td>
<td>7.54</td>
<td>0.26</td>
</tr>
<tr>
<td>Average Peak Acceleration [g]</td>
<td>3.34</td>
<td>4.64</td>
<td>4.80</td>
<td>4.80</td>
<td>3.20</td>
</tr>
<tr>
<td>Average Rate of acceleration [g/s]</td>
<td>46.05</td>
<td>66.68</td>
<td>83.33</td>
<td>79.27</td>
<td>30.43</td>
</tr>
<tr>
<td>EAS [g²/s]</td>
<td>153.62</td>
<td>309.14</td>
<td>399.61</td>
<td>380.39</td>
<td>97.45</td>
</tr>
</tbody>
</table>

5.7 Activity Scores

After the assignment of weighting factors to five major categories, we needed to assign activity scores to a list of upper extremity (UE) physical activities given to us by our client (Table 10). For this purpose, a range of subjective percentages were assigned to each activity, mostly through observation, to quantify the contribution of tested motions in bone loading. Table 11 shows representative activities and their assigned percentages (full list in Appendix F). Using activity percentages and previously measured bone loading values, we created two weighing factors for each activity; one based on measured forces (ELS values) and another based on measured accelerations (EAS values). Equations 11 and 12 show how weighting factors were assigned based on the motions involved. The major difference between the two equations is that the contribution of inertial loading was taken into account for ELS based weighting factors. The resulting weighting factors were normalized by assigning the score of 100 to the highest scoring activity. Table 12 presents activity scores for high, medium and low impact UE activities. Equations 13 and 14 utilize the algorithms from the BPAQ for past (pBPAQ) and current (cBPAQ) activity history, but replaces their weighting factors with ours (Weeks, 2008).

\[
\text{Weighting Factor (ELS)} = \sum[\% \text{ Motion} \times ELS_{\text{motion}}] + 1.6 \times \% \text{ Intertial} \quad \text{Equation 9}
\]

\[
\text{Weighting Factor (EAS)} = \sum[\% \text{ Motion} \times EAS_{\text{motion}}] \quad \text{Equation 10}
\]
Table 10- Client provided list of upper extremity activities

<table>
<thead>
<tr>
<th>Reported Physical Activities</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Gymnastics</td>
<td>Golf</td>
</tr>
<tr>
<td>Basketball</td>
<td>Gardening</td>
</tr>
<tr>
<td>Volleyball</td>
<td>Toning exercises</td>
</tr>
<tr>
<td>Cheerleading</td>
<td>Yoga</td>
</tr>
<tr>
<td>Weight lifting (free)</td>
<td>Track &amp; Field</td>
</tr>
<tr>
<td>Weight lifting (machines)</td>
<td>Bowling</td>
</tr>
<tr>
<td>Rock-climbing</td>
<td>Hopscotch (jump rope)</td>
</tr>
<tr>
<td>Handball</td>
<td>Badminton</td>
</tr>
<tr>
<td>Aerobics (Elliptical)</td>
<td>Mountain biking</td>
</tr>
<tr>
<td>Soccer</td>
<td>Swimming</td>
</tr>
<tr>
<td>Softball</td>
<td>Running</td>
</tr>
<tr>
<td>kung Fu</td>
<td>Walking</td>
</tr>
<tr>
<td>Dancing</td>
<td>Cross Country</td>
</tr>
<tr>
<td>Kickboxing</td>
<td>Jogging</td>
</tr>
<tr>
<td>Tennis</td>
<td>Ice Skating</td>
</tr>
<tr>
<td>Lacrosse</td>
<td>Stationary biking</td>
</tr>
<tr>
<td>Ultimate Frisbee</td>
<td>Hiking</td>
</tr>
<tr>
<td>Cross Country Skiing</td>
<td>Horse riding</td>
</tr>
</tbody>
</table>

\[
cBPAQ = [R + 0.2R(n - 1)] * a \quad \text{Equation 11}
\]
\[
pBPAQ = R * Y * a \quad \text{Equation 12}
\]

Where \( R \) is the activity’s weighting factor, \( Y \) is the years of participation, and \( a \) is the age weighting factor. The age weighting factor for Eq.14 is 0.25 for ages <15 and 0.10 for >15 (Weeks, 2008). The age weighting factor is used because BMD growth potential changes throughout life. Bone loading in the upper extremity (BLUE) versions of these equations were used to define a participant’s past (whole life prior to last 12 months) and current (past 12 months) activity history score.

In order to assign upper extremity physical activity scores, a list of past and current physical activities, frequency of participation and subject age are required. Using our weighting factors and the BPAQ algorithm we can generate our BLUE scores. Equations 15 and 16 show the relation between weighting factors (ELS or EAS based) to current activity history BLUE scores.

\[
\text{BLUE (ELS) Score} = [R + (0.2 * R * (n - 1))] * a \quad \text{Equation 13}
\]
\[
\text{BLUE (EAS) Score} = [R + (0.2 * R * (n - 1))] * a \quad \text{Equation 14}
\]

Where \( n \) is the frequency of participation (per week) and \( a \) is the age weighting factor.
Table 11- Representative upper extremity activities and percent contribution of tested motions in bone loading

<table>
<thead>
<tr>
<th>Rank</th>
<th>Activity</th>
<th>Hammering</th>
<th>Punching</th>
<th>Catching a Ball</th>
<th>Bent Over Row</th>
<th>Falling</th>
<th>Inertial</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Gymnastics</td>
<td>0%</td>
<td>0%-15%</td>
<td>0%</td>
<td>10%-20%</td>
<td>10%-15%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>Volleyball</td>
<td>0%</td>
<td>10%-15%</td>
<td>10%-15%</td>
<td>0%</td>
<td>0-10%</td>
<td>0%</td>
</tr>
<tr>
<td>Med</td>
<td>Softball</td>
<td>10%-20%</td>
<td>0%</td>
<td>10%-20%</td>
<td>0%</td>
<td>5%</td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td>Yoga</td>
<td>5%-10%</td>
<td>0%-10%</td>
<td>10%-20%</td>
<td>0%</td>
<td>0%-10%</td>
<td>5%-10%</td>
</tr>
<tr>
<td>Low</td>
<td>Swim</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>Run</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>
Table 12- Representative weighting factor (R) data for high, medium, and low impact activities.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Activity</th>
<th>R (ELS) Normalized</th>
<th>R (EAS) Normalized</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Gymnastics</td>
<td>100</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>Volleyball</td>
<td>93</td>
<td>74</td>
</tr>
<tr>
<td>Med</td>
<td>Softball</td>
<td>44</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td>Yoga</td>
<td>21</td>
<td>12</td>
</tr>
<tr>
<td>Low</td>
<td>Swim</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Run</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

5.8 Comparison to the BPAQ

To evaluate the relationship between BLUE scores and distal radius BMD, we have used physical activity data obtained in a previous research study and assigned a BLUE score to each subject (Bhatia et al., In Press). An example of a subject’s physical activity history is shown below. As you can see, equation 13 and 14 are employed to calculate both the past and current BLUE scores for this subject. In these equations that were obtained from BPAQ, R is the ELS or EAS values created in this study, y corresponds to years of participation for past activities, n is the frequency of participation for current activities, and a is the age weighting factor. As you can see in tables below, this individual has a score of 70 for past activities and 16.5 for current activities.

