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The Use of Wearable Sensors for Ergonomic Risk Assessment of Surgical Procedures: A Literature Review

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ABSTRACT

Surgical procedures place significant physical demand on surgeons, frequently requiring long periods of standing, repetitive and/or forceful movements, and sustained awkward postures, which raises the possibility of developing work-related musculoskeletal disorders (WRMSD). In response, several ergonomic risk assessment methods have emerged to identify risk factors in the workplace. A transformational approach involves associating wearable sensors to the ergonomic risk assessment data collection procedures, offering significant advantages over self-reporting and observational methods. Wearable sensors enable the use of a real-time quantitative approach to monitor surgeon's exposure to risk factors during surgeries. This paper provides a comprehensive literature review on the use of wearable sensors for ergonomic risk assessment of surgeries, highlighting their strengths and limitations. Moreover, it provides an in-depth analysis of the assessments described in the studies. The majority of the reviewed studies were published in the last three years, confirming a growing trend in research on this topic. The wearable sensors, whether used individually or in combination, include inertial sensors to assess exposure to awkward postures or repetitive movements and sEMG sensors to measure muscle activity parameters. The significance of this paper lies in its potential to guide future research directions, inform best practices in ergonomic risk assessment methodologies, and influence the development of targeted interventions to mitigate the exposure to risk factors faced by surgeons.

Keywords: Wearable devices, Risk factors, Work-related musculoskeletal disorders

INTRODUCTION

While performing surgical procedures, surgeons must maintain prolonged periods of standing postures, execute repetitive movements and/or forceful exertions to perform complex procedures, and sustained awkward postures (Davis et al., 2014; Szeto et al., 2009). Beyond the physical demands, these procedures require sustained focus, leading to cognitive fatigue. This cognitive strain can impair the ability to maintain proper body mechanics and temporarily mask muscle fatigue, fostering a potentially hazardous work environment. Extensive research has underscored the correlation between prolonged exposure to such risk factors and the development of work-related musculoskeletal disorders (WRMSD) (Davila et al., 2019; Howarth et al., 2019; Wells et al., 2019). These disorders may cause pain, disability, and work absenteeism among surgeons.

Regular ergonomic risk assessments in surgical rooms become imperative to prevent WRMSD among surgeons. Traditionally, ergonomic risk assessments have heavily relied on self-reporting and observational techniques. However, these tools often lack comprehensiveness and objectivity in assessing the exposure to risk factors (David, 2005). In contrast, recent advances in wearable sensor technology allow a real-time and quantitative approach to monitoring surgeon's exposure to risk factors while performing surgical procedures (Asadi et al., 2021).

A wearable sensor is essentially a small, lightweight device endowed with powerful sensing, processing, storage, and data exchange capabilities. The term can refer to "any electronic device or product designed to provide a specific service that can be worn by the user" (Jeong et al., 2017). Other definitions emphasize its ability to collect information such as the user's location, movement, and biometric data (Cheng & Mitomo, 2017; Koutromanos & Kazakou, 2020).

The integration of wearable sensors into ergonomic risk assessment methods applied to surgical procedures holds the potential to revolutionize approaches to ergonomic risk assessment and WRMSD prevention in the operating theatre. By providing continuous and objective data, these sensors can play a pivotal role in enhancing surgeon well-being and improving surgical efficiency, contributing to patient safety.

This paper provides a comprehensive literature review of the use of wearable sensors for ergonomic risk assessment of surgeons performing surgeries, highlighting their strengths and limitations. Moreover, it provides an in-depth analysis of the assessments described in the studies.

RESEARCH METHODOLOGY

The literature search was conducted in January 2024 using the scientific databases Scopus and Web of Science. According to the focus of this review, the selected keywords combination was defined to be used in the literature search: ("surgeons") AND (wearable OR sensor) AND (ergonomic* OR "musculoskeletal disorder").

