Dynamic Form Tracking: Advanced Pose Estimation in Gymnastics

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ABSTRACT

This project pioneers a novel approach to gymnastics training and performance analysis through advanced pose estimation technology. Targeting gymnasts, coaches, programs, and researchers, the application aims to address key challenges in gymnastics training, including limited visibility, subjective evaluation, injury prevention, and performance optimization. Leveraging deep learning algorithms and high-resolution cameras, the system tracks dynamic movements and forms in real-time, providing precise feedback and performance metrics. Previous methods relying on manual observation and subjective scoring systems are surpassed by this objective and data-driven approach. Drawing from related work in sports analysis, biomechanics, and gymnastics research, the project promises to revolutionize training methodologies. Evaluation will involve diverse test conditions and user feedback, aiming for accuracy, reliability, and usability. Success will be measured by improved athlete performance and objective assessment of gymnastics techniques. Through iterative refinement, this project seeks to establish itself as a cornerstone in gymnastics training and performance analysis.

1 Introduction

A. Background (Idea/Application)

1. Purpose

This project aims to investigate a novelty approach to gymnastics training and performance analysis. By using pose estimation technology, the outcome of the project might provide coaches and athletes with precise and real-time tracking of dynamic movements and forms, enabling valuable insight into technique, execution, and performance. By delivering detailed visual feedback and individual performance evaluations, the application empowers coaches to tailor training programs and interventions while enabling athletes to optimize their skills and reach peak performance. This innovative sports technology not only enhances coaching methodologies but also provides a competitive edge to gymnastics programs and organizations, positioning them as leaders in athlete development and performance excellence.

2. Target audience / User population:

Gymnasts: Athletes who participate in gymnastics training and competitions, seeking to improve their skills, technique, and performance.
Coaches: Gymnastics coaches who are responsible for training and guiding athletes and require tools and insights to evaluate technique, provide feedback, and tailor training programs.
Gymnastics Programs and Organizations: Institutions, clubs, and organizations involved in gymnastics training, development, and competition management seeking innovative technologies to enhance athlete performance and program effectiveness.
Sports Scientists and Researchers: Professionals and academics in the fields of sports science, biomechanics, and human movement analysis who are interested in studying and advancing knowledge in gymnastics techniques, performance, and training methodologies. Technology Developers and Innovators: Engineers, developers, and entrepreneurs interested in developing and commercializing sports technology solutions, including pose estimation systems, performance analysis tools, and coaching platforms for gymnastics and other sports disciplines.

In summary, the target audience includes a diverse range of professional personnel involved in gymnastics training, coaching, research, and technology development, all of whom stand to benefit from the insights, tools, and capabilities offered by our advanced pose estimation tool.

3. The need for that application

- Limited Visibility During Training: Gymnastics coaches often face challenges in accurately assessing their athletes' form and technique during training sessions. With complex movements and high-speed actions, it can be difficult to observe and analyze subtle movements in real-time, leading to potential errors in feedback and coaching.
- Subjectivity in Performance Evaluation: Traditional methods of performance evaluation in gymnastics rely heavily on subjective judgment, which can vary among coaches and may be influenced by biases or personal preferences. Objective metrics and quantifiable data are needed to complement subjective assessments and provide a more comprehensive understanding of athletes' abilities.
- Injury Prevention and Rehabilitation: Proper form and technique are critical for preventing injuries and promoting long-term health and safety in gymnasts. By accurately tracking dynamic movements and identifying biomechanical imbalances or compensatory patterns,

coaches and medical professionals can intervene early to address potential injury risks and support rehabilitation efforts.

- Performance Optimization and Skill Development: Athletes strive to continually improve their skills and performance levels in gymnastics, requiring detailed feedback and targeted interventions to address weaknesses and optimize technique. Advanced pose estimation technology offers insights into movement quality, alignment, and execution, facilitating skill refinement and performance enhancement.
- Competitive Edge in Training and Competition: Gymnastics programs and organizations seek to maintain a competitive edge in training and competition by adopting innovative technologies and methodologies to enhance athlete development and performance.

4. Previous approaches

Previous approaches to assessing form and technique in gymnastics have typically relied on manual observation by coaches, video analysis, and subjective scoring systems. Coaches observe athletes during training sessions and competitions, providing feedback based on visual cues and their own expertise. Video analysis software may be used to review footage of routines, allowing coaches to identify areas for improvement and track progress over time. Subjective scoring systems, such as judging criteria in competitions, evaluate athletes based on factors like execution, difficulty, and artistry. While these approaches offer valuable insights, they are often limited by human error, variability in judgment, and the inability to provide real-time feedback. Additionally, they may lack the precision and objectivity needed to effectively assess complex movements and dynamic forms in gymnastics. The project addresses these limitations by leveraging advanced pose estimation technology to provide accurate, objective, and data-driven assessments of form and technique in real-time, enhancing coaching effectiveness and athlete performance.

