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Inertial Motion Capture and Digital Human Modeling for Ergonomic Risk Assessment of Accordion Performance

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Reliable ergonomic risk assessment requires methods that capture short, asymmetric, and repetitive postures. We present a wearable, model-based workflow to evaluate posture risk during accordion playing. One experienced right-handed player performed a 10-minute standing piece wearing inertial sensors. Motion data were mapped to a scaled digital human model, the accordion mass was added at the shoulders, and postures were scored using ergonomic methods. Joint-angle exposure and L4/L5 compression, shear, and moments were also measured. The neck and trunk remained mostly near neutral, while the upper limbs showed sustained non-neutral loading, including deep right-elbow flexion and continuous wrist flexion and deviation. Peak L4/L5 compression was around 1750 N, with low shear. Results support strap adjustments, technique coaching, and practice planning to reduce upper-limb risk. This case study shows how IMU data and digital human modeling can provide fast, repeatable risk scoring for performance health.

Keywords:
inertial measurement units,
digital human modeling,
ergonomic risk assessment,
musculoskeletal disorders,
musician ergonomics,
motion capture

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1 Introduction

Ergonomic risk assessment is a cornerstone of occupational health and safety, directly linked to preventing work-related injuries and improving health (Balantič et al., 2016). Traditional ergonomic evaluations often rely on checklists and observers' subjective judgment, which may miss transient or subtle risky postures. To address this, modern approaches increasingly combine the physical, biological, and technological aspects of work environments into a holistic assessment framework (Castillo et al., 2022; Carnazzo et al., 2024). These approaches also leverage advanced technologies (such as IoT and cloud computing) to improve processes and reduce worker strain. Smart ergonomics that use IoT sensors and cloud tools can stream motion data, spot risky patterns, and prompt early action (Sangeethalakshmi et al., 2023; Bances et al., 2024). Integrating these domains requires objective methods for data capture and analysis. The same need for objective, time-based risk monitoring applies to performance tasks, where exposure builds over long periods of practice and repeated movement.

Best practices for studying ergonomics in the workplace include a comprehensive approach that considers various aspects of the work environment and employees' needs (Balantič et al., 2024). Modern wearable motion sensors (inertial measurement units/IMUs) can record a person's movements in three-dimensional space and also add the fourth dimension – time – to the ergonomic analysis. These sensors capture continuous joint angles and body segment orientations throughout a task, and their data can be imported into digital human modeling software to recreate and evaluate the activity virtually. Using this approach, standardized ergonomic methods can be applied to motion data to objectively quantify risk levels. The high consistency and frequency of sensor measurements improve the reliability of risk assessments and allow much faster analysis than manual observation (Lamooki et al., 2022; Akhmad et al., 2020). Therefore, advanced analytical tools can provide ergonomics experts with immediate support in analyzing collected data to reduce risks in the workplaces under consideration (Greco et al., 2020; Kotowski & Gibson, 2023; Hilmi et al., 2024; Rybnikár et al., 2022; Yunus et al., 2021).

This paper presents a case study that applies inertial motion tracking and 4D analysis (full-body 3D movement data collected over time) to the task of playing a piano accordion. This activity involves complex upper-body movements and static load from a heavy instrument. In the context of public health, it is important to note that musicians are among the most vulnerable professional groups to musculoskeletal disorders, with prevalence rates comparable to those of healthcare and industrial workers (Stanhope et al., 2022; Kok et al., 2018; Kok et al., 2013). While much ergonomic research focuses on industrial or office tasks, musicians can also experience work-related musculoskeletal disorders due to awkward postures and repetitive practice. Prior studies have found that young accordion players are prone to shoulder and wrist pain and to altered spinal postures (forward head position and increased lumbar lordosis) compared with non-musicians (Aparicio et al., 2016). These issues underscore the need for ergonomic evaluation in musical performance. High rates of musculoskeletal pain have also been reported among pianists and violinists, especially in the neck, shoulders, and wrists (Ozdemir et al., 2019; Lima et al., 2020). Kinect-based motion analysis has shown potential for evaluating musicians' postures objectively (Buisseret et al., 2018). However, systematic reviews (e.g., Rousseau et al., 2023) emphasize that existing studies are fragmented, typically focusing on one instrument group at a time, and that there is a lack of longitudinal and instrument-specific research. Importantly, no systematic ergonomic assessments have yet been conducted for the accordion, despite its unique challenges: instrument mass (10–15 kg), asymmetric loading from shoulder straps, and repetitive left-hand movements operating the bellows and bass keys.