Figure 21- Example of past physical activity history and BLUE score calculation.

<table>
<thead>
<tr>
<th>Past Activities</th>
<th>R (ELS)</th>
<th>y</th>
<th>a</th>
<th>BLUE Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biking</td>
<td>10.7</td>
<td>13</td>
<td>0.1</td>
<td>13.91</td>
</tr>
<tr>
<td>Tennis</td>
<td>39.5</td>
<td>1</td>
<td>0.1</td>
<td>3.95</td>
</tr>
<tr>
<td>Softball</td>
<td>44</td>
<td>2</td>
<td>0.1</td>
<td>8.8</td>
</tr>
<tr>
<td>Gymnastics</td>
<td>100</td>
<td>3</td>
<td>0.1</td>
<td>30</td>
</tr>
<tr>
<td>Ballet</td>
<td>40.2</td>
<td>1</td>
<td>0.1</td>
<td>4.02</td>
</tr>
<tr>
<td>Volleyball</td>
<td>93.2</td>
<td>1</td>
<td>0.1</td>
<td>9.32</td>
</tr>
<tr>
<td><strong>BLUE score for past activities (BLUE)</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>70.0</strong></td>
</tr>
</tbody>
</table>
BLUE (past activities) = \sum (R \times y \times a) = 70

Figure 22- Example of current physical activity history and BLUE score calculation.

<table>
<thead>
<tr>
<th>Current activities</th>
<th>R (ELS)</th>
<th>n</th>
<th>a</th>
<th>BLUE Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biking</td>
<td>10.7</td>
<td>3</td>
<td>1.1</td>
<td>16.5</td>
</tr>
<tr>
<td>Running</td>
<td>0</td>
<td>2</td>
<td>1.1</td>
<td>0</td>
</tr>
<tr>
<td><strong>BLUE score for current activities (BLUE)</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>16.5</strong></td>
</tr>
</tbody>
</table>

BLUE (current activities) = \sum [(R + 0.2R(n - 1)) \times a] = 16.5

Total BLUE score can be calculated simply by adding the past and current scores, for the example above its 86.5. The BLUE scores for this data set, however, showed no significant correlation to distal radius BMD. (r=0.32, p=0.21 for BLUE (ELS) and r=0.21, p=0.43 for BLUE (EAS)). Figures 21-23 show the relationship between subjects’ BLUE (ELS) scores and measured BMD. Figures 24-26 show the relationship between subjects’ BLUE (EAS) scores and measured BMD.

Figure 23- Correlation of BMD and BLUE (ELS) scores for past physical activity history only.
Figure 24: Correlation of BMD and BLUE (ELS) scores using total physical activity history.

Figure 25: Correlation of BMD and BLUE (ELS) scores using current physical activity history.
Figure 26: Correlation of BMD and BLUE (EAS) scores using total physical activity history.

Figure 27: Correlation of BMD and BLUE (EAS) scores for past physical activity history only.
Figure 28: Correlation of BMD and BLUE (EAS) scores using current physical activity history.
Chapter 6 Discussion

6.1 Overview

In this chapter the results of our project are discussed individually including preliminary testing, design verification, subject testing, and data analysis, weighting factors, activity scores and a comparison to the BPAQ. These results will also be related back to our previously established objectives and constraints. Limitations of our findings will then be discussed followed by the socioeconomic effects of our project.

6.2 Preliminary Testing

After designing our device and building the prototype, its efficacy was validated by relating accelerations at the wrist with force values generated on the AMTI force plate. Three basic impacting actions were performed (which later were included in subject testing); punching, hammering and falling from the knees. These actions were chosen because they involved direct impact at the wrist in both axial (punching, falling) and transverse (hammering) directions. Figure 16 shows a representative correlation plot of acceleration in g’s ($9.8m/s^2$) versus resultant peak forces generated in Newtons (N) for a punching test. This plot demonstrates how peak impact deceleration scales directly with peak resultant force produced per instance ($1g = 132.65N, R^2=0.817$). The figure also displays how each subject’s data forms clusters. This convinced our team that normalization, from subject height (cm), weight (kg) or age (years), was necessary to relate subjects’ data.

6.3 Design Validation

During our design validation we recognized that acceleration data was only related to force plate data at the time of impact. This is because force plate loading remained unchanged until impact while the accelerations continuously fluctuated due to minor movements of the subjects arm in idle times. This can be shown in Figure 17, where the peaks occur nearly simultaneously, but non-peaks do not relate. Because ground reaction forces (GRF’s) can act as a valid proxy for bone strains (Peterman et al, 2001) and large magnitude forces are thought to have the greatest osteogenic effect (Rubin, 1984) peak GRF’s were used as maximum bone strain values for these tested categories. Additionally, rate of force (N/s) and rate of acceleration (g/s) were calculated at these peaks as strain rate (or rate of loading) was established as a potent bone growth impetus (Turner et. al, 1995). In the absence of force data,
accelerometer data can be used in conjunction with correlations to force previously generated (Appendix E), but these are not perfect correlations and therefore limit the accuracy of this method.

Alignment of the peaks, as shown in Figure 18, required an offset of the raw data due to asynchronous starts of data collection between the force plate and accelerometer. During validation testing, offsets, peaks, and rate of peak values were calculated manually from raw data in spreadsheet format, but this was later automated in a MATLAB program created to automate and hasten future testing. The alignment of peaks connected accelerations and resultant forces in our study which allowed us to correlate the two measures. This is important because it demonstrated a relationship between a local measurement (acceleration) at the wrist and a bone strain-inducing GRF.

6.4 Subject Testing

The test setup involved subjects signing an informed consent document and a demonstration of each motion prior to testing. Mounting of the accelerometer was done over the ulnar styloid process on the subject’s dominant hand. A cushioned sports wrap was placed under the accelerometer and athletic tape was wrapped over the device to rigidly, but not uncomfortably, fix the device to a subject’s wrist. These measures helped satisfy the project objectives of remaining comfortable and safe, while also fulfilling the constraints of the device remaining non-invasive and testing according to IRB protocol. A custom sleeve to house the device was discussed, but the varied size of subject’s forearms made that less practical. The total cost of the device and supporting materials was under $75 which fulfilled the objective of being low-cost and the budget constraint of being under $400.

During subject testing, our 16 initial testing motions proved too time consuming and the data was redundant. To satisfy the project testing time constraint of one hour maximum per participant, protocol refinement was necessary. The initial setup utilized the major motions the wrist encounters in various activities, rather than the major loadings. For instance, a horizontal arm swing would emulate shutting a door and a front drag would mirror raking or hoeing in front of oneself during gardening. Our testing protocol was refined based on different types of loading and the five motions that remained (punching, hammering, catching, falling and bent over row) incorporated the loadings of all 16 motions. Punching and falling involved axial loading inward toward the wrist. Catching similarly involved this loading, yet was not induced by bodyweight, but rather by the weight of the ball and the height it was dropped from. Bent over row involved an axial load outward from the wrist and hammering involved a shear load perpendicular to the wrist. Bent over rowing was a motion which may benefit from additional testing. The force plate used was not fixed to the ground and therefore would lift up during high force instances,
thereby limiting the peak forces that could be seen in the test. The compliance of the rope used for testing and friction between the rope and force plate are other factors that influenced testing results.

