An Automated Platform for Coupling Human Motion Capture and Musculoskeletal Dynamic Analysis

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BACKGROUND

As living standards improve and health awareness increases, human movement analysis has become an increasingly important interdisciplinary field, bridging foundational scientific research with practical applications. This field aids in understanding the physiological response mechanisms of the human body under various conditions and provides a scientific foundation for personalized medicine, sports training, and early diagnosis of sports injuries. Key technologies in this area include motion capture systems, such as Inertial Measurement Units (IMUs) and Optical Motion Capture Systems. However, IMUs can accumulate errors over time, impacting data accuracy, while optical systems require stringent installation environments, limiting their use in outdoor or complex settings. Although researchers have made strides in combining these two technologies to overcome individual limitations, most studies still focus on accurately reproducing motion trajectories rather than leveraging the acquired data for in-depth biomechanical analyses. Furthermore, current professional software used for skeletal-muscular system simulation is operationally complex and lacks intuitive presentation of results, thus restricting the efficiency of data utilization. Consequently, there is an urgent need to develop a more user-friendly, intuitive, and powerful analysis platform that supports real-time, efficient motion capture and comprehensive kinetic analysis, enhancing both the accuracy of the data and the user experience to better support medical research and applications.

METHODS

In this study, we adopted a multi-sensor fusion approach for human motion capture and analysis. Specifically, seven Inertial Measurement Units (IMUs) were utilized, each equipped with triaxial accelerometers and gyroscopes, and strategically placed on key anatomical landmarks such as the anterior thigh, lateral calf, ankle, foot, and waist. These IMUs collected synchronized data at a frequency of 50 Hz. To eliminate noise and correct drift, the raw IMU data underwent preprocessing using a Kalman filter algorithm, followed by integration to derive displacement and velocity information for each critical point.

To enhance measurement accuracy, a depth camera was integrated into the system. This device provided high-precision three-dimensional point cloud data used to calibrate and stabilize the IMU data, ensuring accurate representation of motion trajectories. Visual fusion and kinematic analysis techniques were employed to determine the position of motion nodes, and a musculoskeletal model considering bone structure, muscle forces, and joint constraints was constructed using the OpenSim platform. A 3D visualization tool vividly demonstrated skeletal muscle activity, allowing researchers to observe muscle activation and force in an intuitive manner.