2 Related Work

Pose Estimation in Sports Analysis: Previous research has explored the use of pose estimation techniques in sports analysis, including activities such as soccer, basketball, and weightlifting. These studies have demonstrated the feasibility of tracking athletes' movements and poses to analyze technique, performance, and injury risk factors.

Gait Analysis and Biomechanics: Gait analysis research has investigated the use of computer vision and motion capture systems to analyze human movement patterns during walking, running, and other locomotion activities. These studies have provided insights into gait parameters, kinematics, and kinetics relevant to sports performance and rehabilitation.

Sports Performance Monitoring: Various systems and technologies have been developed for monitoring sports performance, including wearable sensors, motion capture systems, and computer vision-based approaches. These systems aim to provide athletes and coaches with real-time feedback, performance metrics, and training insights to optimize athletic performance and reduce injury risk.

Skill Assessment in Gymnastics: Research in gymnastics has explored methods for assessing skill proficiency, technique quality, and form accuracy using subjective scoring systems, biomechanical analysis, and video-based techniques. These studies have identified key factors influencing gymnastics performance and provided guidelines for skill development and training optimization.

3 Experimental Platform

Equipment to be Used:
High-resolution cameras capable of capturing gymnastics movements from multiple angles.
Computer hardware with sufficient processing power to run real-time pose estimation algorithms.
Motion capture systems for generating ground truth data for validation.
Algorithms and Data Structures:
Pose estimation algorithms based on deep learning architectures such as convolutional neural networks (CNNs) or recurrent neural networks (RNNs) from **OpenPose**.
Data structures for representing key body points, joint angles, and movement trajectories extracted from the pose estimation results.
Dataflow:
Image Input: Gymnastics photo captured from the camera are input into the pose estimation system.
Pose Estimation: The pose estimation algorithms analyze image to detect and track key body points.
Data Processing: Extracted pose data, including joint positions and movement trajectories, are processed and stored for further analysis.
Visualization: Processed pose data are visualized using interactive tools and overlays to provide real-time feedback to coaches and athletes.
Analysis and Reporting: Pose data are analyzed to evaluate form, technique, and performance metrics, generating reports and insights for coaching and training purposes.
User Interface:
User-friendly interface designed for coaches and athletes to interact with the system during training sessions. Intuitive visualization tools display pose overlays, performance metrics, and feedback in real-time. Customizable features allow users to adjust settings, view different perspectives, and analyze specific aspects of gymnastics routines.

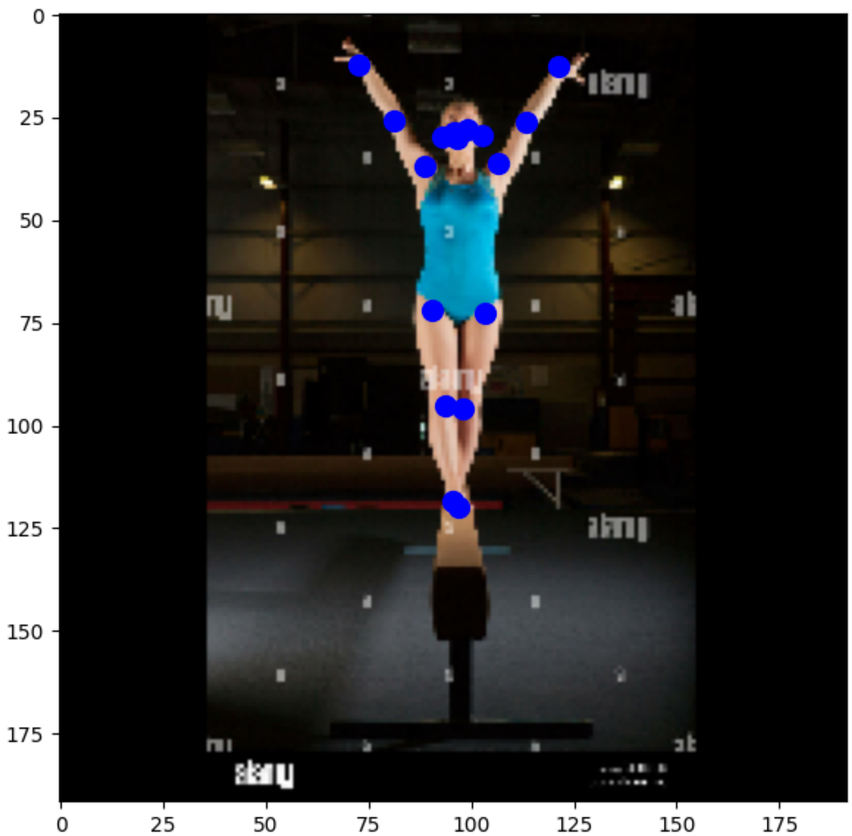


Figure 1: **Female gymnast standing on balance beam from pose estimation**.