Subjects tested varied in age (20-30 yrs.), weight (54.1-118.2 kg), height (180 +/- 10 cm) and sex (2 F, 6 M). The first four subjects performed all 16 initial motions while the final four only did the 5 major motions. Testing time was originally over an hour and was decreased to approx. 30 minutes with the refined protocol. In addition to a reduction in testing time, the refined protocol drastically shortened analysis time.

6.5 Data Analysis

Utilizing the MATLAB program automated the analysis process while improving the accuracy of results. The refinement of thresholds used in the peak detection algorithm, calculating the rate of peak generation, and data filtration were the challenges associated with our initial data analysis. Previous studies, such as the BPAQ, only utilized vertical (Z-axis) ground reaction forces to simplify the data, but acceleration and force values were measured in three axes in this study, therefore resultant values represented complete force and acceleration magnitudes. Figure 19 demonstrates our peak detection algorithm over the 30 second sampling period with acceleration values that were converted from voltages to g’s. The red asterisks indicate the peaks of interest over the threshold we set, which was different for each motion (i.e. 3.5 g for falling and 2.5 g for punching). This data processing was repeated for force data and the time between peaks was used to validate correlation between the associated forces and accelerations. After testing three subjects, our device started malfunctioning and recording unrealistic data (30+ g accelerations while on a desk). Algorithm refinement was done and the device was tested to validate data was being transmitted from each of the output pins to the DAQ. The X-input was found to have an issue, which we determined was caused by the wiring (22 gauge stiff). The wiring was changed to Category V cabling (twisted pair) which reduced overall signal noise, based on observation, and fixed the problem. Testing was re-started afterwards with no additional issues.

After analyzing the magnitude and time point of peaks for both resultant acceleration and force, rates were calculated for both. Impact motion testing results show that loading signals peak over 50-75ms (Figure 17). Therefore, the peak values were used as the second time point in a linear slope equation with the corresponding magnitude (force or acceleration) 50ms prior used to get a rate value. This time interval was used because it was short enough that all peaks were still increasing within 50ms of reaching their peak, which means the rate remained positive.
All peaks and rates were averaged for each subject’s test and the resulting averages were again averaged for all subjects to get a single peak and rate value for the motion. This was done because our goal was to quantify bone loading activities as simply as possible. A similar method was used in previous studies, (Dolan 2006, Weeks 2008), but a much larger sample size than 8 (40 subjects) was used. These average values were used to create our motions bone loading weighting factors and therefore increasing the sample size may alter the final weighting factors generated. A small sample size is a limitation of this study.

6.6 Weighting Factors

Creating our weighting factors required another simplification of data. To do this, the ELS from the BPAQ was used to combine rate and peak values and give motions a single score, our weighting factor. The process was repeated with accelerations (EAS) to observe if a correlation between that and BMD exists and to compare it to ELS. The calculation of these values is straightforward, but force data were normalized and accelerations were not. The force data was normalized against subject’s bodyweight because many motions (punching and falling for example) had forces produced that directly related to subject’s bodyweight. Acceleration data didn’t relate to subject bodyweight, therefore no normalization occurred.

The data from one subject did not record properly and was omitted from the averaging. This appeared to be related to an issue with the force plate zeroing during that test and the accelerometer’s wiring coming loose. Subject five’s rate of force data was omitted as well, as shown in Table 6 due to an algorithm failure. The data was re-run numerous times, but unsuccessfully. The peaks generated during this run were observed to be lower than the assigned thresholds which may be the reason for this failure. This shows in more detail that the assigning of thresholds to each motion was a limitation of our study.

Table 9 shows the averages for peaks and rate as well as the corresponding weighting factors calculated. Falling and punching had the highest weighting factors for ELS which made sense as their force was directly related to subject’s bodyweight. Rowing, Hammering, and Catching were not as directly influenced by bodyweight and therefore their normalization with bodyweight reduced their ELS weighting factors drastically. This could be a source of bias in our calculations that caused the ELS weighting factor for rowing to be much lower than that of falling. Also, rowing was affected by the force plate being unfixed and lifting off the ground during testing. This put a limit on the force being tested to the weight of the force plate. Additionally, this was the only pulling motion and therefore our study did not accurately account for heavy pulling activities. This is another limitation of our study.
EAS weighting factors did not have the same bias as ELS weighting factors towards bodyweight. Hammering had the highest EAS weighting factor, this made sense as the dowel used was light relative to subject bodyweight and a rotational acceleration was added to the linear acceleration of the other tests. Catching and falling accelerations were dictated by subject’s reaction towards gravity upon impact of either the ball in their hand or their body against the force plate. If the subjects allowed themselves to fall with no resistance or catch the ball with no resistance, these values should be similar, but the fact that they were dissimilar says the actions were resisted differently subject to subject. The execution of these activities during testing may need refinement to increase reproducibility. Rowing data may be the least accurate because there was no impact. Instead, the rope went from slack to taut as they pulled backward, with the weight of the force plate as the only resistance. If their acceleration and force were high enough, this weight wouldn’t fully stop their motion, therefore the deceleration peak would be smaller as they could move with a more constant velocity during the test. This highlights why fixing the force plate should be done in future testing to guarantee a nearly full deceleration when the rope is taut. Another consideration was the stiffness of the rope used. If a stiffer rope was used for testing this could also influence the results of our testing. These remain limitations of our study.

6.7 Activity Scores

Activities were first subjectively divided into three groups based on impact involved being high, medium or low. Table 11 shows this designation in the first column. After separating activities into these groups, the % each motion contributed to them was given from observing the actions directly or through videos. A minimum and maximum range was used as most activities had periods of high loading and no loading depending on the type of activity or position played. Soccer for instance was assumed to have low loading for most players and a minimum value was made for them, but the goalies had a higher upper extremity loading and they were used to set the maximum. These minimum and maximum percentages were assigned by each group member individually at first. Following this, our percentages were discussed and compared and a group consensus was determined for our final assigned percentages. Activities involving swinging a bat or another form of shear force on the wrist were assumed to involve hammering, those with direct impact to the hand involved punching or catching a ball, most activities had a percentage of falling included, with gymnastics having the most at 10-15%. Bent over row was used in activities that had high amounts of pulling, such as rock climbing. There was also a constant inertial value used for sports, such as softball, that involved heavy throwing or swinging. This was a calculated average of the weight of items used in various activities and a generic acceleration multiplied to make a force value, which we normalized by average subject bodyweight, to get about 1.6BW for a weighting factor. This
value being constant and lower than the average weighting factor score seemed reasonable as the loading should not be as high as direct impacts, but further refinement should be done to make this value more accurate to each category rather than a generic constant.

The summation of these weighting factors were used to generate the BLUE score for each category and gymnastics resulted in being the largest for ELS, while rock climbing was highest for EAS. Gymnastics’ high loading made sense as it has been shown to be a very osteogenic activity in previous studies (Snow et al 2001). Swimming and running were examples of low or no impact activities that were given a score of 0. This also made sense as swimming has been shown to have a poor bone stimulus (Taaffe et al 1995). EAS weighting factors were not as reasonable as ELS weighting factors with rock climbing having a higher EAS weighting factor than tennis or softball, which involve high accelerations. Utilizing the same percentages for ELS and EAS may be the cause of EAS weighting factors not scaling based on accelerations seen. Creating a loading percentage value and an accelerative percentage value with additional activity observation may be beneficial. Percentages were assigned as objectively as possible, but further observation and refinement may change assignments drastically. This is a limitation of our study and a source of subjectivity.

