2-D Video Analysis for Tracking the Trajectory of a Barbell

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***Abstract*—This paper proposes a method to analyse the barbell trajectory in the barbell back squat using 2-D optical video analysis and feature tracking techniques. This approach aims to provide a detailed analysis of barbell trajectory and provide an assistive visual overlay to help athletes and coaches better understand the movement patterns during the squat, using more accessible technologies than those currently available. This method uses a combination of image analysis algorithms to detect and track the movement of the end of the barbell in side-on video footage. The results indicate an average deviation of 3.91 pixels, a standard deviation of 1.90 pixels, a maximum deviation of 9.85 pixels, and a failure rate of 0.00%. Additionally, a Pearson's correlation coefficient of 1.00 with a p-value of 0.00, demonstrating high accuracy and reliability. This method improves existing techniques and offers a more accessible and cost-effective solution for analysing weightlifting techniques.**

***Index Terms*—Barbell trajectory analysis, Bar path, Weightlifting technique, Feature tracking, Hough Circle Transform, Lucas-Kanade optical flow, Athletic performance analysis, Squat biomechanics**

I. Introduction

Weightlifting is a discipline that requires precise technique to maximise athletic performance while also minimising the risk of injury to an individual. A critical aspect of technique across all weightlifting movements, such as the barbell back squat, is the path the barbell follows throughout the lift. Analysing the barbell's path and critical metrics like the barbell's velocity can provide invaluable insight into an athlete's technique [1] and the intensity of a lift [2].

Studies have shown that one of the common causes of injury amongst professional powerlifting athletes is their technique [3], so perfecting an athlete's technique can limit their risk of injury. Focusing specifically on the barbell back squat, the bar's trajectory provides some vital insights into an athlete's technique. When performing a squat, one of the most important aspects of the technique is ensuring that the barbell remains balanced by keeping the bar's trajectory and centre of gravity moving in line with the athlete's mid-foot [4]. For an individual performing a squat movement, it is not easy to visualise the barbell's trajectory and its alignment to the mid-foot.

Current methods of analysing the weightlifting technique rely on subjective visual assessments or complex and expensive motion capture systems. These methods are impractical for athletes and coaches and create a barrier to perfecting an individual's weightlifting technique. Advances in image processing and video capture technology present new opportunities and techniques for detailed barbell trajectory analysis.

This paper proposes a method to analyse barbell trajectory in the back squat using video analysis and feature tracking techniques, specifically utilising a combination of image analysis algorithms to track the movement of the barbell in side-on video footage. This approach aims to provide a detailed analysis of barbell trajectory and provide an assistive visual overlay on video to allow athletes and coaches to clearly understand the alignment and movement patterns. Through a visualised trajectory, this method helps identify deviations from optimal technique, assisting in injury prevention and performance enhancement.

II. Background

A. Understanding the Biomechanics of the Squat

The barbell back squat is one of the fundamental strength training exercises known for its effectiveness in building lower body strength and training a wide range of muscles in the lower limbs. It is also an integral component of both competitive weightlifting and powerlifting and is widely regarded as a supreme test of lower-body strength [5]. Proper technique is integral to maximising performance and reducing injury when performing a squat movement. For more advanced athletes who have the other aspects of the back squat technique mastered, the barbell trajectory can highlight and visualise any inefficiencies with their movements. Figure 1 shows the ideal trajectory.

The barbell back-squat begins with the lifter upright, knees and hips at full extension. The barbell is placed horizontally across the lifter's upper back. By flexing the knee, ankle, and hip joints, the lifter squats down to their desired bottom position. From here, the lifter returns to the top position through the reverse movement, recruiting muscles such as the quadriceps femoris, hip extensors, hip adductors and abductors, and triceps surae [6].

