# Back Squat - Lifting Analysis

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# 1. Introduction

### 1.1 Goal

The goal of this project is to look for improper form when weightlifting by analyzing video footage of an exercise then looking for key features such as force on joints, correct position, and proper sequence in movements. Taking data extracted from the video, I aim to establish a technical procedure that could be used to analyze lifting form.

### 1.2 The Problem

Weightlifting consists of many exercises but there are essential lifts that are crucial to all movements[1], one of them being the squat. Many exercises are variations of the squat lift, thus having a strong foundation in it ensures proper form and utility from performing them.

While the squat is the start to weightlifting for many people, it is often difficult to get the correct form, leading to injury[2]. Problems that might occur include: backache, knee degeneration, deterioration of joints, etc.… Without a coach, it is difficult correctly learn how to squat.

Tutorials are often helpful but still lack the feedback required for a person to truly improve. On top of that, some movements can look correct but actually put strain on the performer's body. Studies have also show that "showing an individual in the process of acquiring the skill to be learned may accelerate skill acquisition and increase retention more than using a correct model"[3], so instant feedback would greatly help.

### 1.3 Outline

This paper is broken into various sections in order to better understand the process of how weightlifting and training can be improved. First by introducing the back squat by explaining the form, common mistakes, and injuries that occur to people when they perform the lift. Then, I describe my solution that I created to help solve this problem. Finally, I expand on how my solution could be improved in the future.

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[1] (Butler 2010)
[2] (Stone 1994)
[3] (Mccullagh 1997)

# 2. Brief Overview of Lifting

Lifting or more specifically weight lifting is when someone bears a physical load that either requires him or her to push or pull that given load. It is often a key area in many sports, as it prepares the body to be under extreme conditions as well as build muscle mass. These load bearing exercises can cause injury if done with improper form or if the weight is too much for the user. A problem with this is many people can go for extended periods of time using improper and not know that they are causing unknown stresses to the body besides the intended ones[4]. These can lead to injuries to the body that can have disastrous effects[5]. However, with proper form there are many benefits to lifting and thus if the user has proper knowledge, many of the negative side effects can be avoided.

**2.1 The Squat**

One of the staple movements in exercise is squatting. The movement pattern is used to accomplish tasks beyond just exercising and can range from sitting down in a seat to jumping as high as you can. Despite being a movement that is used by almost everyone every day, it is done incorrectly by many. The squat is also very important because by analyzing someone's squat form, trainers can often point out many of the deficiencies that a person has in their body[6].

**A) Proper Form**

A simplified sequence taken from a 22-step progression of squatting[7]:

1. Start with the feet about shoulder width apart and slightly toed out.
2. Keep the midsection very tight.
3. Send your butt back and down.
4. Your knees track over the line of the foot.
5. Do not let the knees roll inside the foot. Keep as much pressure on the heels as possible.
6. Pull yourself down with your hip flexors.
7. Stop when the fold of the hip is below the knees– break parallel with the thigh.
8. Return on the exact same path as you descended.

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[4] (J. Siewe 2011)
[5] (Hedrick 2008)
[6] (Vizcaya 2009)
[7] (Staff. 2010)

9. On rising, without moving the feet, exert pressure to the outside of your feet as though you were trying to separate the ground beneath you.
10. At the top of the stroke, stand as tall as you possibly can

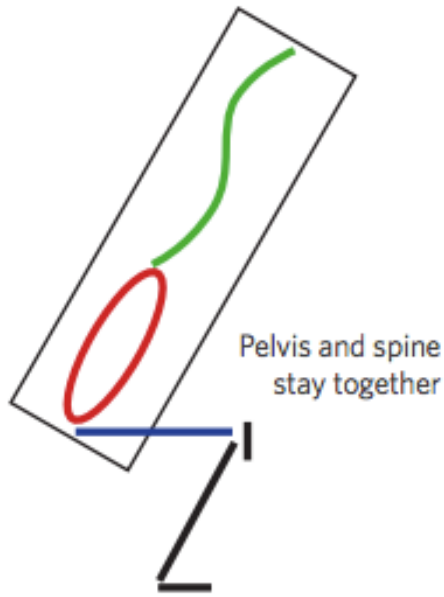


Figure 1: Squat Alignment

**B) Common Mistakes**

Mistakes when squatting can be very costly and lead to injury. Maintaining proper form when lifting with weight becomes more difficult as it gets heavier and causes the performer to have incorrect form[8]. The most frequent cases of broken form are:

1) Not breaking parallel plane with the thigh
2) Dropping head
3) Leaning forward on knees (Heels off the ground)
4) Losing lumbar extension (Rounding of back/bending at hip)

**C) Injuries**

Injuries are common when weightlifting. A study showed approximately 1.2 -1.1 injuries per lifter per year and 4.4 - 4.8 injuries per 1000 hours of training[9]. Types of injuries range from acute (muscle and connective tissue sprains and strains) to chronic and result due to poor technique[10].