In the BPAQ, activities were given the ELS score of the highest loading motion seen in that activity. Our ELS and EAS weighting factors are a combination of various activities. This makes our analysis more complex and potentially subjective, but also allows more complexity in scoring activities. The BLUE scores we generated utilized the same algorithm as the BPAQ, but with our ELS and EAS weighting factors. In order to compare these to BMD in the same way as the BPAQ, we normalized ELS and EAS weighting factors based on the highest scores which were gymnastics and rock climbing respectively. The normalized weighting factors seemed reasonable as, in ELS for example, volleyball had a high loading score of 93 while the weighting factor for yoga was moderate at 21 and swimming was given a weighting factor of 0 for no loading. Percentage values were given to the nearest 5% which may be too specific when examining observed percentage involvement. Refining this precision could be beneficial.

6.8 Comparison to the BPAQ

The current values of our BLUE scores were not significant predictors of variance in BMD or BMC. Subject recall of physical activity history, activity percentage assignments, and the algorithm used
could all be responsible for the lack of correlation. Regardless, refinement is needed. Correlations were not simply identified in previous studies. In the BPAQ, the cBPAQ score was found to be a significant predictor of variance in BMD for men ($R^2 = 0.36-0.68$, $p<0.01$) while the pBPAQ score predicted calcaneal broadband ultrasound attenuation (BUA) for women ($R^2 = 0.48$, $p = 0.001$) (Bhatia et al, In Press). Calcaneal BUA works by passing a range of ultrasonic frequencies through the bone region of interest measuring signal attenuation, and has been shown to be related to BMD (Chappard et al, 1997). The total BPAQ scores were not found to be significant predictors of any bone health parameter. This demonstrates how increased analysis may provide correlation to aspects of bone health and BLUE scores, although none has currently been found. Additionally, increasing our sample size of tested subjects may show correlation to sub-groups based on age, BMI, or sex and would also increase the power values of our results.

6.9 Limitations

Quantifying bone loading is a complex task and simplifying physical activity history into a single number requires numerous assumptions and limits the accuracy of the study. Although this study was performed as objectively as possible, limitations do exist. The sample size for our subject testing, which was used to determine our weighting factors, is a limitation. Increasing this size could improve the average ELS and EAS weighting factors in our study. Some other suggestions for refining our study would be to increase the age range beyond 20-30 years old, increase female participation (only 25%) and add a more robust analysis. Additional analysis could be performed to include the effects of subject BMI, sex, or age group on ELS and EAS weighting factors. Another limitation of our study was the analysis that was performed. We utilized the previously established algorithm of the BPAQ, but further adjustment to this could be used to possibly find a correlation between BMD and our BLUE scores.

Lack of a fixed force plate was a limitation of the row weighting factor being generated. The row was the only motion that involved pulling on the wrist. Additional pulling motions should be tested, but with a fixed force plate to generate accelerations and forces consistent with those of the impact categories.

Subject recall and the assignation of percentages to motions are also limitations of this study. All questionnaires are limited by the ability of participants to correctly recall their activity history and neglecting to accurately do so can drastically change the BLUE scores generated. The percentage’s each motion applies to the activities is a limitation of this study requiring refinement. These percentage values were applied as objectively as possible, but further observation of the activities by numerous examiners could change these percentage values and their corresponding ELS and EAS weighting factors. Changes
to recall and activity ELS or EAS greatly affect BLUE scores created downstream, therefore refinements would be beneficial to the efficacy of the BLUE score.

6.10 Economics

Although our study doesn’t have a direct impact on economics, the study of bone loading physical activities could help reduce the number of people affected by low BMD diseases later in life. This could save millions in fragility fracture procedures and osteoporosis related therapies. Additionally, accelerometers are being used in many activity monitors and mobile phones to track caloric expenditure or daily activities. In the future, daily bone loading could be another metric added to these devices via the link between accelerations and bone loading forces that was seen in this study.

6.11 Environmental Impact

There is no significant environmental impact related to the device designed or the testing performed in this study. Therefore the environmental impact of this study is not applicable.

6.12 Societal Influence

The societal influence of this study can be related to an increased awareness of individuals bone health by providing a means to track how physical activities can affect bone degradation or generation in the present. This study’s influence would be for upper extremity bone health specifically and could help bring awareness and potential preventive action earlier in people’s lives.

6.13 Political Ramifications

There are no significant political ramifications related to the device designed or the testing performed in this study. Therefore the political ramifications of this study are not applicable.
6.14 Ethical Concerns

There are no significant ethical concerns related to the device designed or the testing performed in this study. Therefore the ethical concerns of this study are not applicable.

6.15 Health and Safety Issues

The Health and Safety issues associated with this device are only related to the information gained from the testing it was designed for. The data acquired in this study could benefit researchers in connecting bone loading physical activities to BMD in the upper extremities. If a connection can be made, preventive activities could benefit people in reducing BMD issues later in life by prescribing preventive actions earlier in life. This could improve bone health overall.

6.16 Manufacturability

The device used in this study was only meant for the study’s data acquisition. There are no plans to manufacture this device and therefore the manufacturability of this device is not applicable.

6.17 Sustainability

The device used in this study was only meant for the study’s data acquisition. There are no plans to sustain use of this device and therefore the sustainability of this device is not applicable.
Chapter 7: Final Design and Validation

Overview

This chapter presents our final design and the methods taken to achieve all objectives and constraints. Our project was divided into two parts: device design and the analysis and generation of weighting factors. We will discuss the project in its entirety, including a brief introduction, methods, results and discussion.

7.1 Introduction

Approximately half of women and a quarter of men over the age of 50 will have an osteoporosis related fracture in their lifetime. There are over 9 million adults in the U.S. diagnosed with osteoporosis and an additional 45 million currently have low bone mineral density (NOF, 2013). Wrist fractures are the most common upper extremity fracture, even more common than hip fractures, with an annual incidence of 8-10 per 1000 in the elderly (Madhok, 1993). Physical activity history is related to bone mineral density because bone adaptation is driven by strain-producing activities (Rubin, 1984). Physical activity history has been previously shown to be a significant predictor of bone mineral density in the lower body, but no significant relationship between upper extremity physical activity history and upper extremity bone mineral density has been established (Weeks, 2008).

Surveys and questionnaires have been used to study the relationship between bone loading physical activity history and bone mineral density. This is achieved by weighting activities relative to their magnitude and rate of bone loading. The BPAQ and BLHQ are examples of these, specifically for total body and lower body BMD (Weeks, 2007 and Dolan, 2006). The BPAQ utilizes empirical ground reaction force (GRF) measures from select lower body motions to assign weighting factors to common sports and activities. The lower body motion origin of these data, however, makes these weighting factors irrelevant for the upper extremities.

