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Use of an Intraoperative Head, Neck, and Back Support Exoskeleton on Surgeons' Pain and Posture

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Structured Abstract

- Objective: Evaluate the effectiveness of an intraoperative exoskeleton that supports surgeons' heads, necks, and backs to reduce neck discomfort.
- Summary Background Data: Surgeons are at a considerable risk of developing neck pain and related injuries. Passive exoskeletons are a potential intervention to support surgeons' body parts and alleviate strain and discomfort.
- Methods: The NekSpine^{TM} (a passive neck exoskeleton) was trialed on twelve surgeons (seven male, five female) across six specialties. Each surgeon performed four surgical procedures, two with the NekSpine^{TM} (exoskeleton) and two without (baseline).

Exoskeleton and baseline surgeries were paired primarily by surgical procedure and secondarily by duration. Surgeons completed surveys that included the NASA-TLX and usability questions before and after surgical procedures to evaluate body part discomfort, overall fatigue, workload, and potential disruptions to the surgical workflow. Surgeons also wore inertial measurement units (IMUs) to objectively record their upper arms, neck, and torso postures.

- Results: Use of the exoskeleton yielded significant decreases in discomfort in the neck, left shoulder, right shoulder, and left arm. Reductions in percent surgical duration in Risk 4 (extreme risk postures) coupled with increases spent in Risk 2 (moderate risk postures) for the neck and torso were noted. Surgeons reported overall favorable usability results with the exoskeleton not interfering with the surgical workflow, and most stated that they would use the exoskeleton again.
- Conclusions: The NekSpine™ is a promising intervention to alleviate surgeons' neck discomfort and improve their neck and torso postures.

Introduction

Surgeons are at risk for developing work-related neck pain and fatigue due to holding ergonomically risky postures during extended surgeries[1]. This may lead to musculoskeletal disorders (MSDs) and can decrease surgeon's performance, necessitate early retirement, increase burnout, and decrease career satisfaction[2–4]. A survey of 775 surgeons from the Society for Vascular Surgery (SVS) revealed significant increases in musculoskeletal pain before and after each operation; 45.2% of those surgeons stated that the body segment in the most pain was their neck[5].

Previous studies demonstrated that risky postures affect numerous surgical specialties and can increase fatigue and work-related neck pain[2,5–8]. One study by Mayo Clinic analyzed 116 surgical procedures and observed that surgeons held risky neck postures during 42% of laparoscopic surgeries and 80% of open surgeries[9]. Likewise, a quantitative assessment of breast surgeons' neck postural exposure showed high intraoperative mean flexion angles ranging between 27.3-32.9°, which is considered risky for developing musculoskeletal neck pain[10].

One promising intervention for mitigating this risk is passive exoskeletons. Passive exoskeletons are non-powered devices that rely on energy storage in their elastic parts to support users' body segments during awkward postures to reduce postural load, fatigue, pain, and physical demand, thereby reducing the likelihood of developing pain and, ideally, MSDs. This intervention has yielded positive results in non-healthcare environments, especially during physically demanding tasks focused on the upper extremities[11,12] and the lower back[13–15], by reducing muscle activities at targeted body parts, subsequently decreasing perceived discomfort levels and increasing workers' endurance times.

Due to the success of exoskeletons in non-healthcare settings, back and arm exoskeletons for surgeons[16] and other healthcare professionals[17,18] have been previously tested. However, only a few studies have trialed exoskeletons that support surgeons' heads and necks, with one being a Ph.D. thesis[19] and the other a lab-based study on undergraduate students[20]. While these studies are promising, the actual operating room (OR) has unique constraints that make implementing passive neck exoskeletons much more challenging[21].

This project aims to assess the ergonomic characteristics and usability of a passive exoskeleton that supports the head-neck complex during surgical procedures with high-risk neck flexion postures. Specifically, this project will evaluate the exoskeleton's ability to reduce surgeons' neck discomfort and pain while performing open surgeries in various specialties without significantly restricting their range of motion. Additionally, the exoskeleton's usability will be evaluated to ensure that the exoskeleton is not impeding the surgeon and their surgical team.

It was hypothesized that I) the exoskeleton would lead to significant reductions in self-reported neck discomfort and II) reduce extreme, awkward, and ergonomically high-risk postures relative to baseline conditions. Additionally, III) we expected favorable usability scores, demonstrated by the exoskeleton not interfering with the surgeon's or their team's workflows and their desire to use it again during future procedures, and IV) there would not be significant differences in surgeons' perceived workloads between exoskeleton and baseline surgeries.