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[8] (Staff. 2010)
[9] (J. Keogh 2003)
[10] (Stone 1994)

# 3. My Approach

### 3.1 Tools

The goal of this project is to create a solution to improving squat form. Thus, the decision was made to forgo using high quality cameras with 4k resolutions. Instead, with the idea of portability in mind, I chose to use an IPhone 6 camera (1080p HD video recording (30 fps or 60 fps))[11]. The IPhone's video recording ability is similar to its competitors in the market and has almost half the market share in mobile devices [12]. With this, the quality of video shot for testing is 1080p and 30fps.

### 3.2 Subjects

In order to ensure that the data collected for the exercise covered all levels of lifting experience the following subjects were chosen to be recorded and analyzed: one competitive college Varsity athlete (4 > years experience), two college students with lifting knowledge (> 2 years experience), and three beginners (1 < year experience). The age range of the subjects was primarily early 20s, but also included one individual in their late 40s.

### 3.3 Point of View

To simplify the data collection and analysis, I decided to capture the video from a two-dimension plane as recommended by Professor Taylor. In order to capture all the major joints involved in the back squat movement, the videos were shot to include the entire figure of the performer from a side view. This was chosen above the option of a frontal view perspective because it is easier to extract key angles from the side view. The frontal view only includes only 1 important angle, as seen in the figures on the next page.

### 3.4 Procedure

To record the results of the squat, the camera was set up at around the users waist level from 10 feet away. The performer would then do a body weight squat, as they believed it should be performed. The videos were then cut into 3-4 second clips to only include the beginning and end of the squat. This was done in order to collect only necessary information.

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[11] (Apple 2016)
[12] (Edwards 2015)

Figure 2: Side View

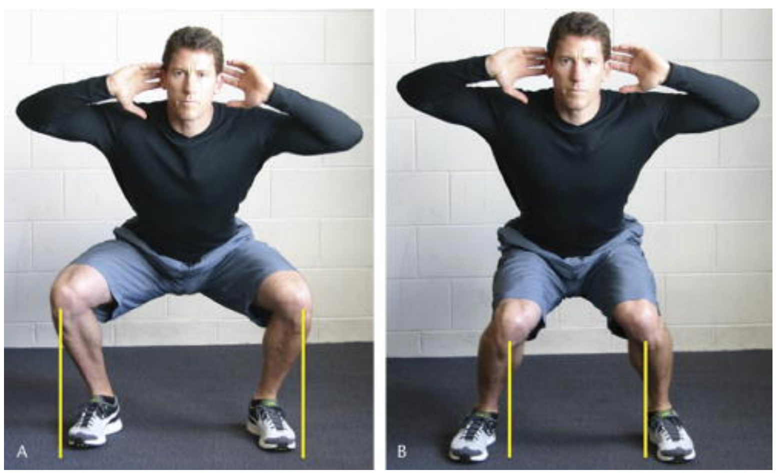

Figure 3: Frontal View

# 4. Code Overview

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### 4.1 MATLAB

When starting the project I considered using either MATLAB or Python's OpenCV. I eventually chose to do all programing in the MATLAB environment by consider several variables.

MATLAB Pros:

- MATLAB includes and extensive matrix library which allows for easy calculation of the major angles
- Image Processing and Computer Vision Toolbox contain implementations many processing algorithms such as Kanade-Lucas-Tomasi (KLT), feature-tracking algorithm used in this project.
- MATLAB comes with great documentation and examples that are easily accessible within the IDE.

MATLAB Cons:

- Cost to upgrade MATLAB after research
- No prior experience with MATLAB

OpenCV Pros:

- Free to upgrade
- Portable and can be run on web backend
- Python has a large number of scientific libraries
- Experience with Python

OpenCV Cons:

- The documentation and support for OpenCV is lacking in comparison with MATLAB

### 4.2 Blob Analysis

When starting the project, Professor Taylor and I first decided the best approach to track the movement of the body would be to create bounding boxes between all the major regions of the body. These were sectioned off as: head, torso, upper leg, and lower leg.

This approach turned out to be more difficult than we originally planned. While using MATLAB's Computer Vision for blob analysis was able to correctly identify the figure and extremities of the performer, it created a bounding box around the entire figure as opposed to previously mentioned sections. This made measuring the major angles between the sections of the body difficult, as tracking specific regions was not accurate.

