ADVANCING LUMBAR LOAD ANALYSIS: A COMPARATIVE LUMBAR BURDEN ANALYSIS TECHNIQUES AND PROPOSED CAMERA-BASED POSE ESTIMATION FRAMEWORK

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Abstract:

Accurate evaluation of lumbar loads stands as an essential requirement for both understanding lower back risks and injury prevention in occupational and clinical scenarios. This paper examines existing methods used to analyze lumbar burden while outlining their integration with modern human pose estimation algorithms. Precise measurements emerge from traditional methods like electromyography, finite element models, and wearable sensor systems yet their practical use faces challenges due to invasiveness, computational requirements, and placement sensitivity. Real-time human pose estimation has achieved advancements through methods like RTMPose, OpenPose and HRNet which offer non-invasive scalable solutions for real-time motion analysis. This paper reveals the advantages and shortcomings in both domains while identifying the value of integrating pose estimation frameworks with lumbar load analysis for better accuracy in real-world usage. The assessment reaches its conclusion by evaluating present roadblocks while suggesting future research agendas to combine motion tracking systems with biomechanical modeling frameworks.

Keywords:

lumbar burden, real-time biomechanical analysis, computer vision, neural networks

1. Introduction

Lumbar load analysis is critical in occupational and clinical settings to evaluate lower back stress and prevent injuries [1]. The growing prevalence of musculoskeletal disorders (MSDs), particularly those affecting the lower back, has driven research toward more accurate and practical methods of assessing lumbar burden. According to the World Health Organization (WHO), low back pain is the leading cause of disability worldwide, affecting approximately 619 million people, highlighting the urgent need for improved assessment techniques [2][3]. Traditional approaches, such as electromyography (EMG), finite element (FE) modeling, and motion capture systems, provide precise insights into lumbar stress but come with challenges related to invasiveness, high computational requirements, and complex setup procedures [4][5]. These limitations hinder their real-world applicability, particularly in dynamic work environments where continuous and non-intrusive monitoring is essential.

In recent years, human pose estimation techniques have emerged as promising tools for non-invasive biomechanical analysis. Models such as OpenPose [6], HRNet [7], and RTMPose [8] enable real-time tracking of human movement with reasonable accuracy. By leveraging computer vision and deep learning, these methods allow for scalable and accessible motion analysis without the need for extensive hardware setups. However, their effectiveness in estimating lumbar loads remains an open question due to factors such as occlusion, depth perception limitations, and the need for biomechanical validation [9][10].

For instance, tasks of analysis in a team environment, including construction, healthcare settings, or production line work, require the ability to discern group motions for safety, efficiency, and order to enhance performance. That is why there is a need to create new systems that can detect and analyze multiple people with increasing complexity of backgrounds.

This paper provides a comparative of lumbar load analysis methods, highlighting their respective strengths and limitations. It explores the potential for integrating these approaches to enhance the accuracy and practicality of lumbar stress assessments in various environments. By bridging the gap between pose estimation and biomechanical modeling, this study aims to pave the way for more efficient, real-time lumbar burden analysis systems suitable for both occupational safety and clinical rehabilitation applications.

TABLE 1. Lumbar burden analysis methods advantages and limitations

Method	Advantages	Limitations
IMU, Curvature Sensor, Muscle Stiffness Sensor [4]	Portable, real-time data collection, non-invasive	Limited accuracy compared to full motion capture, sensitive to placement
DOLLY 3 (Motion Capture, Force Plates, Modeling, EMG) [5][11][12]	Comprehensive, high accuracy, combines multiple techniques	Expensive, requires specialized equipment and expertise
6-Camera Motion Capture + EMG + OpenSim [13]	Highly accurate movement tracking, integrates muscle data	Requires large space, expensive, needs skilled operators
CT Imaging + Deep Learning Segmentation [9]	Automated segmentation, detailed spinal imaging	High computational cost, potential errors in AI segmentation
OptiTrack Motion Capture (82 Markers) [10][14]	High precision 3D tracking, full-body movement analysis	Requires many markers, can be time-consuming to set up
Computational Methods for Low Back Disorders [15-20]	Efficient, scalable, can simulate different conditions	Require detailed data input, may lack real-time feedback
Electromyography (EMG) [21-23]	Direct measurement of muscle activity, real-time analysis	Only measures muscle activity, not direct forces
3D Finite Element (FE) Model [24]	Detailed stress and strain analysis, high accuracy	Computationally intensive, requires detailed input data
Smartphone-Based Estimation [25-27]	Portable, cost-effective, easy to implement	Lower accuracy compared to specialized motion capture systems
EMG-Assisted Biomechanical Modeling [28]	Combines muscle data with biomechanics, more realistic modeling	Relies on accurate EMG placement, complex data processing
AnyBody Dynamic Mathematical Model [29]	Full-body dynamic simulation, adaptable to different tasks	Requires expertise, computationally demanding
In Vivo Force Measurement [30]	Highly accurate real-time force measurements	Highly invasive, only feasible in clinical studies
Wearable Sensor Systems [31]	Portable, real-life motion analysis, non-invasive	Limited force data, sensor placement can affect accuracy