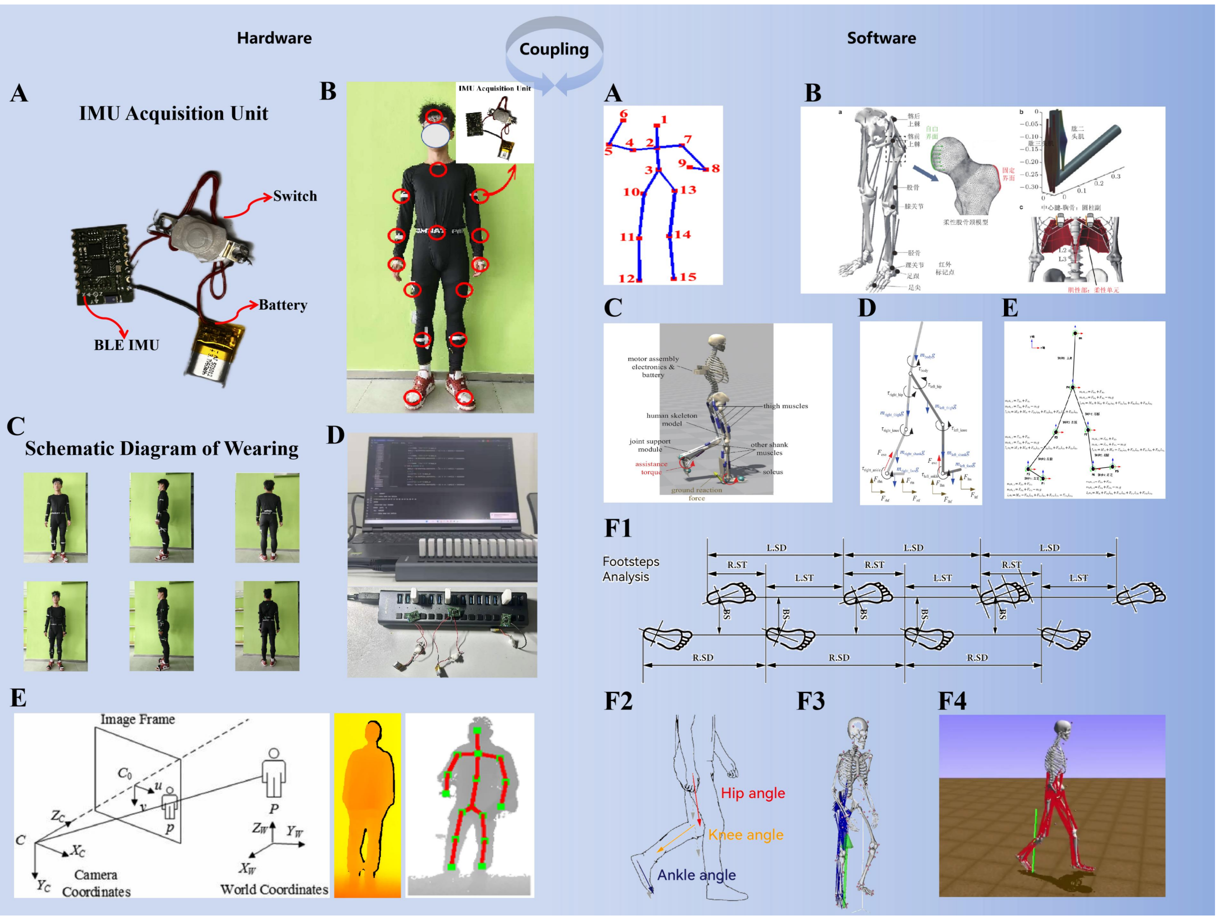

Fig. 1 This figure provides a comprehensive overview of a human motion capture system, detailing both hardware and software components. The hardware section includes an Inertial Measurement Unit (IMU) acquisition unit with a switch, BLE IMU, and battery (A), and illustrates the strategic placement of these IMUs on key anatomical landmarks such as the head, torso, arms, and legs (B). The correct orientation and placement of IMUs are shown from multiple angles (C), and the data collection setup features a computer with real-time data collection and analysis software (D). The relationship between camera and world coordinates is explained in the image frame and coordinate systems (E). The software components cover IMU data integration (A), detailed anatomical models of joints and bones (B), a musculoskeletal model integrating IMU data with skeletal and muscle forces (C), joint angle analysis (D), and force analysis (E). Gait analysis is further broken down into footsteps analysis (F1), joint angle analysis (F2), 3D visualization of the musculoskeletal model during movement (F3), and real-time visualization of the skeletal model during a gait cycle (F4). The coupling section highlights the seamless integration of hardware and software to ensure accurate and real-time data processing and analysis.

RESULTS

Based on the optimized data from our multi-sensor setup, gait analysis was performed to extract key parameters such as stride length, walking speed, stance phase duration, swing phase duration, and changes in joint angles, with particular attention to the movement trajectories of the hip, knee, and ankle joints throughout a gait cycle. The incorporation of depth camera data significantly improved the accuracy of motion trajectory representation, effectively correcting any drift or instability in the IMU data.

The comprehensive analysis through the visualization of the 3D musculoskeletal model revealed fundamental principles of human movement. This not only elucidated the mechanics of human locomotion but also laid a solid foundation for subsequent biomechanical studies and practical applications. The detailed insights gained from this methodological framework underscore its potential for advancing the field of human movement analysis and enhancing the understanding of underlying biomechanics. Additionally, this research holds significant implications for developing new rehabilitation training devices, assessing athletic performance, and preventing falls in the elderly, providing new ideas and technical support for improving quality of life.

DISCUSSION

In this study, automated coupled motion analysis and musculoskeletal dynamics analysis have demonstrated their significance in the fields of biomechanics and rehabilitation medicine. By integrating data from multiple sensors such as Inertial Measurement Units (IMUs) and depth cameras, this approach can capture complex three-dimensional human movements in real-time, overcoming the limitations of traditional laboratory settings and extending its applicability to the assessment of individual daily activities in natural environments. Coupled with musculoskeletal modeling and 3D visualization techniques, this analysis provides deep insights into muscle activation patterns, joint load distribution, and force changes during movement, offering a comprehensive perspective on the quality and efficiency of human motion. It is invaluable for identifying abnormal movement patterns, diagnosing movement injuries, and formulating personalized rehabilitation plans.

Looking ahead, the application prospects of this technology are vast. As algorithms improve and technology costs decrease, automated coupled motion analysis is poised to become an integral part of routine health monitoring and to design more effective movement intervention measures for specific populations. However, to fully realize its potential, it is essential to address current technological limitations regarding accuracy and robustness, such as IMU data susceptibility to magnetic field interference and the limitations of depth cameras under low-light conditions. Developing smarter data processing algorithms to enhance performance in complex environments is critical. Additionally, large-scale validation experiments and long-term tracking studies should be conducted to ensure the validity and reliability of the analysis results.

In summary, despite the challenges, automated coupled motion analysis and musculoskeletal dynamics analysis represent a crucial driving force for advancing biomechanical research and will play a significant role in improving human health.

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