This project aims to produce weighting factors, derived from upper extremity motions to examine the relationship between physical activity and upper extremity bone mineral density. This was accomplished by designing a biometric data acquisition and analysis system to measure parameters related to force and rate of force generation during strain producing upper extremity activities. And use the system designed to collect data and assign weighting factors to upper extremity activities, based on magnitude and rate of force generation.
7.2 Methods

7.2.1 Part 1: Device design

In order to examine the relationship between physical activity and upper extremity bone mineral density, the selection of a metric for noninvasively measuring bone strain in the wrist was necessary. Some of the objectives that were taken into consideration while selecting the design include low cost, accurate, and automatic. As a result, we decided on an ADXL 326-5V tri-axial accelerometer and measure the accelerations at the wrist during upper extremity physical activities. The accelerometer was connected to a National Instruments USB-6008 data acquisition (DAQ) device for objective data analysis. In addition, the team chose to measure corresponding forces at the wrist simultaneously with an AMTI Net Force plate. Preliminary testing was conducted to ensure the device provided a good measure of bone loading in the wrists. Data were obtained and compared to indicate the direct relationship between force and acceleration. After performing the preliminary tests on group members, the team created a study protocol and submitted it to the WPI Institutional Review Board in order to allow for human subject testing for multiple categories of upper extremity physical activities.

7.2.2 Part 2: Collection and analysis of data

Upon IRB approval, eight healthy adults (age: 25±5 years old, height: 180±10cm, and weight: 54-118kgs.) were recruited for testing. All subjects gave written informed consent prior to participation. Force and acceleration data were collected at 50 Hz, for 30 seconds per activity. Impact motions were repeated 5-10 times per test. An upper extremity physical activity motion list was generated for human subject testing. This list consisted of 16 different motions of upper extremity activities, including: overhand throw, underhand throw, vertical arm swing, front arm raise, lateral arm raise, overhead arm extension, catching a ball, punching, falling, hammering, side dragging, front dragging, shovel heave, reverse curling and a horizontal arm swing. After testing four subjects, the team realized we could decrease the number of motions tested to five major motions: punching, hammering, falling, catching a ball and rowing. Our rationale for the selected motions was that activity weighting factors could be estimated based on percentages of 5 major motions involved if we include and consider an inertial force contribution in bone loading.

A custom MATLAB code was created to automate the data analysis. A peak detection algorithm was used to identify the peak impacts for acceleration and force. After these peaks were found, averages were calculated and recorded for further analysis. Average rate of force generation and average rate of
acceleration were also calculated and recorded for further analysis. Peak loading forces were normalized based on subjects’ body weight. Using these values, effective loading stimuli and effective accelerative stimuli were calculated for the five major motions. Using these equations:

\[ ELS = \text{Average peak force} \times \text{Average rate of force generation} \]

\[ EAS = \text{Average peak acceleration} \times \text{Average rate of acceleration} \]

Next, weighting factors were assigned to a client-provided list of upper extremity physical activities. Subjective percentages were assigned to each activity, based on observation and intuition, to quantify the contribution of tested motions for bone loading. Using these activity percentages we have an ELS weighting factor and an EAS weighting factor for each activity. These were normalized to the highest scoring activity. Following this, BLUE scores were generated using the ELS and EAS weighting factors. BLUE score equation follows:

\[ \text{BLUE (ELS)Score} = [R + (0.2 \times R \times (n - 1))] \times a + (R \times a \times y) \]

\[ \text{BLUE (EAS) Score} = [R + (0.2 \times R \times (n - 1))] \times a + (R \times a \times y) \]

Where \( n \) is the frequency of participation (per week), \( y \) is the years of participation in the past and \( a \) is the age weighting factor. Now, using the BLUE scores we obtained we applied this to previous research data to evaluate the relationship between BLUE score and distal radius bone mineral density.

7.3 Results

7.3.1 Part 1: Device design

To validate acceleration and force data occurred concurrently, peak values were synchronized. Subject testing produced approximately 30-40 peaks per motion. Alignment confirmed a direct relationship between forces and accelerations during impacts. Figure 27 shows the correlation of peak forces and corresponding acceleration during a punching motion.
7.3.2 Part 2: Collection and analysis of data

Table 13 shows a summary of averaged peaks and rates for the five tested motions and their respective ELS and EAS weighting factors.

Table 13: Average loading measurements, ELS and EAS weighting factors, and the assigned BLUE scores for five major motions

<table>
<thead>
<tr>
<th>Activity</th>
<th>Catching</th>
<th>Falling</th>
<th>Hammering</th>
<th>Punching</th>
<th>Rowing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Peak Force [BW]</td>
<td>0.18</td>
<td>0.89</td>
<td>0.23</td>
<td>0.64</td>
<td>0.13</td>
</tr>
<tr>
<td>Average Rate of Force Generation [BW/s]</td>
<td>2.76</td>
<td>8.04</td>
<td>3.81</td>
<td>11.77</td>
<td>1.98</td>
</tr>
<tr>
<td>ELS [BW²/s]</td>
<td>0.51</td>
<td>7.17</td>
<td>0.87</td>
<td>7.54</td>
<td>0.26</td>
</tr>
<tr>
<td>Average Peak Acceleration [g]</td>
<td>3.34</td>
<td>4.64</td>
<td>4.80</td>
<td>4.80</td>
<td>3.20</td>
</tr>
<tr>
<td>Average Rate of acceleration [g/s]</td>
<td>46.05</td>
<td>66.68</td>
<td>83.33</td>
<td>79.27</td>
<td>30.43</td>
</tr>
<tr>
<td>EAS [g²/s]</td>
<td>153.62</td>
<td>309.14</td>
<td>399.61</td>
<td>380.39</td>
<td>97.45</td>
</tr>
</tbody>
</table>

Minimum and maximum ELS and EAS weighting factors were calculated for each activity based on % motion contribution. The average ELS and EAS were normalized with the corresponding peak activity score to scale values. Representative ELS data are listed in Table 14 for activities with high, medium and low effective loading. The total BLUE scores, however, showed no significant correlation to distal radius BMD. (r=0.32, p=0.21 for BLUE (ELS) and r=0.21, p=0.43 for BLUE (EAS)). These scores employ data values for past physical activity history, not current or total physical activity history.
### Table 14: Sample weighting factors (R)

<table>
<thead>
<tr>
<th>Rank</th>
<th>Activity</th>
<th>R (ELS) Normalized</th>
<th>R (EAS) Normalized</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Gymnastics</td>
<td>100</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>Volleyball</td>
<td>93</td>
<td>74</td>
</tr>
<tr>
<td>Med</td>
<td>Softball</td>
<td>44</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td>Yoga</td>
<td>21</td>
<td>12</td>
</tr>
<tr>
<td>Low</td>
<td>Swim</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Run</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### 7.4 Discussion

#### 7.4.1 Part 1: Device design

After designing our device and building the prototype, its efficacy was validated by relating accelerations at the wrist with force values generated on the force plate. Three basic impacting motions were performed (which later were included in subject testing); punching, hammering and falling from the knees. Our rationale for choosing these motions was that they involved direct impact at the wrist in both axial (punching, falling) and transverse (hammering) directions. A positive correlation was found between acceleration and resultant peak force, indicating that peak impact deceleration scales directly with peak resultant force produced per instance ($R^2=0.87$). This correlation also proved that data processing was necessary to relate our subject data.