The main contribution of this study is a practical workflow that combines inertial motion capture with digital human modeling for ergonomic evaluation in musicians. While musculoskeletal risk in instrumental performance has been studied previously, integration of IMU-based kinematics, biomechanical modeling, and ergonomic scoring remains limited. This case study demonstrates how motion data can be translated into joint loading estimates and time-based posture risk scores for musician health.

1.1 Research problem

Conventional ergonomic methods struggle to capture the dynamic, asymmetric, and repetitive nature of playing a musical instrument. Although systematic reviews (e.g., Rousseau et al., 2023) have highlighted common musculoskeletal risks among musicians in general, they also note that most studies are fragmented, instrument-specific, and rarely longitudinal. Importantly, no systematic ergonomic assessments have been conducted for accordion playing, despite its unique load profile. The challenge is to improve risk assessment by combining inertial motion tracking with digital human models, moving beyond subjective observation and static postural snapshots. This dual focus addresses both a methodological gap (the limitations of conventional observational approaches) and a content-related gap (the lack of instrument-specific studies on accordion players). Therefore, this study addresses the following research question: How can inertial motion capture combined with digital human modeling identify time-dependent ergonomic risks during standing accordion performance, and which body regions exhibit the highest exposure? To answer this research question, the case study had four aims:

1. Measuring dynamic accordion playing postures.
2. Linking motion data to ergonomic criteria.
3. Identifying critical exposure regions.
4. Supporting preventive interventions.

2 Methods

This case study involved an experienced male accordion player performing a typical musical piece while wearing a full-body inertial motion capture suit (Figure 1). The participant was 28 years old, weighed 95 kg, was right-handed, and had over 15 years of playing experience. The participant (who is also a co-author) gave written consent for data collection and publication. A set of 17 wireless Xsens IMUs were placed on key body segments to capture the subject's movements in real time. The participant reported that the sensors did not restrict playing movements during the 10-minute task, although the suit and sensor straps may still affect comfort during longer recordings. The case study design (single participant) is a pilot-level investigation that provides detailed insights but limits generalizability.

The sensors were calibrated according to the manufacturer's guidelines (Xsens Technologies, 2021) to establish a baseline neutral pose before recording. During the experiment, the player stood and performed a 10-minute set of traditional pieces (waltz and polka) without breaks. At the same time, the system streamed motion data at 60 Hz, allowing the inertial system to log the dynamic joint angles and accelerations throughout the activity. The standing posture was deliberately selected, as it places the full weight of the instrument on the shoulder girdle, thereby accentuating upper-limb loading compared with seated performance.

Figure 1: The accordion player wearing sensors before and during the experiment
Source: Own

Before simulation, detailed anthropometric data were collected from the participant, including body height, arm span, limb lengths, and segment circumferences. These values were used to scale the digital human model so that joint centers, limb proportions, and mass distribution matched the player's actual body. Accurate anthropometric input is essential, since it directly affects joint angle calculations and biomechanical load estimates, allowing the model to reflect the ergonomic stresses experienced by this individual. For clarity, only the most relevant anthropometric measures are reported in Table 1.