B. Importance of Barbell Trajectory

The trajectory of the barbell during the squat is an essential indicator of the technique quality. Ideally, to keep the lifter

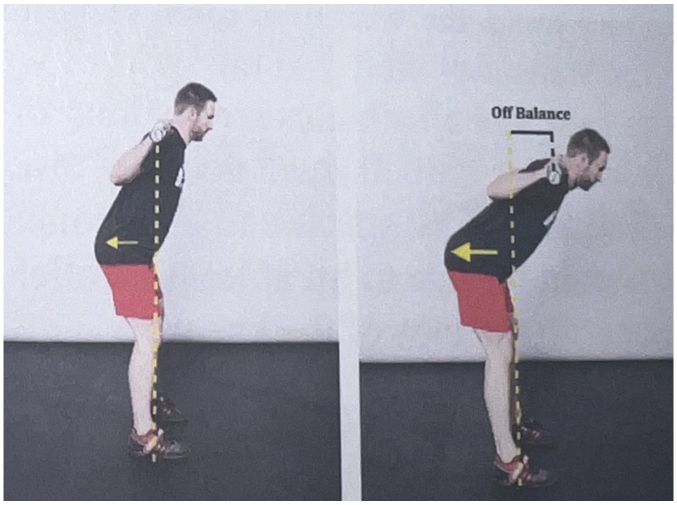

Fig. 1. The ideal trajectory of a barbell during the back squat, demonstrating how an athlete becomes off balance when the trajectory deviates from the vertical path. Reproduced from [4].

in a stable and balanced position throughout the motion, the barbell trajectory must travel vertically over the athlete's mid-foot, keeping the centre of gravity stable. This is pictured in Figure 1.

Deviations from this path can be indicative of technique issues such as:

- **Forward or Backward Tilt:** This can lead to a loss of balance and incorrectly place the centre of pressure, potentially placing unnecessary strain on the joints and musculature.
- **Knee Valgus:** Where the knees collapse inward during the ascent phase of the movement, increase the risk of knee and joint injuries.
- **Hip Shooting:** Where the athlete attempts to extend at the knee without a complimentary hip joint extension. Leading to potential loss of balance and strain on the lower back.

C. Visual Assessment by a Coach

Several approaches are currently employed to analyse an athlete's squat technique, each with advantages and limitations. The simplest is a visual assessment by a coach. Using their expertise, a coach can visually evaluate an athlete's technique to determine where they can improve. However, this is inherently subjective and lacks quantitative precision. It also lacks the ability for an athlete to see and understand their own technique issues visually.

D. 3-D Camera Based Capture Systems

3-D camera-based capture systems are a highly reliable method of capturing barbell trajectory, providing precise and comprehensive data of an athlete's movement pattern [7]. These systems use multiple 3-D cameras positioned strategically around the lifting platform to capture the squat from different angles. These 3-D cameras often work by tracking specialised reflective markers on the end of the barbell, as shown in Figure 2.

Fig. 2. Reflective markers placed on the end of a barbell for a 3-D motion tracking system. Reproduced from [8].

This data is processed using specialised software to create a detailed, three-dimensional model of the barbell's trajectory. The 3-D camera-based tracking systems are proven and effective, providing a solid basis for camera-based system accuracy [7] [8].

However, the high cost and complexity of these systems limit their accessibility. A significant initial investment is required to obtain specialised 3-D cameras, reflective markers, high-powered computers and software. These systems also require controlled environments and technical expertise to operate and use the data. These factors make the 3-D motion capture systems impractical for most athletes and coaches operating in typical training settings, restricting their use to elite training facilities and research institutions.

E. Physical Measurement Systems

Another approach exists for measuring the trajectory of barbells using physical measuring devices. One of these devices is the Linear Position Transducers (LPTs), which attach a cable to one end of the barbell and measure variables using a rotary encoder[9]. This device is a cost-effective and accurate method of tracking barbell kinematics. However, as the device works through a single cable attached to the barbell, data can only be captured in one dimension [10]. So, while helpful in capturing velocity data, the LPT will not suffice for measuring barbell trajectory. An alternative approach is on-barbell inertial sensors. These are placed on the end of the barbell, and through their on-board sensors, the movement of the barbell is recorded. These devices can record data in 3-dimensions, making them a better candidate for measuring the trajectory of the barbells. However, studies have shown that they do not possess practically acceptable reliability or accuracy [11].