2. Comparison of Lumbar Burden Analysis Methods

Different approaches used today to estimate lumbar load estimation considerable differences regarding their precision level and their practicality as well as their level of invasiveness (can be seen in Table 1). Portable methods that integrate IMU sensors together with wearable systems and smartphone detection enable user-friendly solutions although they degrade accuracy through sensor positioning delicacy combined with restricted force evaluation capabilities.

Modern motion capture systems like DOLLY 3, OptiTrack and multi-camera arrangements with EMG and biomechanical modeling provide exact lumbar load evaluation but need extensive resources and trained operators in controlled surroundings. The accuracy of Electromyography (EMG) methods depends on both electrode positioning accuracy as well as the necessity for additional biomechanical modeling when assessing muscular contributions to lumbar loads. The use of finite element models in combination with dynamic simulations through AnyBody software provides thorough understanding of lumbar mechanics at the expense of heavy computational requirements and specialized personnel expertise that hinders real-time implementation. Real-time monitoring using imaging-based techniques becomes challenging because AI segmentation of CT imaging requires extended computational power which renders such methods impractical for continuous observation. The precise gathering of data with invasive techniques occurs in clinical settings through in vivo force measurements although this approach remains restricted due to its necessity of medical invasiveness.

The current methods need improvement because they demonstrate conflicting requirements between precision and practicality and the invasiveness of implementation thereby highlighting the critical need for new lumbar load determination systems that offer non-invasive precision in real-time operation. Camera-based human pose estimation systems demonstrate promise as an effective solution that handles the mentioned drawbacks through efficient practical assessments at low costs.

3. Identified Gaps and Needs

The existing methods for lumbar load measurement can generally categorized into three groups: sensor-based methods, computational-based methods as well as motion capture-based methods utilizing body-mounted reflective markers. These three methods present different restrictions together with specific development zones that need attention.

Sensor-Based Methods such as wearable devices (IMU, curvature sensors, and muscle stiffness sensors) and smartphone sensors are portable along with being non-invasive and they give real-time information which makes them suitable for daily use. These methods experience accuracy issues because their sensor placement sensitivity along with their capability to measure direct forces and their vulnerability to movement artifacts.

The lumbar load scenario analysis becomes highly detailed and accurate through Computational-Based Methods which include finite element models and dynamic biomechanical simulations. The technical requirements and specialization demand along with high computational needs make these approaches ineffective for real-time usage during routine monitoring tests.

When reflective markers are attached to the body for use with Motion Capture-Based Methods (e.g., OptiTrack, DOLLY 3, infrared camera systems) they enable very precise three-dimensional tracking and detailed biomechanical data integration. Precision in these methods comes at a significant cost due to expensive equipment together with complicated and invasive setup procedures and specialized environments which require extensive calibration time as well as specialized operators.

The existing lumbar load estimation methods demonstrate clear deficiencies according to these constraints. The development of new methods requires integration of accuracy standards while remaining user-friendly at affordable costs with non-intrusive elements that support real-time applications are needed. The gaps in current lumbar load estimation methods make camera-based human pose estimation frameworks attractive because they deliver practical yet accessible and accurate solutions.

4. Proposed Solution: Camera-Based Pose Estimation Framework

In our previous research, we developed a system for real-time biomechanical analysis of lumbar burden using stereoscopic cameras and MediaPipe to extract 3D body keypoints [32], followed by JACK-based calculations for lumbar load estimation. This approach demonstrated effective real-time monitoring in practical environments, particularly under varied lighting conditions. However, the system was limited to single-person detection, which constrained its applicability in real-world occupational and clinical settings where multiple individuals often perform tasks simultaneously.