Table 1: Anthropometric measures of the accordion player

Body Dimension	Measurement
Body Height	188 cm
Shoulder Height	160 cm
Shoulder Width	47 cm
Elbow Span	95 cm
Arm Span	188 cm
Hip Height	110 cm
Knee Height	56 cm

Motion capture data from the Xsens system were processed in MVN Analyze and imported into Siemens Tecnomatix Process Simulate for ergonomic analysis (Siemens, 2024). The virtual avatar (Figure 2) was scaled to the subject's anthropometry and placed in a simulated standing posture. The 13-kg accordion was modeled as an external load attached to the torso via shoulder straps to match the real weight distribution. IMUs provided continuous kinematic data, while digital human modeling enabled standardized ergonomic assessment and biomechanical load estimation. This workflow allowed simultaneous evaluation of dynamic postures and internal loading. Ergonomic modules in Tecnomatix were then applied using OWAS (Ovako Working Posture Analysis System) and RULA (Rapid Upper Limb Assessment), along with tools for joint-angle exposure and lower-back load calculation. OWAS classifies whole-body postures into 4 action categories, where higher numbers indicate a greater need for corrective action. RULA scores upper-limb, neck, trunk, and wrist postures on a scale from 1 to 7, where higher scores indicate higher ergonomic risk. The analysis covered five outcome domains: OWAS categories, RULA scores (left/right), time in neutral/caution/high-risk postures (neck, trunk, shoulders, elbows, wrists), L4/L5 compressive and shear forces, and L4/L5 trunk moments.

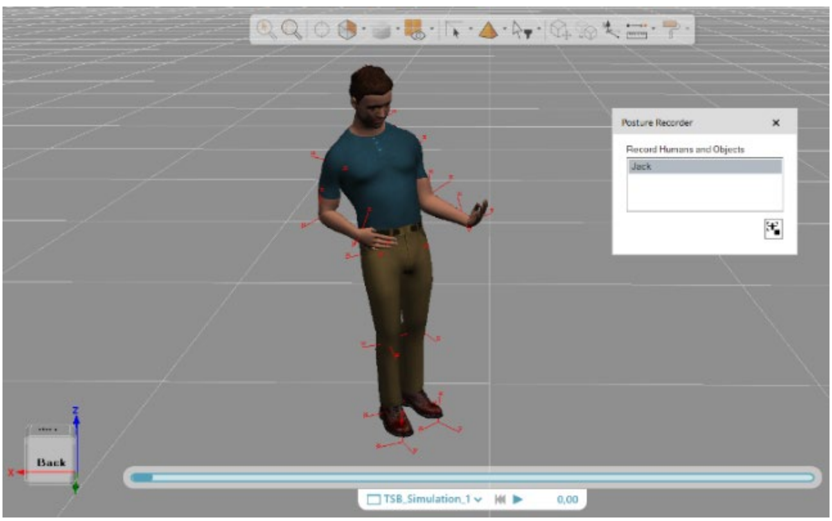

Figure 2: Accordion player's model inside the Tecnomatix Process Simulate environment
Source: Own

3 Results

Using an inertial-sensing and simulation approach, we obtained a detailed ergonomic risk profile for accordion playing. The analysis combined high-level scores (OWAS categories and RULA results) with biomechanical metrics, including joint-angle distributions and L4/L5 forces and moments. Posture classification identified moderate-risk postures but no sustained extreme or immediately dangerous exposures. The accordion's mass and the player's arm positions were the main contributors to elevated risk scores. The shoulders, elbows, and wrists emerged as the most exposed body regions, while the trunk remained largely neutral.

Figure 3 shows the OWAS results for the recorded accordion performance. It indicates the proportion of time spent in each OWAS action category during the task. Most of the players' postures fell into AC 2 (yellow). Category 2 indicates a posture that may cause harm to the musculoskeletal system; corrective actions are required in the near future. This moderate-risk classification is mainly due to the slightly bent trunk posture. No high-risk OWAS categories were observed, indicating the player avoided extreme bending or twisting while playing. However, the prevalence of continuous AC 2 suggests that posture variability was low, which aligns with the sustained asymmetric loading observed in the upper limbs.