F. 2-D Video Based Capture Systems

2-D-based capture systems utilise standard video camera footage to record and analyse the back-squat movement. This offers a practical and accessible alternative to the more complex and expensive 3-D systems. These systems can effectively capture the trajectory of a barbell, providing valuable data for technique analysis. Studies have shown that 2-D video analysis provides sufficient accuracy compared to 3-D analysis systems [8]. 2-D capture systems record the squat from a lateral perspective, allowing the camera to track the vertical and horizontal movements of the barbell. As the analysis in this method is done based on video post-analysis, any device capable of recording high-quality video footage is suitable. When done correctly, video analysis to calculate a barbell trajectory achieves similar accuracy to physical devices, such as the LPT's [12].

G. Tracking the Barbell

Multiple methods are available to track the path of the barbell in the lateral squat footage. One option is to place a distinctive coloured marker on the end of a barbell, which the software can then track. However, this can add an additional barrier to entry and lower the accessibility of the tracking solution to individuals who cannot get this marker. It is feasible to track the barbell without a distinctive marker, using some features standard to weighted barbell back-squats. Most squats athletes perform use circular, weighted plates placed on the end of the barbell. These plates are typically of a standardised size and can be of unique colouring. The size and colours of the barbell end can then be used for tracking [8] [13].

To track the movement of the barbell within the captured video, the Kanade-Lucas-Tomaso (KLT) algorithm can be used [8]. However, this requires strong feature selection, which is not always possible when viewing a barbell from a lateral angle. Other methods use a region of interest (ROI) to find the centre of the barbell, which can be calculated and tracked between frames to create a barbell trajectory [13].

H. Limitations of Prior Research

Across the current literature studying the trajectory and kinematics of barbell movements, there is a lack of studies regarding the barbell back squat. The research is skewed heavily towards the Olympic weightlifting movements like the snatch and clean-and-jerk. For these studies, a lot of barbell trajectory analysis is done using expensive 3-D motion capture systems and intrusive mechanical measurement systems. Of the studies performed investigating the validity of 2-D video analysis techniques, more investigation needs to be done into the practical application of the result findings and how individuals can use barbell trajectory tracking in their training.

III. Method

A. Overview

The proposed method uses various techniques to identify and track the barbell's trajectory through video footage. The user will select a ROI bounding box around the barbell's end, from which a circle detection algorithm will detect and calculate the position of the barbell end's centre. From this, an optical flow tracking algorithm can be used to track this key point movement through the footage, and a line showing the barbell's apparent trajectory can be superimposed on the footage.

B. Barbell End Detection

To track the barbell's trajectory, it must first be established where the end of the barbell is, generating a trackable feature. As a gym environment often contains multiple barbells and weights that may be visible on the camera footage, a ROI must be selected around the end of the barbell of interest. Using the fact that the end of a barbell is always circular, the Hough Circle Transform can be employed for detection [14]. This method works to identify circular shapes based on edge detection and geometric properties. The ROI is first converted to grayscale, and a Gaussian blur is applied. This works to reduce noise and enhance edge detection. The Gaussian function is defined as:

$$G(x,y) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}} \tag{1}$$

From here the Hough Circle Transform can be applied. It works using the parametric representation of a circle, defined as:

$$(x-a)^2 + (y-b)^2 = r^2 \tag{2}$$

The Hough Circle Transform algorithm works using voting in a 3-D accumulator space to find potential circle centres and radii, which, based on several parameters, only specific circles of the expected size of a barbell end will be highlighted. The detected barbell end can now be visualised as shown in Figure 3, which was found using the above calculations.

C. Barbell End Tracking

Once detected, the end of the barbell's movement can be tracked across frames in the video using the Lucas-Kanade optical flow method [15]. This algorithm calculates the displacement of a feature point between consecutive frames based on the assumption that the flow is essentially constant in the small region surrounding each pixel. The Lucas-Kanade method is derived by minimising the error function:

$$E = \sum_i \left[I(x_i+u, y_i+v, t+1) - I(x_i, y_i, t) \right]^2 \tag{3}$$

where I is the image intensity, (x_i, y_i) are the coordinates of the feature point, and (u, v) are the flow vectors to be estimated.

Fig. 3. The detected circles within the selected ROI found using the Hough Circle Transform.