**4.3 Key Points**

Instead of using blob analysis to determine the movement of the body, I determined if someone were able to place points on key areas of the body we could measure the desired angles. Although with this, the ability to auto-detect regions was lost.

To do this, I allow the video to go through the first twenty frames (0.67 Seconds) of the video, in order to account for the initial set up people have when getting ready to squat. At the twentieth frame the video is paused and the user must provide six points in the order from head, shoulder, hip, knee, ankle, and toes. Represented as
$p_1 = head, p_2 = shoulder, p_3 = hip, p_4 = knee, p_5 = ankle, p_6 = foot$
These points are saved and fed into MATLAB's point tracker as an array of
$points = [p_1, p_2, p_3, p_4, p_5, p_6]$

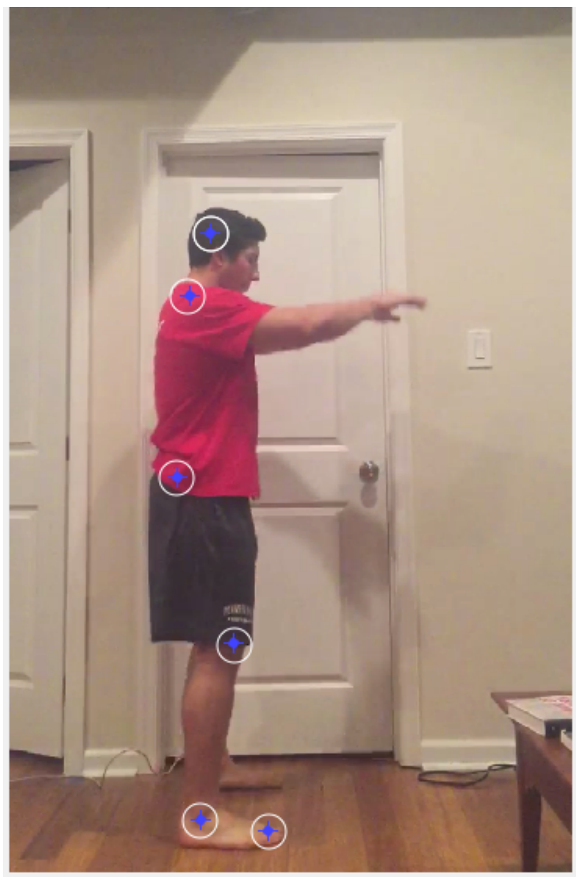

Figure 4: Point Tracker

### 4.4 Point Tracker

The set of *points* listed above is then tracked by MATLAB's Computer Vision toolbox tool called the Point Tracker. The point tracker uses the Kanade-Lucas-Tomasi (KLT) feature extraction algorithm to determine the new location of the points and also returns a confidence score of the result for each frame of the video. A result of the videos being cut to only include the beginning and end of the squat and only include two-dimensional plane is that I avoided the pitfalls of the KLT algorithm (i.e. lighting variation, out of plane rotation)[13]. This was confirmed when tracking the validity of our points throughout the video. The Point Tracker validity feature outputs the confidence score ranging from 0 - 1. My results were consistently > 0.998 for my testing because of the factors mentioned above.

### 4.5 Vector Calculation & Angle Calculation

With the points being track from the above tool, I extracted the vectors that make up the human figure during a squat motion. With these vectors, I produced the cos $(\theta)$ for the neck, hip, knee, and ankle.

The follow vectors and cos $(\theta)$ are produced each frame:

* Vectors formed to ensure direction matches for angle calculation

$$v_1 = head - shoulder$$
$$v_2 = hip - shouler$$
$$v_3 = shoulder - hip$$
$$v_4 = knee - hip$$
$$v_5 = hip - knee$$
$$v_6 = ankle - knee$$
$$v_7 = knee - ankle$$
$$v_8 = foot - ankle$$

Calculation for angle between vectors:

$$\text{acos}\,(\frac{v_i * v_j}{|v_i| * |v_j|})$$

# 5. Data Collection

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### 5.1 Angle Of Major Joints

The recording of angles calculated above was chosen to attempt to represent the table below:

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[13] (Matlab 2016)

| Table 1<br>Kinematic considerations of the bilateral bodyweight squat | | | | |
|---|---|---|---|---|
| Downward and upward movement phases of a bilateral body weight squat | | | | |
| **Anatomical region** | **Baechle (5)** | **Bloomfield (6)** | **Kinakin (28)** | **Summary** |
| Head | Neutral position | Held up | Neutral position | Neutral |
| Thoracic spine | Flat: maintain torso to floor angle | Angled slight forward and held straight | Flat: maintain torso and shin angle | Slightly extended |
| Lumbar spine | Flat: maintain torso to floor angle | Curved slightly inward | Flat: maintain torso to shin angle | Neutral |
| Hip joints | Flexed | Flexed | Flexed: remain under the shoulders | Flexed and aligned |
| Knees | Flexed: knees aligned over the feet | Flexed | Flexed: knees over the feet | Aligned with feet |
| Feet/ankles | Shoulder width/remain on the floor | Shoulder width, toes pointing forward | Shoulder width stance | Flat not rolling in or lifting up |

Figure 5: Key Tracking Regions

These angles were recorded every frame throughout the video and stored in order for more detailed extraction.

### 5.2 Interval Collection

As seen in earlier studies, the timing of a squat varies depending on the level of experience of the performer[14]. Therefore, in order to record the speed of the movement and how fast the angles are changing, I recorded the angle of the user every 15 frames (0.5 Seconds).

### 5.3 Start – Min – Finish Angles

The squat can be divided into a downward phase, eccentric contraction (E), and an upward phase, concentric contraction (C)[15]. With this I also included my own phase, to represent the lowest point in the squat. These were recorded in order to track the overall change of the angles over the entire duration of the squat and helped recognition of extremes that occurred.

### 5.4 Initial Expected Readings

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[14] (Miletello 2009)

[15] (Pereira, et al. 2010)

Using the ranges based off of squat analysis, the ideal ranges for change in the joint areas were set to the following expected levels to be consider valid squat form[16]:
Neck: $Start\ \pm\ 4.5°$
Hip: $Start -\ (95° \pm\ 27°)$
Knee: $Must\ Break$ 90°
Ankle: $Within$ 25°