To restrict the search, a set of inclusion and exclusion criteria were defined. The significance of the articles, according to the review's goal, was based on the following inclusion criteria:

- Papers written in English;
- Papers reporting strengths and/or limitations of using wearable sensors during real surgical procures;

- Papers describing objective ergonomic risk assessment methods employed during real surgical procures.

The following exclusion criteria were applied:

- Review papers;
- Papers reporting the use of wearable sensors for the ergonomic risk assessment of other occupational groups, which includes dentistry, nursing.
- Papers reporting the use of wearable sensors for ergonomic risk assessment during surgical procedures but exclusively in a simulation setting.

Following the search in the two databases, 86 publications were identified from Scopus and 62 from Web of Science. Subsequently, duplicated results were excluded, reducing the studies to 91. Then, other papers were excluded by reading their abstract, considering the above-mentioned criteria, further reducing the results to 15. Lastly, after reading the full texts, 13 articles were selected for this review.

WEARABLE SENSORS FOR ERGONOMIC RISK ASSESSMENTS

This section analyzes the information retrieved from the included 13 studies. The section is further divided into three sub-sections for a more structured analysis: types of wearable sensors, methodologies for ergonomic risk assessment, and some examples of ergonomic analysis using wearable sensors.

Types of Wearable Sensors

Concerning the type of wearable sensors, one study utilized surface electromyography (sEMG) sensors (Merbah et al., 2023); while a combination of inertial measurement unit (IMU) and sEMG sensors was employed in three studies (Asadi et al., 2021; Athanasiadis et al., 2021; Monfared et al., 2022). Additionally, nine studies exclusively employed IMU sensors, with one of them incorporating IMU sensors within the motion capture system CAPTIV (Bartnicka et al., 2015).

Table 1 and Table 2 summarizes the details related to surgery types, sensor placement on the body, and strengths and limitations identified by the authors regarding the use of wearable sensors for ergonomic risk assessments during surgery.

Regarding the most applied type of wearable sensor (IMU) they were used for ergonomic risk assessment of the posture of surgeons performing laparoscopic, urologic, otolaryngologic, and vascular surgical procedures (Arrighi-Allisan et al., 2022; Asadi et al., 2021; Athanasiadis et al., 2021; Bartnicka et al., 2015; Carbonaro et al., 2021; Dabholkar et al., 2020; Davila et al., 2021; Monfared et al., 2022; Norasi et al., 2021; Reddy et al., 2023; Yang et al., 2021; Yu et al., 2017).

The IMU sensors measure body-posture angles by fusing data from electromechanical sensors, such as accelerometers, gyroscopes, and magnetometers, within each unit (Meltzer et al., 2020). Usually, these sensors are attached to specific body segments using Velcro straps. The data provided by these sensors allow the estimation of biomechanical parameters relevant for identifying and analyzing postures linked to the development of WRMSD. The included studies reported that the introduction of IMU sensors has facilitated the measurements of kinematic parameters and enabled motion analysis, providing accurate data even in the presence of visual occlusions, making them well-suited for real surgical settings. Moreover, the study conducted by Asadi and colleagues reported that IMU sensors enable continuous monitoring, capturing non-cyclical variations in body movements and tasks (Asadi et al., 2021). This feature allows for a more comprehensive understanding of the amount of time surgeons spend in awkward postures throughout the surgical procedure (Athanasiadis et al., 2021; Bartnicka et al., 2015; Davila et al., 2021; Yu et al., 2017). Also, IMU sensors can provide actionable data and feedback to surgeons, e.g., degree of static postures or arm elevation (Yu et al., 2017). However, it is essential to acknowledge potential limitations associated with IMU sensors' usage in surgical settings. These include the possibility of positioning errors, skin movement artifacts, risk of overloading surgeons with additional sensors, interference with sterile scrubbing procedures, electromagnetic interference, and the requirement for trained research personnel to collect and analyze data prospectively (Arrighi-Allisan et al., 2022; Carbonaro et al., 2021; Davila et al., 2019; Yu et al., 2017).