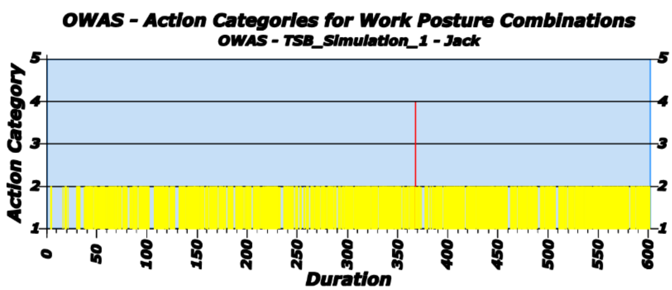

Figure 3: OWAS action categories during the 10-minute accordion performance

Source: Own

The RULA evaluation of the accordion-playing task yielded final scores of 6 on the left and 5 on the right, indicating a high risk that calls for intervention. This score was driven primarily by the arm and wrist positions required to play the instrument's keyboard and operate the bellows. In particular, the left wrist was held at extreme angles, and the left shoulder was raised for prolonged periods, which contributed to the high RULA score. According to the RULA action levels, scores of 5 and 6 mean that further investigation is required and changes should be implemented soon to reduce the risk of injury. These findings underline that upper-limb postures are the main risk drivers, while the trunk remained largely neutral.

The next analysis evaluated ergonomic metrics as the percentage of time body segments were held within defined posture ranges and projected these exposures to a simulated 4-hour playing duration. A total of 26 segments were tracked and classified into three risk levels (green, yellow, red). Figure 4 shows the twelve segments with the highest exposure. Neck and trunk postures remained mostly neutral, confirming that trunk loading was limited. In contrast, the upper limbs showed sustained non-neutral positions. The right shoulder remained in extension for most of the task, while the left shoulder showed prolonged internal rotation. Elbow postures were asymmetric, with the right elbow frequently in high flexion. The most extreme exposure occurred in the wrists, which stayed in large flexion and deviation angles for most of the recording.

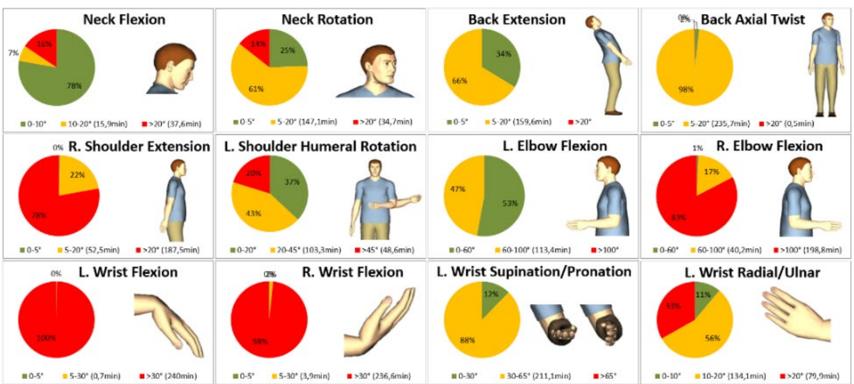

Figure 4: Time share (%) spent in neutral, caution, and high-risk joint-angle ranges for the most exposed body regions

Source: Own

We continued with lower back loading, as indicated by L4/L5 compressive and shear forces throughout the performance. The red curve in Figure 5 shows the compressive force on the lumbar spine, peaking at approximately 1750 N. This peak is below the NIOSH-recommended maximum of 3400 N for safe lumbar compression (Albers et al., 2005), indicating that the vertical load from the accordion remained within acceptable limits. The blue and green curves show anterior-posterior and lateral shear forces, respectively. These shear forces were minimal, staying below 50 N at all times – far below the 700 N threshold often cited as the threshold for concerning shear loads (Afshari et al., 2018). Measurements of L4/L5 compressive and shear forces, therefore, remained within established safety thresholds, confirming that trunk loading was moderate compared to the persistent postural strain in the upper limbs.