(Image Credit: https://www.alamy.com/stock-photo-female-gymnast-standing-on-balance-beam-48946424.html.jpg)

4 Methodology

Gather a diverse dataset of gymnastics videos capturing various routines, exercises, and skill levels performed by gymnasts. Ensure the dataset covers a wide range of movements, angles, lighting conditions, and athlete characteristics to represent real-world scenarios. Train the pose estimation model on a subset of the annotated dataset and validate its performance on a separate validation set. Measure metrics such as joint detection accuracy, pose estimation error, and tracking consistency to assess the model's accuracy and reliability. Gather feedback from gymnastics coaches and athletes regarding the usability, effectiveness, and practicality of the method in gymnastics training and performance analysis. Incorporate user feedback into iterative improvements and refinements of the pose estimation system.

1. Defined as success

Success will be demonstrated by positive feedback from athletes regarding its effectiveness in enhancing athlete performance. Additionally, success will be measured by the tool’s ability to contribute to the objective measurement of gymnasts' performance, technique, and execution of movements.

2. Test conditions

The number of test conditions, including the complexity of gymnastics movements, the diversity of the dataset, and the specific objectives of the testing phase.

- Movement Complexity: Test the pose estimation performance across a range of gymnastics movements with varying levels of complexity
- Lighting Conditions: Evaluate the robustness to different lighting conditions, including bright indoor lighting, dim lighting, and variations in natural lighting (e.g., daylight, artificial light).
- Camera Angles and Perspectives: Test the ability to accurately track poses from different camera angles and perspectives, including frontal views and side views. Athlete Variability:
- Assess the performance across a diverse range of athletes with different body types to ensure generalizability and adaptability to various athlete characteristics.

3. Number of test subjects

The project plans to conduct testing with two real subjects representative of the gymnastics population.

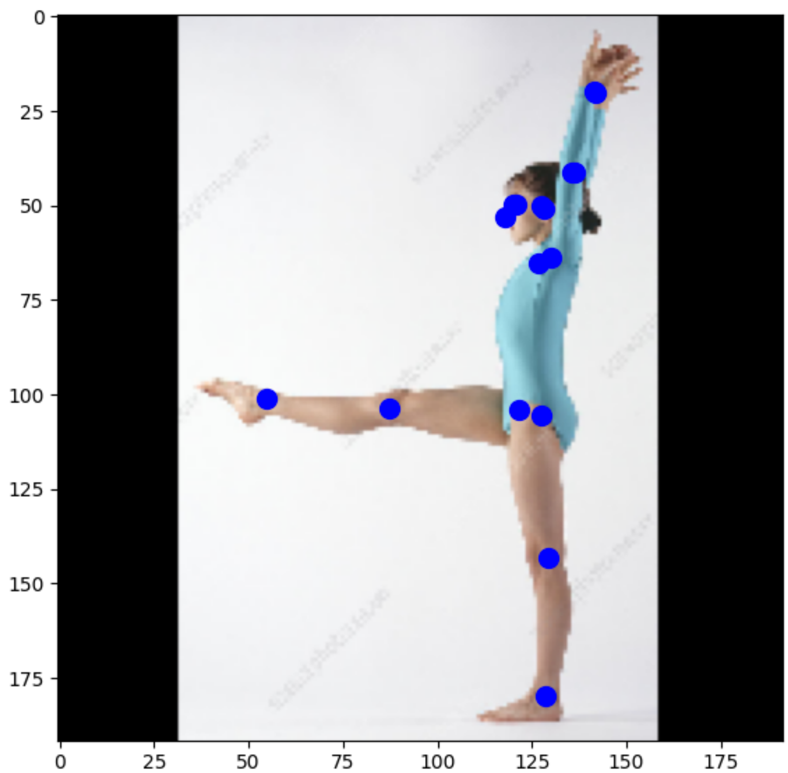
4. Evaluate your results

Quantitative Metrics: Calculate quantitative metrics to measure the accuracy of the pose estimation, such as joint detection error, pose estimation error, and tracking consistency. These metrics provide numerical assessments of the system's performance and can be compared across different test conditions and subjects.
Comparison with Ground Truth Data: Compare the tracked poses generated by the pose estimation system with ground truth data obtained through manual grading. Assess the level of agreement between the estimated poses and the ground truth poses to validate the tool's accuracy and reliability.
Visual Inspection: Conduct visual inspections of the tracked poses overlaid on the original gymnastics videos to identify any discrepancies or errors. Examine the quality and consistency of the tracked poses across different movements, camera angles, and lighting conditions.
User Feedback: Gather feedback from gymnasts regarding their perceptions of the pose estimation tool’s usability, practicality, and effectiveness in gymnastics training and performance analysis.