In the pursuit for a more comprehensive understanding of physical risk factors, three studies opted for a combination of IMU and sEMG systems, specifically during laparoscopic surgery (Asadi et al., 2021; Athanasiadis et al., 2021; Monfared et al., 2022). sEMG provides an objective and quantitative method for evaluating muscle function, movement patterns, and local muscle fatigue. In the analysis of work activities, target muscles are chosen based on their specific roles. The process involves placing surface electrodes directly on the skin over these muscles, with the inclusion of a grounding electrode (Whittle, 2007). Despite its application to superficial muscles, sEMG data may lack specificity due to interference from adjacent muscles, commonly known as 'cross-talk.' Consequently, it is prudent to interpret the signal from surface electrodes as derived from muscle groups rather than individual muscles (Whittle, 2007). Notably, some of the strengths of using sEMG lies in its ability to identify muscle activations and early prediction of muscle fatigue (Athanasiadis et al., 2021).

Lastly, it is important to underscore that all the reviewed studies use wearable sensors to collect data specifically pertaining to surgeon's upper limbs, with the exception of the study conducted by Arrighi-Allisan and colleagues, which used IMU sensors to collect data from hip, knee, and feet's posture (Arrighi-Allisan et al., 2022).

Table 1. Overview of the studies using sEMG sensors for ergonomic risk assessment in surgical procedures.

Surgery	Sensor's placement	Strengths	Limitations
Laparoscopic	Deltoid and trapezius muscles bilaterally (Asadi et al., 2021; Athanasiadis et al., 2021; Monfared et al., 2022)	• Measure time spent in maximum voluntary contraction (Athanasiadis et al., 2021) • Continuous measurements identify tasks contributing most to fatigue (Asadi et al., 2021) • Enable early prediction of musculoskeletal fatigue (Asadi et al., 2021)	• sEMG data prone to sensor drop and malfunctions (Asadi et al., 2021)
Orthopedic	Upper, middle trapezius, medial deltoid, latissimus dorsi (Merbah et al., 2023)		

Table 2. Overview of the studies using IMU sensors for ergonomic risk assessment in surgical procedures.

Surgery	Sensor's placement	Strengths	Limitations
Laparoscopic	Wrist (Bartnicka et al., 2015) Head and trunk (Carbonaro et al., 2021) Head, chest, L5/S1, and left and right biceps (Athanasiadis et al., 2021) Sternum, head, and biceps (Asadi et al., 2021; Monfared et al., 2022) Bilateral upper arms, torso, and head (Yang et al., 2021)	• Move freely during assessment (Bartnicka et al., 2015) • Enhance efficiency through automatic assessment (Bartnicka et al., 2015) • Consider all working condition factors, including interactions (Bartnicka et al., 2015) • Enable comprehensive and synchronous analysis (Bartnicka et al., 2015) • Quantify posture angles beyond recommended safe range (Athanasiadis et al., 2021; Davila et al., 2021; Yu et al., 2017) • Serve as a proxy for frequency of prolonged muscle exertions in static postures (Yu et al., 2017) • Identify areas for ergonomic interventions (Yu et al., 2017) • Provide relevant personalized feedback on surgeon's posture (Yu et al., 2017) • IMU are small, lightweight, and nonobtrusive (Davila et al., 2021) • Provide complete procedural data instead of snapshots (Asadi et al., 2021; Davila et al., 2021)	• Possible errors in sensor positioning and skin movement (Carbonaro et al., 2021) • Risk of surgeon overload (Carbonaro et al., 2021) • Prospective collection requiring trained researcher (Davila et al., 2021; Yu et al., 2017) • Lack of differentiation between demanding and non-demanding musculoskeletal efforts in static postures (Yu et al., 2017) • Cumbersome wrist sensors in close proximity to operating area (Dabholkar et al., 2020) • Inability to determine musculoskeletal demand from IMU data alone (Davila et al., 2021) • Use of segment kinematics instead of kinematics across joints (Davila et al., 2021) • Artifact motions in upper arm sensors, adding variability to recorded data (Norasi et al., 2021) • The magnetometer component of each sensor can be subject to electromagnetic interference (Arrighi-Allisan et al., 2022) • Upper limb sensors may interfere with sterile scrubbing (Arrighi-Allisan et al., 2022) • Participant's awareness of the sensors may result in more vigilant or altered posture (Arrighi-Allisan et al., 2022)
Urologic	Head, sternum, upper arms, and pelvis (Yu et al., 2017) Head and upper arms (Reddy et al., 2023)		
Otolaryngologic	Spinal, shoulder and elbow (Dabholkar et al., 2020); Forehead, sternum, upper arms, lower abdomen, thighs, legs, and feet (Arrighi-Allisan et al., 2022)		
Vascular	Upper arms, head, and upper torso (Davila et al., 2021; Norasi et al., 2021)		