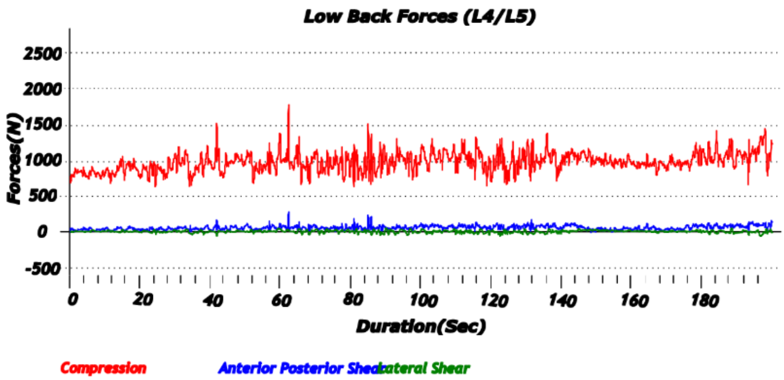

Figure 5: L4/L5 compressive and shear forces during accordion performance

Source: Own

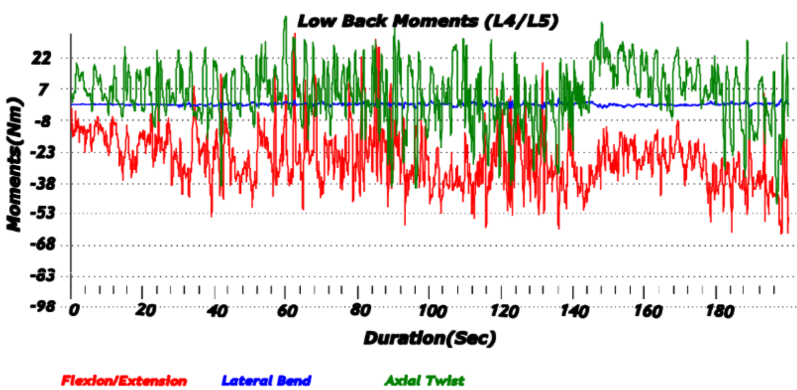

Figure 6: L4/L5 moments in flexion/extension, lateral bending, and axial twisting during accordion performance

Source: Own

Figure 6 shows L4/L5 moments in three planes: flexion/extension, lateral bending, and axial twisting. Flexion/extension was the dominant component and increased when the player adjusted under the accordion's weight. Lateral bending moments remained near zero, while axial twisting showed repeated peaks of about 30 Nm during torso rotation and bellows movement. Although moderate, these repeated twisting moments may contribute to lower-back fatigue over time.

4 Discussion

This case study evaluated ergonomic risk during standing accordion performance using inertial motion tracking and digital human modeling. Wearable sensors, software, and algorithms now support movement data collection and analysis across fields (Lind et al., 2020; Hilmi et al., 2024; Bances et al., 2024), offering objective insight for better ergonomic decisions and work processes (Lind, 2024). The main contribution is a practical workflow that combines inertial sensors with digital human modeling to produce repeatable posture scores and spinal load estimates for musician ergonomics.

The results show that inertial tracking with 4D simulation can reveal risks in complex, dynamic tasks that visual observation may miss. Sustained wrist flexion and deviation, high elbow flexion, shoulder loading, and repeated trunk moments were identified, matching reports of frequent upper-limb and shoulder complaints in musicians (Aparicio et al., 2016; Ozdemir et al., 2019; Lima et al., 2020). Time spent in moderate- and high-risk postures supports preventive actions, such as strap redesign, instrument support changes, technique coaching, and hip-strap systems to reduce shoulder and lower back load. Combining these data with wider ergonomic indices, including cognitive and environmental demands, may improve risk ranking and prevention (Rezvanizadeh et al., 2023). The same workflow may also support sports or military training, although OWAS and RULA should be used cautiously in high-intensity tasks.