The method involves solving the following system of equations for each point:

$$\begin{bmatrix} \sum I_x^2 & \sum I_x I_y \\ \sum I_x I_y & \sum I_y^2 \end{bmatrix} \begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} \sum I_x I_t \\ \sum I_y I_t \end{bmatrix} \tag{4}$$

where I_x and I_y are the image gradients in the x and y directions, respectively, and I_t is the gradient in time.

This allows the trajectory of the barbells end to be tracked across frames in a video, from which coordinate data and other metrics can be calculated and visualised for squat technique analysis, as shown in Figure 4.

IV. Results

The results generated in this paper were produced using the following system specifications:

Device:

- **Model:** 2021 14-inch MacBook Pro
- **Processor:** Apple M1 Pro
- **Speed:** 3.2 GHz (8-core CPU)
- **OS:** macOS Sonoma 14.5
- **IDE:** NeoVim
- **Programming Language:** Python 3.10

Camera:

- **Resolution:** 1080p
- **Frame Rate:** 30 FPS

Software:

- **OpenCV Version:** 4.9.0
- **Numpy Version:** 1.26.4

To evaluate the accuracy of the barbell tracking, the tracked path was compared against manually marked ground-truth

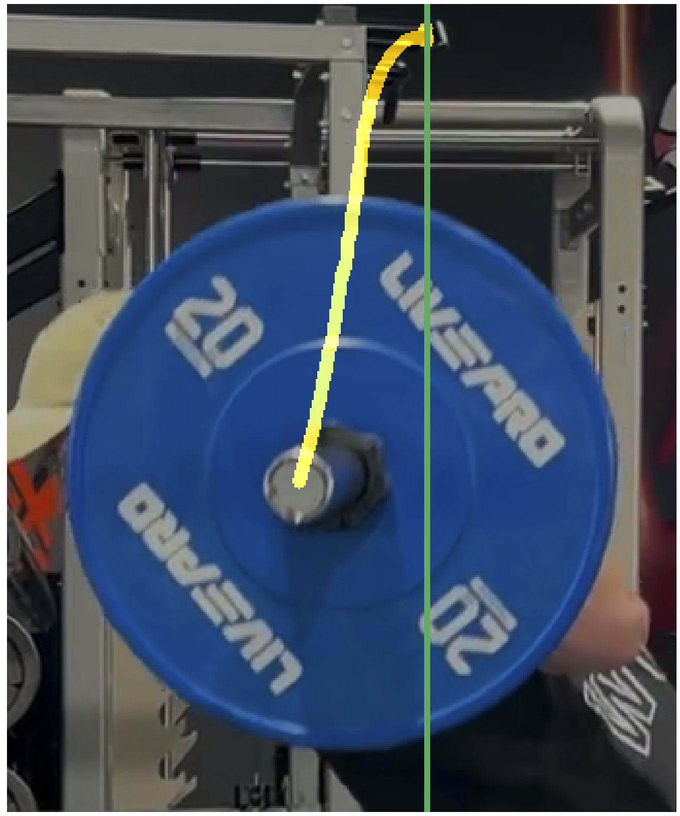

Fig. 4. The tracked trajectory of the barbell, as calculated by the Lucas-Kanade optical flow method.

points in the video frames. The average deviation between the tracked points and the ground truth was measured in pixels. Metrics were calculated for Average Deviation, Standard Deviation, Maximum Deviation and Failure Rate to determine the accuracy of the tracking algorithm compared to the manually marked points. These results were captured across ten separate squat videos, and the average results are shown below in Table I.

TABLE I
AVERAGE TRACKING METRICS ACROSS 10 SQUAT VIDEOS COMPARED TO THEIR MANUALLY MARKED COUNTERPARTS.

Metric	Average Value
Avg. Deviation (pixels)	3.91
Std. Deviation (pixels)	1.90
Max Deviation (pixels)	9.85
Failure Rate (%)	0.00
Avg. Stability (pixels)	6.26

A. Metric Explanation

For the metrics shown in Table I, the deviation measures the distance between the automatically tracked points and the ground-truth points in pixels. The Standard deviation gives the average deviation between the points. The maximum deviation gives the most significant recorded distance between the points. The failure rate is the percentage of points for which the deviation is above 10 pixels in distance. The average stability is the average distance between consecutive tracked points.