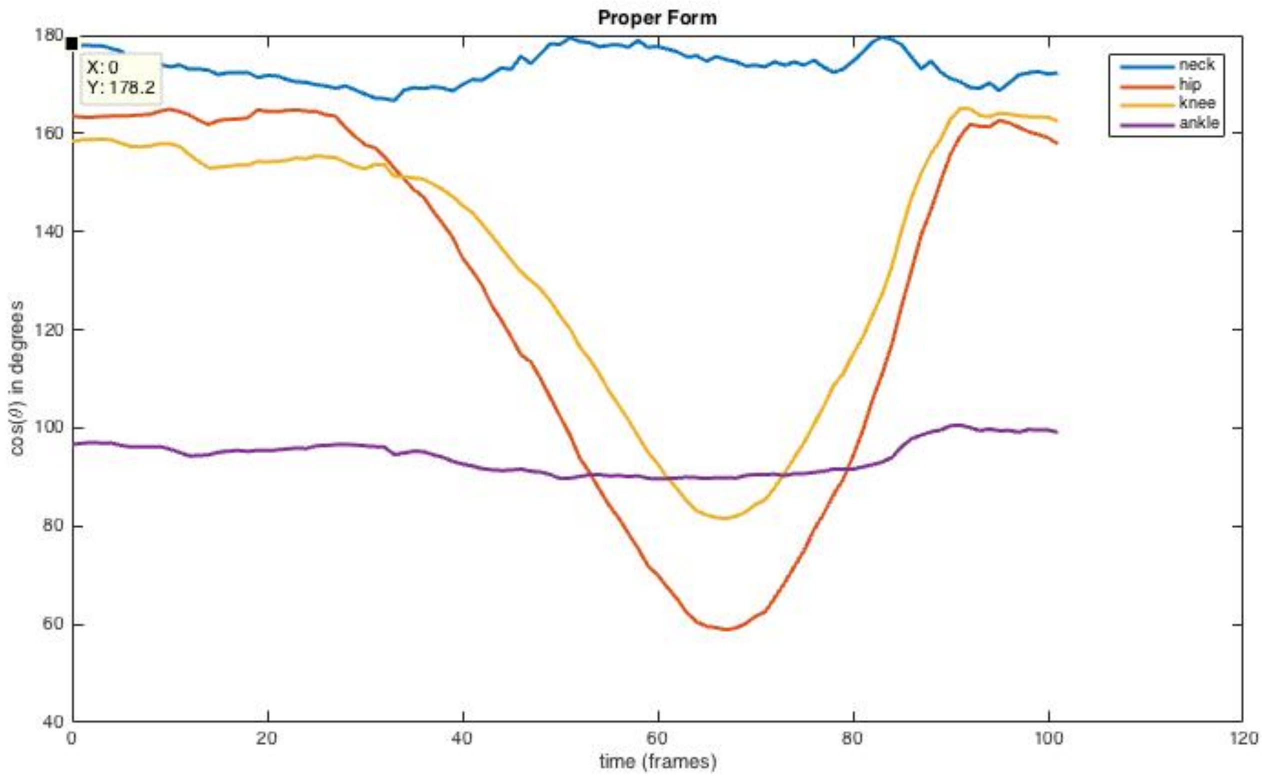
### 5.5 Results

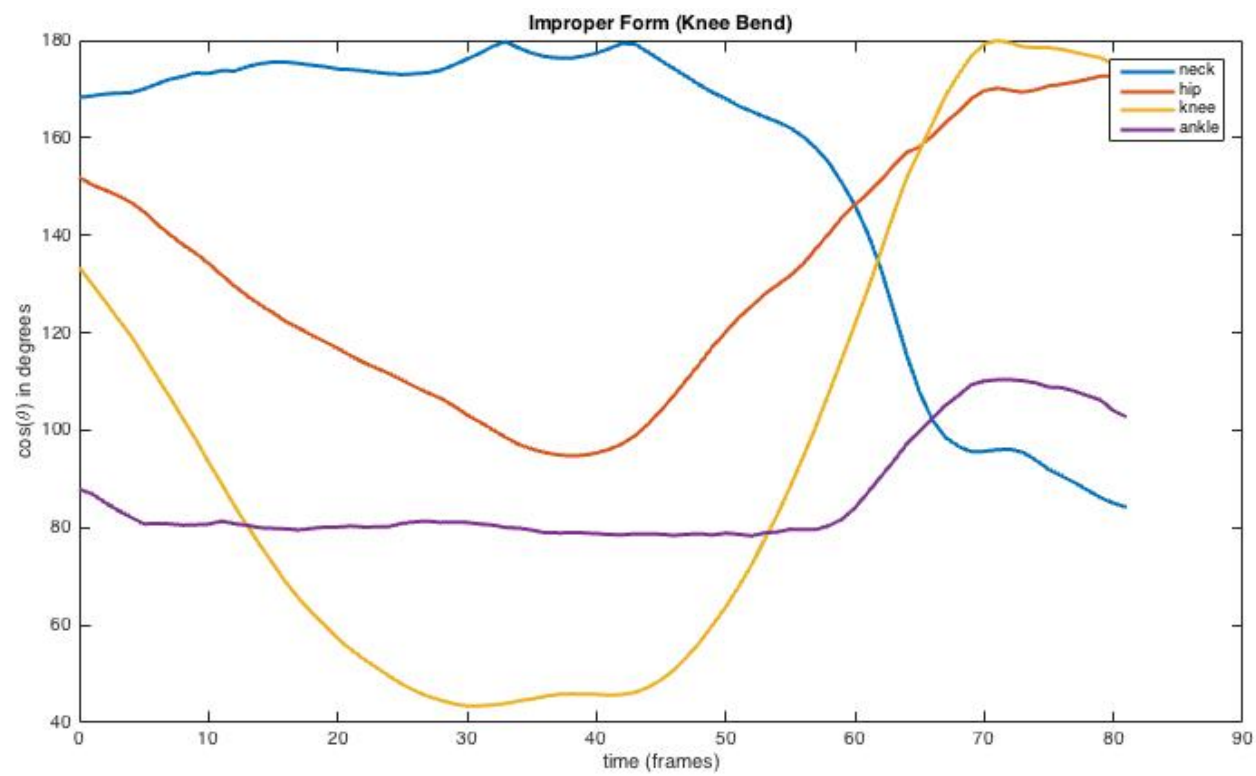
Upon running test for each video of various forms and mistakes, I found that the angles related to the ankle and neck were not needed to see errors in the form. Looking at the angles produced from the knee and hip joints, I could derive the common mistakes listed earlier. Given the data of the 6 participants the following values were produced. The start angles for the knee consistently were $150 - 160°$, while for the hip they were $160 - 170°$. The variation for the min $\theta$ are listed in the chart below:

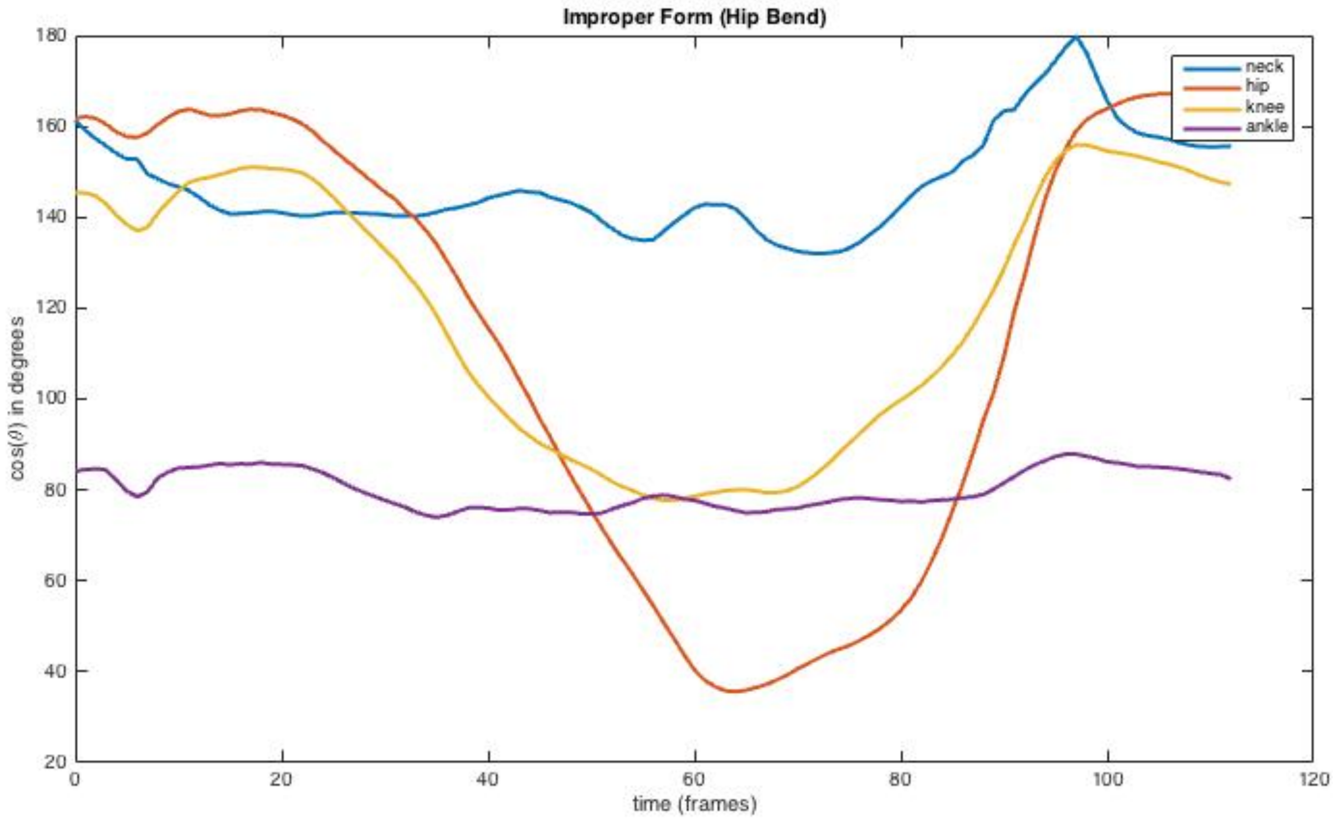
| **Form Quality** | **Joint** | **Min Angle** |
|---|---|---|
| Proper | Knee | $80 - 85°$ |
| | Hip | $55 - 65°$ |
| | | |
| Improper - | Knee | $40 - 50°$ |
| Knee Bend | Hip | $80 - 90°$ |
| | | |
| Improper - | Knee | $80 - 90°$ |
| Hip Bend | Hip | $30 - 40°$ |
| | | |
| Improper | Knee | $90 - 105°$ |
| - Depth | Hip | $70 - 80°$ |