The assessment showed that trunk and upper-limb demands differed. Most trunk-related postures fell into the OWAS action category 2, showing moderate risk and the need for future correction. In contrast, RULA scores of 5 on the right and 6 on the left indicate the need for early intervention. Thus, overall risk was moderate, but the wrists, elbows, and shoulders showed persistent high-risk exposure, while trunk loading remained secondary. This agrees with reports of wrist and shoulder problems among musicians (Kok et al., 2016) and supports targeted changes such as strap adjustment, technique modification, and planned rest.

Ergonomic research on musicians remains fragmented, often focusing on violin, piano, and wind instruments, while other instruments receive less attention (Rousseau et al., 2023). This study helps address that gap by examining accordion performance. Unlike violin studies, where neck load is often dominant (Kok et al., 2016), and piano studies, where wrist asymmetry is common (Lima et al., 2020), accordion playing mainly stressed the shoulders, elbows, and wrists, with moderate trunk loading.

Earlier work on young accordion players found marked changes in head and lumbar posture (Aparicio et al., 2016), but trunk posture in this study remained mostly neutral. This may reflect the player's experience or posture control, supporting the value of training. The standing setup is also a limitation: the 13-kg instrument load acted through the shoulder straps, likely increasing upper-limb strain. Seated play could shift some of the load to the thighs and lower back, altering the risk pattern.

The L4/L5 analysis showed repeated flexion–extension and axial rotation moments, which require trunk muscle co-contraction and increase compression beyond instrument weight. Sustained compression with repeated asymmetric moments can contribute to disc loading and degeneration (Cui et al., 2022). Although compression values were moderate, dynamic trunk moments suggest cumulative spinal loading, which may help explain chronic low-back pain in musicians over long practice or performance periods (Hasegawa et al., 2018). In this case, however, upper-limb exposure remained the main risk.

Methodologically, combining IMUs with digital human modeling yielded a more objective and comprehensive assessment than visual observation alone. IMUs provide joint-angle data suitable for ergonomic tools (Rybnikár et al., 2022; Yunus et al., 2021), reducing subjectivity. The 4D analysis also captured time-dependent risk, including wrist flexion duration and peak spinal load timing, which snapshot-based methods may miss. The workflow also supports fast feedback and continuous improvement. Motion data were automatically recorded, and OWAS, RULA, ergonomic metrics, and L4/L5 loads were calculated quickly. This can help detect unsafe patterns and guide changes to equipment or technique, as shown in earlier work on real-time or near real-time feedback (Santos et al., 2024; Lamooki et al., 2022; Akhmad et al., 2020).

For broader use, the workflow should serve as a decision-support tool rather than a diagnostic tool. Simple outputs, such as time spent in high-risk wrist postures, peak spinal load, and RULA/OWAS action levels, could guide teachers, performers, ergonomists, and health staff in choosing strap or technique changes, rest plans, or clinical referral. Broader use would require faster setup, repeatable sensor placement, secure storage of movement data, and clear consent rules, especially when data connect to health records or are shared in schools, clinics, or workplaces.

5 Conclusion

This study shows that combining inertial sensors with digital human modeling enables objective and repeatable ergonomic risk assessment during accordion performance and other complex tasks. The proposed workflow allows accurate tracking of movement, calculation of joint exposure, and estimation of spinal loading, providing reliable data for evaluating performance health. Such sensor-based methods support precise analysis of repetitive and asymmetric tasks and can improve ergonomics prevention strategies (Vox et al., 2021). With the ongoing development of wearable sensors, digital simulation, and machine-learning methods, these tools are expected to provide more detailed and personalized ergonomic evaluations in the future (Hilmi et al., 2024).

The present case study involved one experienced player and a single 10-minute standing performance, so the results cannot be generalized to all accordion players. The main contribution is the demonstration of a feasible IMU–digital human modeling workflow that can be applied to musician ergonomics and similar tasks involving sustained and asymmetric loading.

Future research should include larger samples, different playing conditions, and longer recordings. Combining motion tracking with physiological measures such as EMG, heart rate, and perceived fatigue would allow a more complete assessment of ergonomic exposure and support the development of evidence-based recommendations for musicians and other professions with similar physical demands.

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