#### 7.4.2 Part 2: Collection and analysis of data

A sample of preliminary data analysis was initially performed manually in EXCEL. These data were later analyzed in MATLAB and compared with manually processed results to validate the analysis system. Utilizing the MATLAB program automated and mechanized our analysis process while improving the accuracy of our results. Resultant acceleration and forces for three dimensions were used in our analysis to account for maximum acceleration and forces acting upon the wrist. Previous studies, such as the BPAQ, only utilized vertical (Z-axis) ground reaction forces to simplify the data, but because our accelerations were measured in three dimensions, we wanted to correlate them to forces in 3D. After analyzing the magnitude and time point of peaks for both resultant acceleration and force, rates were calculated for both. The peak value was used as the second time point in a linear slope equation with the corresponding magnitude (force or acceleration) 50ms prior used to get a rate value. All peaks and rates were averaged for each subjects test and the resulting averages were again averaged for all subjects to get
a single peak and rate value for the motion. These average values were used to create our motions bone loading weighting factors and therefore increasing the sample size may alter the final weighting factors generated. A small sample size is a limitation of this study.

Creating our weighting factors required another simplification of data. To do this the ELS from the BPAQ was used to combine rate and peak values and give motions a single score. The process was repeated with accelerations (EAS) to observe if a correlation between that and BMD exists and to compare it to ELS. Force data were normalized based on subjects’ body weight to find the forces generated as a ratio of subjects weight. This normalization was not necessary for accelerations since results are not affected by weight of the subjects.
Chapter 8: Conclusions and Recommendations

8.1: Conclusions

Currently, 54 million Americans have low BMD or osteoporosis. Those with low BMD are at great risk of fragility fractures, but changing factors that affect your BMD earlier in life could help reduce these incidences. Physical activity remains a controllable factor affecting BMD, but the relationship between the two must be refined to determine optimal bone loading activities. Physical activity history’s relationship to BMD has been validated through surveys and questionnaires by assigning weighting factors to different bone loading activities and adding up activities performed as a physical activity score. The BPAQ (Weeks, 2007) was a questionnaire that validated lower body motion’s relationship with BMD, but this and other questionnaires did not address upper extremity motions. In this study, that relationship was examined.

Our group utilized prior research to design a device that could measure acceleration and rate of acceleration at the wrist during various activities. These values’ bone loading potential were validated with force and rate of force generated during impact. We were able to relate these forces and accelerations at their peaks and automate an analysis system to obtain average peaks during testing. We performed IRB approved subject testing for five basic motions, generating empirical upper extremity impact data. Using these data, weighting factors were created for 34 activities and applied to previous subject data to generate a bone loading in the upper extremities (BLUE) score. These BLUE scores were then compared to subject’s distal radius BMD to relate findings.

Weighting factors and scoring generated in this study add vital information to the general research on physical activity’s effect on BMD. By gathering force and acceleration data during upper extremity motion testing, a variety of activities were able to be weighted based on their bone loading potential. Additionally, a study protocol, device and analysis system were created to attain additional data in the future. Utilizing the data from this study can help further define what upper extremity activities have the greatest bone loading potential. This information could help create an optimal upper extremity bone loading activity routine and ideally help reduce fragility fractures, and their associated complications, at the wrist.


**8.2: Recommendations**

This project accomplished our primary objectives and fulfilled our client statement, but there were areas for growth. These include:

- **Fixing the force plate during pulling tests.** The force plate was not fixed to the ground in our testing and this affected the rowing motion results. During this test, some subjects could lift the force plate off the floor. This may have been a cause for the lower weighting factor generated by this motion and future testing should be performed with a fixed force plate to verify. Downstream, if this weighting factor is changed, BLUE score totals will change and their relationship to BMD will have to be re-evaluated.

- **Assignment of Activity Percentages:** The proportion a tested motion was involved in a common activity was assigned through observation, but limitations in time made this data more subjective than we intended. Future work should more accurately quantify loading periods similar to those from the five tested motions in each activity in order to have more objective percentages. This could be done with additional direct activity observation.

- **Normalization Methods:** Future work should refine normalization methods for motions tested based on the amount of bodyweight involvement. We normalized all tested motions forces by subject bodyweight, but some motions such as hammering and rowing weren’t affected by subject bodyweight as much as falling. Refining normalization methods may change weighting factors making them more accurate to actual bone loading potential.

- **Increasing Sample Size:** The sample size of our study was 8 subjects, but more testing should be performed. This would increase the data pool to refine weighting factors generated and allow for sub-group correlations such as by sex or age group.

- **Further Analysis of BLUE Scores Relationship to Bone Parameters:** Analyzing the relationship between the BLUE scores and measured bone parameters for subject data in a previous study could show significant relationships not currently found. Also, this could allow for sub-group correlations or relating BLUE scores to different bone parameters such as bone mineral content.
Future work could utilize the foundation that this study has created in its device, analysis system, and study protocol to refine BLUE scores as a more accurate estimator of upper extremity BMD.
References


Appendices

Appendix A: Mounting Alternative Designs

Alternative Design 1: Directly Mount to Wrist:

Figure 30: Accelerometer mounted with tape on top of wrist.

Alternative Design 2: Wrist Band with Stitched on Pocket

Figure 31: Wrist Strap with pocket sewed into it for accelerometer.

Alternative Design 3: Wrist-strap Mount
Figure 32: Accelerometer mounted to wrist watch strap.

Alternative Design 4: Glove Mount in Sewn on Pocket

Figure 33: Accelerometer sewn into glove pocket.
Appendix B: Device Prototype

Figure 34: The above picture is a device prototype of the ADXL326 accelerometer placed on a solder less breadboard with wiring taped down.

Figure 35: This is our USB-6008 DAQ wired to our prototype.
Appendix C: IRB Approval

Worcester Polytechnic Institute

Worcester Polytechnic Institute IRB# 1
HHS IRB # 00007374

29 January 2014
File: 14-006


Dear Prof. Troy,

The WPI Institutional Review Committee (IRB) approves the above-referenced research activity, having conducted an expedited review according to the Code of Federal Regulations 45 (CFR45).

Consistent with 45 CFR 46.116 regarding the general requirements for informed consent, we remind you to only use the attached stamped approved consent form and to give a copy of the signed consent form to your subjects. You are also required to store the signed consent forms in a secure location and retain them for a period of at least three years following the conclusion of your study. You may also convert the completed consent forms into electronic documents (.pdf format) and forward them to the IRB Secretary for electronic storage.

The period covered by this approval is 29 January 2014 until 28 January 2015, unless terminated sooner (in writing) by yourself or the WPI IRB. Amendments or changes to the research that might alter this specific approval must be submitted to the WPI IRB for review and may require a full IRB application in order for the research to continue.

Please contact the undersigned if you have any questions about the terms of this approval.

Sincerely,

Kent Rissmiller
WPI IRB Chair
Appendix D: Extech Datasheet

3-Axis G-Force Datalogger

Built-in 3-axis accelerometers record the time when shock occurs. Measure and compute real-time spectral data using FFT.