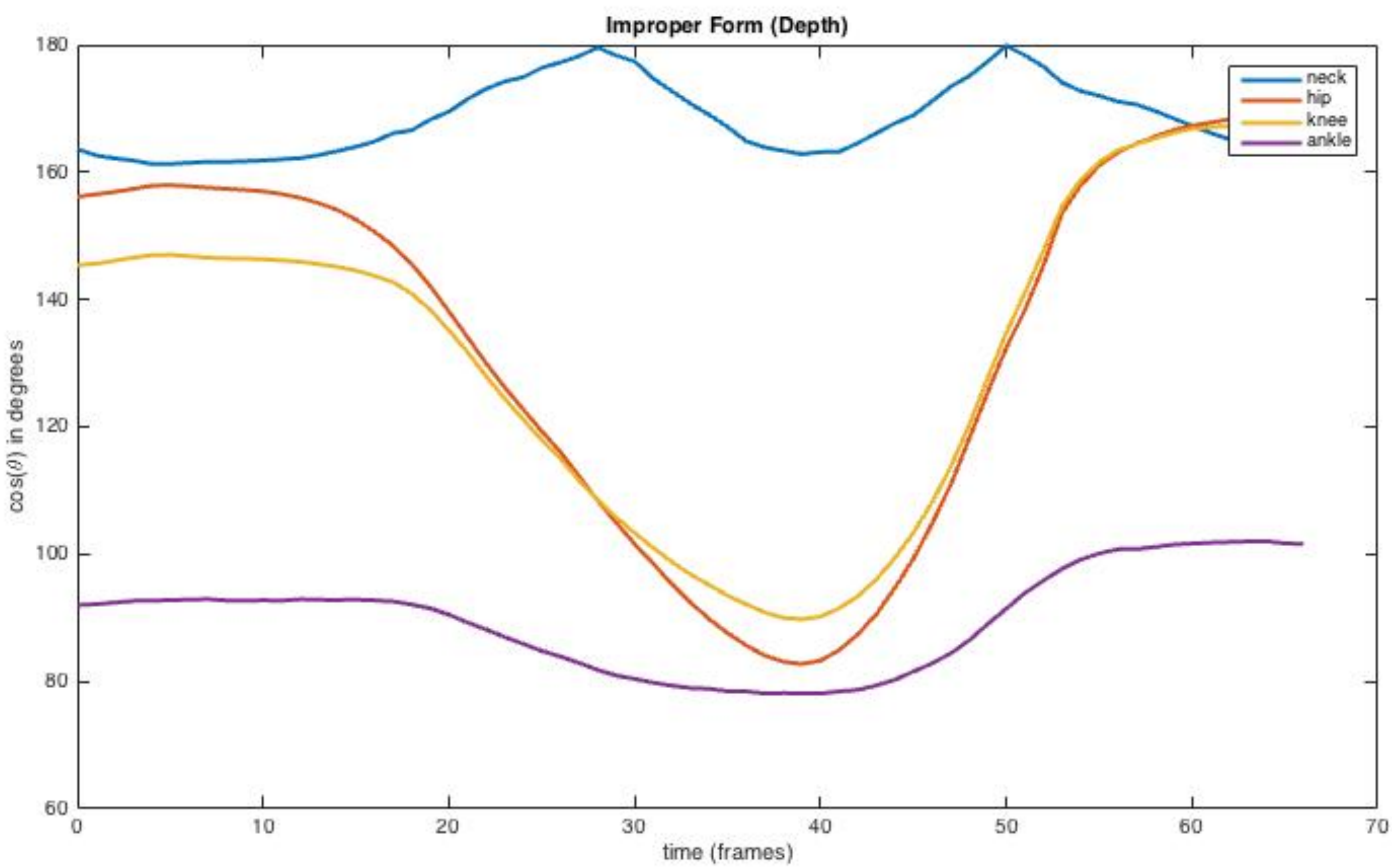
[16] (Kritz 2009)

## 5.6 Results:


Proper Form
X: 0
Y: 178.2
neck
hip
knee
ankle
cos(θ) in degrees
time (frames)
180
160
140
120
100
80
60
40
0
20
40
60
80
100
120


Improper Form (Knee Bend)
neck
hip
knee
ankle
cos(θ) in degrees
time (frames)
180
160
140
120
100
80
60
40
0
10
20
30
40
50
60
70
80
90


Improper Form (Hip Bend)
neck
hip
knee
ankle
cos(θ) in degrees
time (frames)
180
160
140
120
100
80
60
40
20
0
20
40
60
80
100
120


Improper Form (Depth)
neck
hip
knee
ankle
cos(θ) in degrees
time (frames)
180
160
140
120
100
80
60
0
10
20
30
40
50
60
70

# 6. Lifting Analysis

### 6.1 Modeling
With the data recorded, I attempted several ways to track whether or not form was broken. The first idea considered was a ratio of the angle between the knee and hip as the movement is done. While this was promising at first because it recognized valid form, it failed to notice the subtle differences that occur between different forms, such as depth required.

The next approach was to look at the angles at various times and compare. For example, once the knee broke past 90°, I would look to see what acceptable angles for the hip to achieve. This failed to recognize all faults in form because the hip or knee angle could cause error at anytime.

The final approach was to check for the data in multiple facets. First, making sure that certain angles were achieved during the lift for both the knee and hip. Also, the overall change in angle from start to finish was tracked to see if the range of motion exceeded an accepted threshold.