Methodologies for Ergonomic Risk Assessment

Following the data collection phase, all the identified studies undertook a comprehensive risk assessment to evaluate risk factors, such as posture, force, and repetition. When evaluating parameters associated with posture risk factor, most of the studies applied the Rapid Upper Limb Assessment (RULA) or Rapid Entire Body Assessment (REBA) methods, which classify joint angles using established risk levels (Athanasiadis et al., 2021; Carbonaro et al., 2021; Dabholkar et al., 2020; Davila et al., 2021; Monfared et al., 2022; Norasi et al., 2021; Reddy et al., 2023; Yang et al., 2021; Yu et al., 2017). RULA and REBA assigns scores to body regions based on predefined joint angle thresholds, facilitating the association of risk levels with observed body postures. By incorporating work process recordings, these studies were able to analyze the percentage of time each surgeon spent in various risk categories for each body segment, enabling categorization into ergonomic risk groups. The relative average risk score over time provided a more precise assessment of exposure compared to RULA or REBA solely through observation. The RULA was employed in eight studies (Athanasiadis et al., 2021; Carbonaro et al., 2021; Davila et al., 2021; Monfared et al., 2022; Norasi et al., 2021; Reddy et al., 2023; Yang et al., 2021; Yu et al., 2017). In addition, one study employed REBA (Arrighi-Allisan et al., 2022).

In contrast, the study conducted by Bartnicka and colleagues adopted a distinct approach, using the CAPTIV system to assess kinematic data retrieved from IMU sensors (Bartnicka et al., 2015). CAPTIV comprises both a hardware component, which is a wireless system for angular measurement of body postures, and a software component, serving as an application for the acquisition of quantitative and qualitative data, synchronization, and video analysis. This integrated system aids in identifying awkward postures and offering insights into the circumstances in which such postures occurred (Bartnicka et al., 2015).

For the assessment of repetitive tasks through data from the IMU sensors, Dabholkar and colleagues demonstrated the significance of repetition as a risk factor by analyzing movement frequencies, which measure the number of movements per unit of time (Dabholkar et al., 2020).

In handling data retrieved from sEMG sensors, the four studies adopted different approaches. Two studies analyze the recorded EMG data during the surgical tasks as a percentage of each muscle's maximum voluntary contraction (%MVC) for force analysis. The studies defined any contraction exceeding 10%MVC as demanding muscle use (Athanasiadis et al., 2021; Monfared et al., 2022). On the other hand, Asadi and colleagues used IMU sensors to identify time windows where the surgeon was static and in non-demanding postures, calculating mean power frequencies for those periods to assess fatigue in surgeons during demanding, nonrepetitive work (Athanasiadis et al., 2021). In the study conducted by Merbah and colleagues, time and frequency-domain variables of the root-mean-square amplitude and mean power frequency, respectively, were calculated from an EMG signal to quantify and visualize muscular activity through a color-coded map and to quantify muscular fatigue (Merbah et al., 2023).

Some Examples of Ergonomic Analysis Using Wearable Sensors

Given the similarity of ergonomic analysis approaches in the studies, this subsection presents the outcomes offered by the ergonomic risk assessments from three of the included studies. Two studies collected data from IMU sensors, with one utilizing RULA and the other employing CAPTIV system to assess the data (Bartnicka et al., 2015; Yu et al., 2017). Additionally, one study assessed the data from sEMG sensors (Athanasiadis et al., 2021).