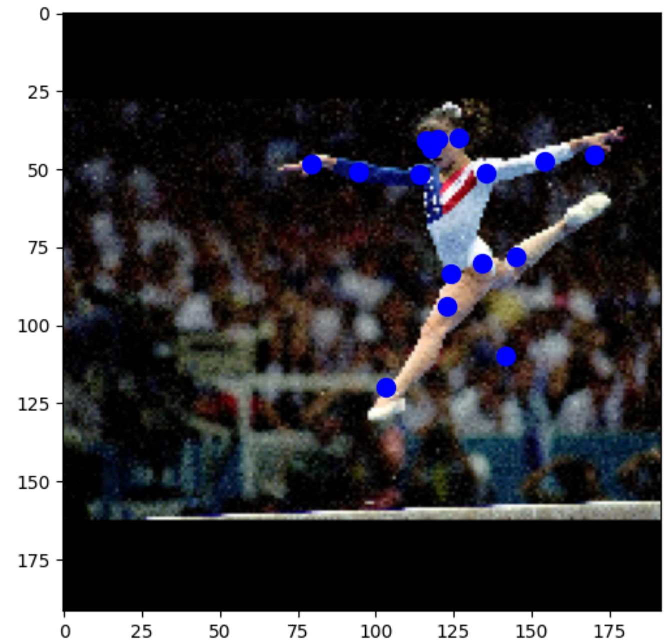
5. Improvement based on the results

Refine the pose estimation algorithms to improve accuracy, robustness, and reliability in tracking gymnasts' movements and forms. This may involve optimizing model architectures, refining feature extraction techniques, or incorporating additional data augmentation strategies to enhance performance under various conditions.

5 Results



(a)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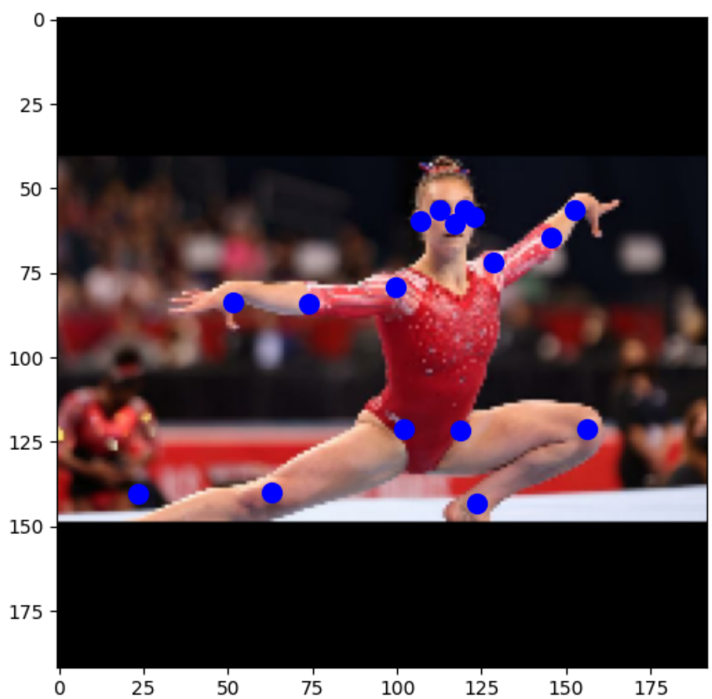
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(c)

Pose estimation, a crucial aspect of computer vision, relies heavily on accurate posture detection for various applications such as activity recognition and human-computer interaction.

However, the precision of pose estimation algorithms can significantly diminish ***if the subject's posture deviates from the frontal plane.*** In other words, when the body orientation isn't facing directly toward the camera or sensor, the system may struggle to accurately infer the position and orientation of key body parts. This limitation underscores the importance of ensuring that subjects maintain a frontal posture during pose estimation tasks, as it directly impacts the reliability and effectiveness of the algorithm's output.

Following interviews with former collegiate gymnasts, it became evident that there is a growing interest in integrating pose estimation technology into competitive gymnastics. Many athletes expressed optimism about the potential for pose estimation to enhance fairness in competitions, as it provides an objective means of evaluating routines and scoring performances.