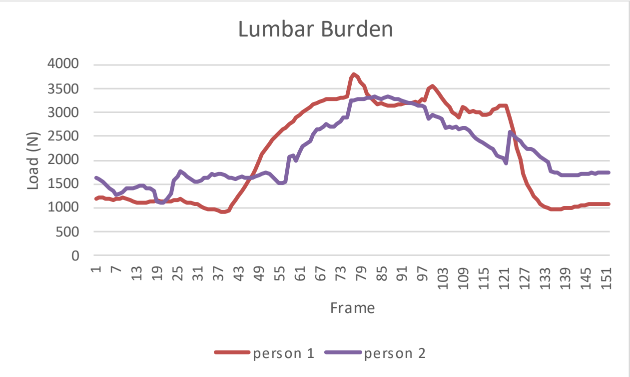

FIGURE 1. Lumbar burden values for lifting tasks

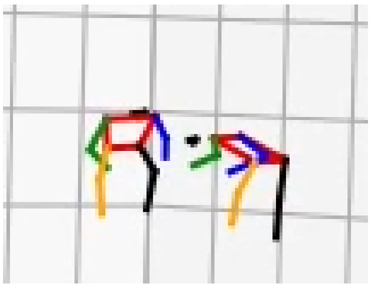

FIGURE 2. Joint angle visualization from 3D keypoints used for lumbar load estimation.

As shown in Figure 1 and Figure 2, the system successfully visualized joint posture and tracked lumbar burden based on the subject's movement across frames and varying load conditions. Figure 1 illustrates the lumbar burden response during lifting task, while Figure 2 shows the skeletal representation used to derive joint angles from 3D keypoints for biomechanical calculations.

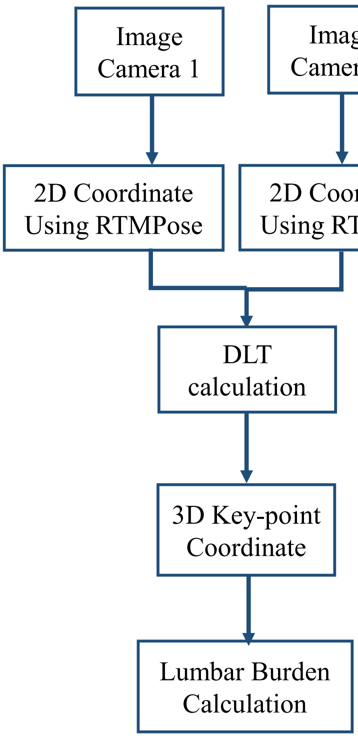

FIGURE 3. Lumbar burden values for lifting tasks.

In this paper, we propose an improvement to the previous system by integrating multi-person detection algorithms using advanced camera-based pose estimation frameworks such as OpenPose, RTMPose, or HRNet. By employing the same foundational methodology—camera-based 3D keypoint estimation and lumbar burden calculation—but enabling detection and tracking of multiple individuals at once, the system becomes significantly more usable in real scenarios. The flowchart of the system can be seen in the Figure 3.

This enhancement offers ergonomic benefits by eliminating the need for attached sensors or markers, thereby reducing discomfort and setup time. Economically, it presents a cost-effective alternative to traditional motion capture systems, which require expensive equipment and expert operation. By leveraging scalable and widely accessible camera technology, the proposed system becomes a practical, efficient, and non-invasive solution for multi-person lumbar load analysis in dynamic environments such as workplaces, rehabilitation centers, or clinical facilities.

5. Challenges and Future Directions

The camera-based pose estimation framework holds promising benefits but encounters various technical along with methodological obstacles. Absolute detection accuracy for the key body points becomes severely degraded when body parts conceal themselves from the camera view. The system's operational performance suffers from environmental factors which bring inconsistent lighting and challenging background conditions. Researcher face ongoing difficulties when trying to make computational analyses run in real-time for biomechanical purposes especially when dealing with high-resolution multi-source data.

Researchers should pursue specific development of robust detection algorithms which handle environmental effects and handle hidden objects effectively while utilizing advanced artificial intelligence concepts like attention mechanisms or temporal modeling. The accuracy and responsiveness of the proposed framework can be enhanced through dedicated development of biomechanical modeling algorithms which specialize in integrating with camera-derived data. Organizing cameras into new innovative setups designed specifically for biomechanical uses will help distinguish this method from conventional setups while boosting practicality and reliability.

6. Conclusion

This paper provides a comparison between different lumbar load estimation approaches to demonstrate both advantages and disadvantages of each technique. Different techniques must compete between precise measurement capabilities and practical deployment as well as levels of invasiveness and financial expenditure to achieve broad usage. Human pose estimation through camera systems presents a very promising solution for lumbar load analysis because it provides real-time non-invasive camera-based functionality that operates at low cost and practical convenience.

Computer vision algorithms when integrated with biomechanical modeling systems develop an efficient system for both professional injury prevention and occupational health assessments. On-going research to tackle technical specifications such as occlusions in addition to environmental changes and computational efficiency will strengthen the practical features of this groundbreaking solution.

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