Features:
- Record storage, transport or operational data over time.
- USB interface for easy set-up and data download.
- Record and time 3-axis shock and peaks.
- Real-time FFT Frequency and Time-Domain Vibration Analysis.
- Datalogs 112028 Motion Detection samples per axis, or 169842 Normal samples.
- Selectable X-, Y-, Z-axis or any combination (via software).
- Selectable data sampling rate: 50ms to 24 hours.
- Manual and Programmable start modes.
- User-programmable record threshold.
- Long battery life.
- Complete with Magnetized/Bolt-on Mounting Base, 3.6V Lithium battery and Windows® 98, 2000, XP, and Vista compatible analysis software.

Specifications:

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor Type</td>
<td>MEMS semiconductor</td>
</tr>
<tr>
<td>Acceleration Range</td>
<td>±1g</td>
</tr>
<tr>
<td>Acceleration Resolution</td>
<td>0.00025g</td>
</tr>
<tr>
<td>Acceleration Accuracy</td>
<td>±0.5g</td>
</tr>
<tr>
<td>Data Rate</td>
<td>2 to 24kHz</td>
</tr>
<tr>
<td>Sampling Rate (Software)</td>
<td>500 ms to 24 hours</td>
</tr>
<tr>
<td>Memory</td>
<td>4GB Flash, 112028 Motion Detection samples per axis, or 169842 Normal samples</td>
</tr>
<tr>
<td>Data Format</td>
<td>Time stamped peak acceleration, average and peak vector sum</td>
</tr>
<tr>
<td>Dimensions</td>
<td>3.7 x 1.1 x 0.7&quot; (95 x 28 x 21mm)</td>
</tr>
<tr>
<td>Weight</td>
<td>1oz (25g)</td>
</tr>
</tbody>
</table>

Ordering Information:
- VE300 ........ Three Axis G-Force Datalogger
- 42299 .......... 3.6V Lithium Battery (pkg of 2)

www.extech.com
Appendix E: Original Protocol Correlation Plots:

The plots generated in this section represent the force and acceleration relationship for ten originally tested motions. These tests were performed preliminarily between 3 subjects and 5-10 repetitions of each motion were performed. The mean of these repetitions were plotted in the charts below to demonstrate the force and acceleration relationship from our device and the force plate. A description of each action is as follows:

- **Bent Over Row**: A rope is mounted to the bottom edge of the force plate. A subject is bent over the plate, with their back perpendicular to it and pulls the rope upward from full extension until the hand is parallel to the trunk. The rope length was made to be taught at full contraction of the arm.

- **Horizontal Swing**: A rope is mounted to the bottom edge of the force plate. A subject stands parallel to the force plate and swings their arm horizontally across the body while holding the rope. The rope length was determined so that the full horizontal extension of the arm, across the body, would leave the rope taught.

- **Lateral Raise**: A rope is mounted to the bottom edge of the force plate. A subject holds the rope while standing next to the plate and extends their arm from their side 90 degrees laterally to parallel with the force plate. The rope length was determined so that it would be taught at full extension.

- **Overhand Throw**: A one kilogram ball was tossed on the force plate with an overhand motion. The subject stood approx. 10 feet away during this test.

- **Catch the Ball**: The subject lay on their back, on the force plate, while a one kilogram ball was dropped from approx. 5ft high onto their extended hand. The subject was instructed to catch the ball and then let the arm drop upon impact so the elbow would contact the force plate and then drop the ball to the side.

- **Falling**: Falling occurred from the knees landing on the hands on the force plate. The subject absorbed impact with their hands down to their chest on the force plate. They then pushed off the ground outside the plate to return to the starting position.

- **Punching**: The subject bent over with their trunk perpendicular to the force plate. They then extend their arm with the fist closed and impact the force plate at full extension.

- **Hammering**: The subject holds a 0.5 kilogram wooden dowel and impacts the force plate by rotating the forearm at the elbow approx. 90 degrees, from upward vertical to horizontal, striking the plate with the dowel.

- **Reverse Curl**: The subject holds a one kilogram ball in their hand standing above the force plate with the bicep in full contraction and extends the arm 180 degrees, releasing the ball down to the force plate.

- **Underhand Throw**: The subject tosses a one kilogram ball underhand at the force plate. The subject stands approx. ten feet back when doing this.
Figure 36- Mean peak forces and accelerations for preliminary testing on bent over row

Figure 37- Mean peak forces and accelerations for preliminary testing on Horizontal arm swing
Figure 38-Mean peak forces and accelerations for preliminary testing on lateral raise

Figure 39-Mean peak forces and accelerations for preliminary testing on overhand throw
Figure 40-Mean peak forces and accelerations for preliminary testing on catching a ball

Figure 41- Mean peak forces and accelerations for preliminary testing on falling
Figure 42-Mean peak forces and accelerations for preliminary testing on punching

Figure 43-Mean peak forces and accelerations for preliminary testing on hammering
Figure 44-Mean peak forces and accelerations for preliminary testing on reverse curl

Figure 45-Mean peak forces and accelerations for preliminary testing on underhand throw
Appendix F: Five Tested Motions Force/Acceleration Relationship

Below are peak force, in units of subject tested bodyweight (BW), and acceleration, in acceleration due to gravity (g), correlation plots. These are based on the average force and acceleration values for each subject during each test.

Figure 46: Correlation of peak impact force and peak acceleration during Hammering tests.

Figure 47: Correlation of peak impact force and peak acceleration during Catch a Ball tests.
Figure 48: Correlation of peak impact force and peak acceleration during Falling tests.

Figure 49: Correlation of peak impact force and peak acceleration during Punching tests.
Figure 50: Correlation of peak impact force and peak acceleration during Bent-Over Row tests.
Appendix G: Activity Percentages

Below is a table of min and max percentage involvement of the motions we tested in each activity given to us by our client. An inertial component was also included for activities with an object used in the hand. Percentages were given based on observation of activities, but additional observation should be performed to increase objectivity.

Table 15-Percent Contribution of tested motions in upper extremity activities

<table>
<thead>
<tr>
<th>Activity</th>
<th>Hammering</th>
<th>Punching</th>
<th>Catching a Ball</th>
<th>Bent Over Row</th>
<th>Falling</th>
<th>Inertial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gymnastics</td>
<td>0%</td>
<td>5% - 10%</td>
<td>0%</td>
<td>10% - 20%</td>
<td>10% - 20%</td>
<td>0%</td>
</tr>
<tr>
<td>Basketball</td>
<td>0%</td>
<td>10% -20%</td>
<td>10% - 20%</td>
<td>0%</td>
<td>5%</td>
<td>0%</td>
</tr>
<tr>
<td>Volleyball</td>
<td>0%</td>
<td>10% - 20%</td>
<td>10% - 20%</td>
<td>0%</td>
<td>5%</td>
<td>0%</td>
</tr>
<tr>
<td>Cheerleading</td>
<td>0%</td>
<td>5%</td>
<td>0%</td>
<td>0%</td>
<td>5% -20%</td>
<td>0%</td>
</tr>
<tr>
<td>Weight lifting (free)</td>
<td>0%</td>
<td>5% - 10%</td>
<td>5% - 10%</td>
<td>5% - 10%</td>
<td>5% - 10%</td>
<td>0%</td>
</tr>
<tr>
<td>weight lifting (machines)</td>
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<td>5% - 10%</td>
<td>5% - 10%</td>
<td>5% - 10%</td>
<td>5% - 10%</td>
<td>0%</td>
</tr>
<tr>
<td>Rock-climbing (stairmaster)</td>
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<td>0%</td>
<td>20% - 40%</td>
<td>10% - 15%</td>
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<tr>
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<td>5%</td>
<td>10% - 20%</td>
<td>0%</td>
<td>5%</td>
<td>10% - 20%</td>
</tr>
<tr>
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<td>5%</td>
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<td>0%</td>
<td>5%</td>
<td>10% - 20%</td>
</tr>
<tr>
<td>Dancing</td>
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<td>0%</td>
<td>0% -10%</td>
<td>0%</td>
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<td>5%</td>
<td>10%-15%</td>
</tr>
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<td>5%</td>
<td>10%-20%</td>
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<td>0%</td>
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<td>0%</td>
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<td>Toning exercises</td>
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<td>0% - 5%</td>
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<td>Track &amp; Field</td>
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</tr>
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<tr>
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<td>0%</td>
<td>0%</td>
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</tr>
<tr>
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<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Horse riding</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>
Appendix H: Activity Scores