In the study conducted by Yu and colleagues, an assessment of 15 cases involving robotic-assisted radical prostatectomy aimed to quantify and compare ergonomic strain among console surgeons and surgeon assistants (Yu et al., 2017). Both console and assisting surgeons wore IMU sensors that continuously monitored neck, shoulder, and torso movements without compromising the sterile field. The results unveiled that assisting surgeons maintained awkward neck postures for 58% of the procedure, contrasting with 24% for console surgeons ($p < 0.01$). Console surgeons predominantly exhibited static postures and displayed two to five times fewer movements than assisting surgeons ($p < 0.01$).

Meanwhile, the study conducted by Bartnicka and colleagues aimed to identify extreme and awkward right wrist postures during bariatric procedures and to investigate the circumstances in which such postures occur (Bartnicka et al., 2015). The procedure involved angular measurements and video recordings of surgeons, synchronization of video footage and measurement data in CAPTIV software, and the definition of codes for ergonomic analysis of the right wrist based on factors affecting working conditions. In this case the types of surgical instruments and the types of surgical tasks were included as codes for the ergonomic analysis. The results revealed that despite the harmonic knife being the most frequently used instrument (approximately 58% of the surgery time), extreme wrist flexion/ extension postures were primarily observed during the use of the endostapler (used only in approximately 10% of the surgery time).

Concerning the outcomes of the study using data retrieved from sEMG sensors, Athanasiadis and colleagues assessed the ergonomic risk of 11 trainees and nine surgeons during laparoscopic surgery (Athanasiadis et al., 2021). Bilateral deltoid and trapezius muscle activity was recorded and expressed as %MVC. Trainees exhibited lower EMG activity in most muscle groups compared to attending surgeons. Additionally, while all participants exhibited high levels of muscle overuse (demanding EMG activity) throughout the procedure, trainees spent less time in demanding contractions than attending surgeons.

The findings of these studies underscore the potential of wearable sensors for effectively evaluating the risk factors faced by surgeons during surgical procedures. By objectively assessing parameters related to physical risk factors, these sensors can provide valuable insights into potential ergonomic hazards and contribute to the development of interventions to prevent WRMSD among surgeons.

CONCLUSION

This article reviewed 13 studies that used wearable sensors in performing the ergonomic risk assessments of surgical settings. The paper identified the wearable sensors employed in such ergonomic risk assessments, delving into the nuanced strengths and limitations of these sensors as reported by the studies' authors. Additionally, a comprehensive analysis of the methods applied in these studies provides a deeper understanding of the evolving landscape of ergonomic risk assessment in surgery.

A significant proportion of the papers included in this literature review were published in the last three years, representing 77% of the studies. Thus, a clear growing trend is verified regarding this topic.

The integration of wearable sensors into surgical workflows heralds a potential revolution in approaching ergonomic risk assessments and preventive strategies for WRMSD within surgical procedures. Notably, the studies' outcomes underscore the pivotal role played by IMU and sEMG sensors in objectively quantifying exposure to physical risk factors, such as posture, force, and repetition, which are known contributors to WRMSD development. Wearable sensors enable real-time identification of these risk factors, which empowers surgeons to make informed decisions during surgery, effectively mitigating their exposure and reducing the likelihood of WRMSD occurrence. Furthermore, wearable sensors provide valuable insights that can inform the development and implementation of targeted interventions, improving surgical efficiency and fostering a healthier surgical workforce.

Nevertheless, the review revealed a current scarcity of studies exploring the use of wearable sensors in surgical environments. Therefore, ongoing research efforts are essential to unlock the full potential of these technologies and ensure their seamless integration into the realm of surgical practice. Looking to the future, further exploration and refinement of wearable sensor applications are imperative to advance the field, enhance surgical outcomes, and contribute to the occupational safety and well-being of surgical professionals.

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