After they saw the initial results, which showcased the technology's ability to offer more consistent and transparent assessments, they showed highly interested in this technology. Despite this optimism, it's acknowledged that errors still occur in the estimation process, potentially affecting the accuracy of scores. However, the pose estimation represents a significant step forward in modernizing and standardizing gymnastics judging, offering a promising foundation upon which to build fairer and more equitable competitions in the future.

6 Discussion

The results of the experiments conducted within the project provide valuable insights into the feasibility and efficacy of pose estimation technology in the context of gymnastics competitions. While the initial objectives aimed to leverage this technology to enhance fairness and objectivity in scoring routines, the outcomes present a mixed picture. On one hand, there were notable successes in utilizing pose estimation to provide more consistent and transparent assessments of gymnastic performances. Athletes and coaches expressed optimism about the potential for this technology to revolutionize judging practices, fostering a more equitable competitive environment.

However, it would be premature to claim a success, as the experiments also revealed certain limitations and challenges. One notable issue was the occurrence of errors in the estimation process, which could potentially impact the accuracy of scores.

These errors may come from various factors, including limitations in the algorithms and lack of complex poes in the train data, variations in lighting conditions, or complexities in capturing certain movements accurately. While these challenges present hurdles to overcome, they do not negate the overall potential of pose estimation in gymnastics judging. Instead, they emphasize the need for continued refinement and optimization of the technology. Moving forward, efforts could focus on improving data collection methodologies so that we can have more robust results.

7 Conclusion and Future Work

In summary, our work has focused on exploring the application of pose estimation technology in gymnastics competitions with the aim of improving fairness and objectivity in judging. Through a series of experiments and interviews, we have demonstrated the potential of pose estimation to provide more consistent and transparent assessments of gymnastic performances.

While our results have shown promising advancements toward achieving these objectives, challenges such as errors in the estimation process have highlighted areas for further refinement. Nonetheless, our work lays a solid foundation for the integration of pose estimation technology into gymnastics judging systems, offering a pathway towards modernizing and standardizing scoring practices in the sport.

Looking ahead, there are several potentials for future work that can build upon the findings of this project. Firstly, continued optimization of pose estimation algorithms is essential to improve the accuracy and reliability of scoring routines. This may involve refining existing algorithms, exploring novel machine-learning techniques, or integrating additional sensors to enhance data capture. Secondly, there is a need for comprehensive validation studies to assess the real-world performance of pose estimation systems in diverse gymnastics environments. By conducting rigorous testing under varying conditions and with a broader range of athletes, researchers can gain deeper insights into the robustness and generalizability of the technology. Additionally, efforts to develop user-friendly interfaces and tools for judges and coaches could facilitate the adoption of pose estimation technology in gymnastics competitions, ultimately enhancing the sport's competitiveness and appeal.

REFERENCES

[1] Lastname A., Lastname B., and Lastname C. Title of the paper. *Name of the journal*. Volume. Number. pp. 123–456. Year. Optional notes (e.g. “in French” or “See Fig. 7b.”).

[2] Lastname A. *Book title* (Publisher name. Publisher city and state/country. Month, Year). Edition if more than one edition. Optional Notes.

[3] Lastname A., Lastname B., and Lastname C. Title of a conference paper. In *Proceedings of the 123-th ABC International Conference on XYZ*. pp. 123–456. (City, State, Year). Notes.

[4] Lastname A., Lastname B, and Lastname C. Title of a book chapter. In *Title of an Edited Book* (Publisher name. Publisher city and state/country. Month, Year). pp. 123–456. Optional notes.

[5] Lastname, A. and Lastname B. *Title of a web page.* http://example.org/ (Date accessed).

[6] Lastname, A. *et al.* (use this for more than three authors). …

[7] Lastname, A. *Title of a technical report.* Institution. Identifier of the technical report. Year.

[8] Graduate S. *Title of a PhD dissertation.* Department name, University name. Year. Optional notes (e.g., “Chapter 3”).

APPENDIX B: Source Code

```
# Convert tensor to numpy for visualization
image_np = image.numpy()[0]
keypoints_np = keypoints.numpy()[0, 0]
print(keypoints_np)
height, width, _ = image_np.shape
# Draw the keypoints on the image
plt.figure(figsize=(10, 10))
plt.imshow(image_np.astype(np.uint8))
for kp in keypoints_np:
    plt.plot(kp[1]*width, kp[0]*height, 'bo',markersize=10)
```

APPENDIX C: Additional Resources

https://github.com/CMU-Perceptual-Computing-Lab