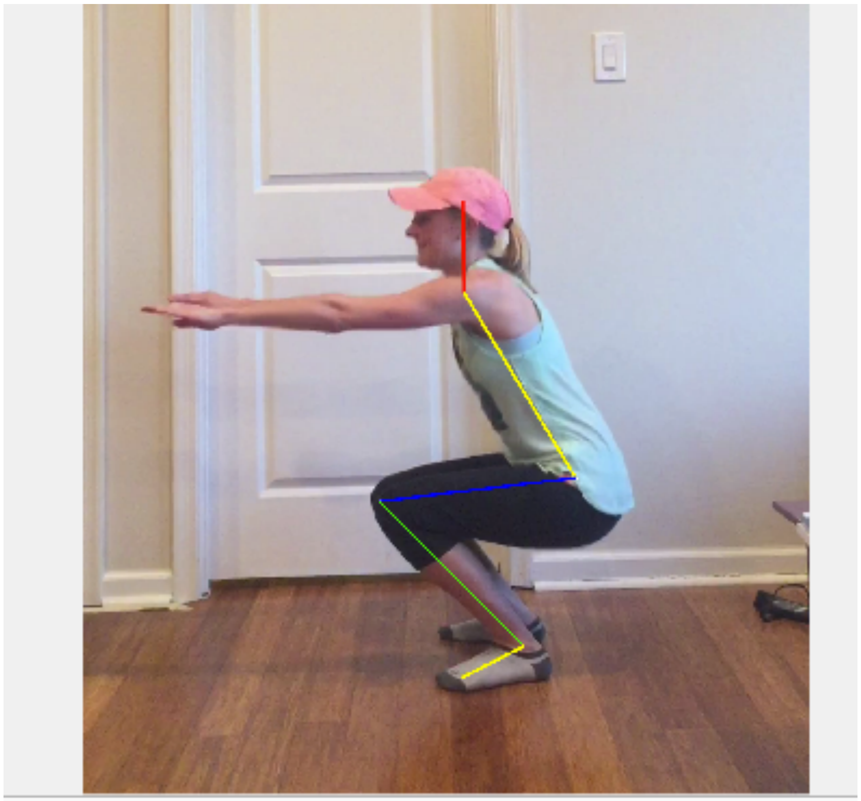
### 6.3 Output
The output is based off the model described above. The mistakes that are made during the movement are tracked after all the data has been collected from the video and tested against what is considered valid to my model. The output consists of two parts. The first part is the mistakes that I have isolated, and the second recommendations on how to improve your current form[17].

### 6.4 Example Output
Program output:

[17] (Staff. 2010)

Mistakes:

Bending at knees too much
Suggested Drills:
Bar-Holds



# 7. Summary & Future Work

## 7.1 Summary

The goal of this project was to create software that could recognize faults in someone's squat form. Through the use of MATLAB's computer vision tools, I analyzed the form of 6 individuals with varying experience levels. By selecting key joints involved in the squat I was able to accurately track the angles that are crucial to correct form. These angles are then tracked and evaluated to see if the user has made any faults. If mistakes are made they are reported to the user.

This proved that we could accurately extract the qualities of the squat that determine if the movement is correct. Below I have outlined some features that could be added to help improve the quality of the results in the future.

**7.2 Auto-detection**

Currently, the system works by the user inputting the points in a specified order. This was a major slowdown in the project as with each recording input was needed from the user.

In the future, it would be would be much easier for a user to have the key points for the angle calculations be picked automatically. Ideas for this detection could be to implement a skeletal analysis tool for Computer vision tools.

**7.3 Force Calculation**

Another area missed by my project is the force that is being put on the joints. The force is what actually leads to the injuries and thus tracking the force on all joints would be very useful information to have.

Possible ways to implement this could be to have the user wear sensors that allow you to track the force applied throughout the joints. With the recent increase in wearables, this option is a promising next step.

**7.4 UI/Interface & OpenCV Conversion**

To make the project more portable, I recommend the analysis be ported to OpenCV. This would allow the project to run on a webserver and also increase the speed at which the computation is done. With this a UI could be made to allow users to upload their videos, and track their progress as they progress through learning to squat.

# 8. Figure Reference

Figure 1: Staff., Glassman G and. *CrossFit Level 1 Training Guide.* 05 2010. http://library.crossfit.com/free/pdf/CFJ_2015_OctoberComp.pdf (accessed 03 22, 2016).

Figure 2: Kritz, Matthew. "The Bodyweight Squat: A Movement Screen for the Squat Pattern." *Strength and conditioning journal* 31, no. 1 (02 2009): 76.

Figure 3: Kritz, Matthew. "The Bodyweight Squat: A Movement Screen for the Squat Pattern." *Strength and conditioning journal* 31, no. 1 (02 2009): 76.

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