B. Pearson's Correlation Coefficient

Pearson's product-moment correlation coefficient was calculated between the manually and automatically tracked points. This correlation coefficient was 1.00 with a p-value of 0.00, indicating a perfect positive linear relationship and strong statistical significance.

V. Conclusion

The method demonstrated an average deviation of 3.91 pixels, a standard deviation of 1.90 pixels, and a maximum deviation of 9.85 pixels, with a failure rate of 0.00%. This indicates a high accuracy and reliability in tracking the barbell's trajectory.

Compared to prior research, these results show an improvement over previous studies in terms of correlation between the automatically tracked points and those tracked through more accurate systems. Using a similar optical tracking method, Balsalobre-Fernández et al. [16] reported a Pearson's correlation coefficient ranging from 0.792 to 0.902 with all p-values less than 0.001. This method achieved a Pearson's correlation coefficient 1.00 with a p-value of 0.00, indicating a perfect positive linear relationship between the manually and automatically tracked points. This would suggest that this tracking algorithm is more accurate and consistent than previous methods.

A study by Achermann et al. [13] showed their optical tracking method to have a Pearson's correlation coefficient of 0.83. This method outperforms these trackers in terms of consistency and accuracy. Another study by Nagao et al. [8] utilised a Bland-Altman plot and regression to examine the agreement between their methods. They reported intraclass correlation coefficients ranging from 0.971 to 0.999. Their Bland-Altman plot showed a slight bias of -0.001m to 0.001m, suggesting a similar level of agreement as the one found in this study.

A. Limitations of Research

1) **Camera Angle and Positioning:** Variations in camera angle or positioning can impact the accuracy of the detected trajectory, as the method assumes a consistent side view of the lift. It also assumes the camera is positioned in a fixed position on a tripod. The changing of angles may also impact the ability of the Hough Circle transform to detect the barbell's end.
2) **Accuracy of Manual Marks:** The automatically tracked points are being compared against a set of manually marked points, which, while generally accurate, are not necessarily a perfect estimation of the centre of the barbell in every frame.
3) **Frame Rate:** The accuracy of this tracking is heavily dependent on the frame rate of the video footage. A lower frame rate may result in less precise tracking, especially for fast movements.
4) **Lack of Video Analysed:** The data in this study was captured by recording ten repetitions of a body-weight squat by one individual. Due to the lack of diversity in lighting and environmental conditions, the tracking algorithm may perform differently in different settings.

B. Future Research Opportunities

By addressing these areas, future work can help to enhance further the accuracy and reliability of 2-D optical barbell trajectory tracking, making it a more effective and accessible tool for analysing and improving squat technique.

1) **Robustness to Camera Angle Variations** As this algorithm relies very heavily on the camera footage being perfect lateral footage, with the camera placed in the middle of vertical travel, improvement could be made to increase the algorithm's robustness. If the camera angle is not straight on, then the detection of the barbell end is impacted. Implementing a Perspective Transform algorithm could help improve the footage range that this algorithm will work on.
2) **Accuracy of Manual Marks:** The automatically tracked data in this study is compared against manually marked ground-truth data of the centre of the barbell. While all measures were taken to ensure that it was generally accurate, perfection can not be guaranteed. Implementing a different method of collecting ground truth, such as using an advanced 3-D capture analysis system, would help further prove this algorithm's validity and reliability.
3) **Frame Rate:** The optical tracking of the barbell end relies heavily on the frame rate of the recorded footage, as the Lucas-Kanade optical flow works frame-to-frame. Exploring techniques to improve tracking accuracy across videos with lower frame rates could be explored. This would help to increase accessibility to the system and ensure robustness across different recording setups.
4) **Lack of Video Analysed:** The tracking algorithm must be further tested in various environments and lighting conditions to ensure its robustness and accuracy. Collecting and analysing more data from multiple individuals performing squats across variable conditions will provide a more comprehensive validation of the tracking algorithm.

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