Values in the table below represent raw and weighted ELS and EAS based weighting factors (R) for activities given to us by our client. ELS units are Bodyweight²/s and EAS units are g²/s.

<table>
<thead>
<tr>
<th>Bone Loading in Upper Extremities</th>
<th>Raw Scores</th>
<th>Normalized Scores</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R (ELS)</td>
<td>R (EAS)</td>
</tr>
<tr>
<td>Gymnastics</td>
<td>3.36</td>
<td>89.52</td>
</tr>
<tr>
<td>Basketball</td>
<td>3.13</td>
<td>95.56</td>
</tr>
<tr>
<td>Volleyball</td>
<td>3.13</td>
<td>95.56</td>
</tr>
<tr>
<td>Cheerleading</td>
<td>2.55</td>
<td>57.66</td>
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<tr>
<td>Weight lifting (free)</td>
<td>2.32</td>
<td>70.55</td>
</tr>
<tr>
<td>weight lifting (machines)</td>
<td>2.32</td>
<td>70.55</td>
</tr>
<tr>
<td>Rock-climbing</td>
<td>2.21</td>
<td>127.82</td>
</tr>
<tr>
<td>Handball</td>
<td>1.97</td>
<td>57.52</td>
</tr>
<tr>
<td>Soccer</td>
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<td>38.32</td>
</tr>
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<td>75.40</td>
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<td>1.06</td>
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<td>99.90</td>
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<td>0.89</td>
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<td>Toning exercises</td>
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<td>Yoga</td>
<td>0.72</td>
<td>15.46</td>
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<td>Track &amp; Field</td>
<td>0.63</td>
<td>17.72</td>
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<td>Running</td>
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<td>0</td>
</tr>
<tr>
<td>walking</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cross country</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Jogging</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ice skating</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Stationary biking</td>
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<td>0</td>
</tr>
<tr>
<td>Hiking</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Horse riding</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Appendix I: MATLAB Scripts
The MATLAB script below was employed to automate the analysis system that quantifies bone loading in the upper extremities. This code uses analog voltages from accelerometer as its input. Using conversion factors that were calculated by calibration, signals are converted to acceleration values in x, y and z direction. After that, peak values of resultant acceleration were detected and their average was displayed as an output. Acceleration rates were also calculated at each peak and their average was displayed as the second output. Amirhossein Farvardin was the primary author. It was last edited on 4/4/14. Raw acceleration values were output to a text file with x y and z as the columns and units in acceleration due to gravity ‘g’.

clc; clear; close;

% get connected devices
d = daq.getDevices;
%create session
s = daq.createSession('ni');

file_name =  input('Enter experiment name: ');
file_name = [file_name,'.txt'];

file_id = fopen(file_name,'w+');

% add analog channel s.addAnalogInputChannel('ID',channel num, 'measurement type')
s.addAnalogInputChannel('Dev1',2, 'Voltage')
s.addAnalogInputChannel('Dev1',3, 'Voltage')
s.addAnalogInputChannel('Dev1',4, 'Voltage')
%
% set rate of scan 100 scans/second , run for 30 seconds
s.Rate=100;
s.DurationInSeconds=30;
SampNum=s.Rate*s.DurationInSeconds;
v= s.Channels(1);
set(v)
%
v.TerminalConfig = 'Differential';
v.Coupling = 'DC';
%
% Plot data

h = s.addlistener('DataAvailable', @(src,event) plot(event.TimeStamps, event.Data./.001));
s.NotifyWhenDataAvailableExceeds = 200;
% [data,time] = s.startForeground;
figure (1)
hold on
xlabel ('Time (s)')
ylabel ('Voltage (vol)')

%%
disp('Start to get data...');
[data,time] = s.startForeground;
disp('Done.');
%s.release()

% reading samples
%s.startBackground;
x_data = data(1:SampNum,1);
y_data = data(1:SampNum,3);
z_data = data(1:SampNum,2);

%% Converting to g
a1=-21.7; b1=4.58;
x1= (x_data*a1)+b1;

a2=-19.64; b2=31.487;
y1= (y_data*a2)+b2;

a3=-19.64; b3=4.287;
z1= (z_data*a3)+b3;

Data_for_file = [x1,y1,z1];
fprintf(file_id,'%f , %f , %f 
',Data_for_file);
fclose(file_id);

%% Plotting Acceleration data

% X-Axis
F2 = figure(); hold on
x = smooth(x1);
plot(time,x,'b');
xlabel('time [sec]'); ylabel('Acceleration (g)');
title('3-axis Acceleration data');

% Y-Axis
hold on
y = smooth(y1);
plot(time,y,'r');
xlabel('time [sec]'); ylabel('Acceleration (g)');
title('Acceleration in the Y-axis');

% Z-Axis
hold on
z = smooth(z1);
% Vector Sum

AccelData= sqrt((x.^2)+(y.^2)+(z.^2));

% Plot Total acceleration

F3 = figure(); hold on
grid on
plot(time,AccelData,'b'); hold on
xlabel('time [sec]'); ylabel('Vector Sum [g]');
title('Total Acceleration due to Loading');

%% Estimating the locations of all peak Values
threshold=2.0; %g
n=30; % 30 seconds

for n=0:29
    l=100*n +1; % 100 signals in each second
    r=100*n+100;
    k=[]; h=[];
    for i=l:r
        if(AccelData(i)>threshold)
            k=[k,AccelData(i)];
            h=[h,time(i)];
        end
    end
    [Max,Imax] = max(k);
    t_peak = t_peak(h(Imax));
    y_peak = y_peak(Max);
end

plot(t_peak,y_peak,'r*'); %show the peaks in read

AveragePeak = mean(y_peak);
disp(['Average Peak Acceleration is ', num2str(AveragePeak)]);

% Rates = [];
for k=1:length(y_peak)
    if(AccelData(round(t_peak(k)*100))<threshold)
        Rates(k)=((AccelData(round(t_peak(k)*100))- AccelData(round((t_peak(k)*100)-
5)))*20);
    end
end
AverageRate = mean(Rates);
disp(['Average Acceleration rate is ', num2str(AverageRate)])
Figure 15: Acceleration during 30 seconds of data collection. Falling motion was repeated nine times and peak accelerations (shown as asterisks in red) were detected each time.