Methods

This study evaluated a commercially available passive exoskeleton (NekSpine™, Composite Manufacturing Inc., San Clemente, CA). The NekSpine™ is a biomedically

engineered spinal support system designed to reduce stress on the cervical and thoracic spine. Its action supports the head-neck during awkward intraoperative flexed neck postures. As shown in Figure 1, the device consists of three main parts: 1) a carbon-fiber support beam running the length of the lumbar, thoracic, and cervical spine to transfer the load from the head to the hips, 2) an adjustable backpack-like component that houses the support beam, and 3) an adjustable headpiece which connects to the support beam via an inextensible cable fixed to a block that slides up and down the beam enabling head flexion and rotation; this headpiece can also support surgical headlights. When wearing the NekSpine™, surgeons should feel that their head is supported, as if a hand is holding their forehead gently while they look down.

Twelve attending surgeons from a single academic hospital were recruited and voluntarily participated in this study; specialties with extreme neck flexion were targeted[1], and those recruited subsequently suggested other surgeons who performed similarly applicable surgeries. Surgeons were then asked to identify open surgeries where they typically held risky neck postures, ideally lasted at least 2 hours, and would personally perform at least 50% of the surgery. Participants performed two pairs of two surgical procedures (four completed in total), with each pair consisting of the same type of surgery (e.g., skin-sparing mastectomy (SSM)); one done with the exoskeleton and one without (baseline). These matching exoskeleton and baseline surgeries were then compared. If surgeons performed the same surgical procedure during both pairs of cases, they were matched based on duration (e.g., if a surgeon performed four SSMs, the longest baseline surgery would be paired with the longest exoskeleton surgery) during the data analysis. The order of exoskeleton and baseline surgeries were randomized by participant to reduce potential bias.

Surgeons were introduced to the exoskeleton outside of the OR to find the appropriate exoskeleton size and comfortable settings, as established by Wang et al.[16]. Each surgeon trialed the exoskeleton during a short (~1 hour) portion of a surgery to ensure they were comfortable with the exoskeleton and did not anticipate any issues for themselves, staff, or their patients.

During surgeries with the exoskeleton, the researchers were present in the OR to fit, don, and doff the exoskeleton. After confirming the exoskeleton's comfort, the researchers stayed outside the OR to be available for any adjustments the surgeon might need during the surgery, ensuring it remained supportive and comfortable throughout the procedure.

Surgeons completed a survey and wore inertial measurement units (IMUs) by APDM Wearable Technologies Inc. (Portland, OR). Surveys were administered immediately before and after each surgery and evaluated overall fatigue and body part discomfort (modified Nordic Musculoskeletal Questionnaire (NMSQ))[22] on a Borg CR-10 scale[23] (0 to 10 scale, with 0 = none and 10 = extreme (maximum)) before, during, and after surgical operations; intraoperative workload based on NASA-Task Load Index (TLX)[24] (0 to 20 scale, with 0 being very low and 20 being very high), difficulty relative to a "standard" procedure, actual difficulty relative to their initial expectations, and intraoperative exoskeleton usability[25]. Usability questions asked surgeons to evaluate the exoskeleton on a 0 to 10 scale about its potential interference, improvements, changes in range of motion, and changes in physical comfort. Three yes/no questions asked whether surgeons would want to use the exoskeleton again, if the exoskeleton interfered with their workflow, or whether it interfered with surgical equipment or colleagues.

IMUs were worn on the back of the head, right and left upper arms, and upper torso to track surgeons' intraoperative postures. These postures were then interpreted using the methodology developed by Davila et al.[26] and Morrow et al.[27,28] to calculate mean body part

angles and the percentage of surgical duration spent in specific risky postures and based on the Rapid Upper Limb Assessment (RULA) of McAtamney & Corlett[29]. Angles of each body part were quantified into one of four risk categories, with one being minimal risk, two as mild, three as moderate, and four being extreme risk, and the percent surgical duration in each risk category was calculated[26]. A list of dependent variables is shown in Table 1:

Matching procedures were paired, and the pairs' differences in workload, discomfort, difficulty, and postures were calculated. Body segment discomfort and overall fatigue were evaluated at three separate time points: before, during, and after the surgical procedure ("during" and "after" fatigue/discomfort scores were simultaneously and retroactively reported after the surgery). Changes in these scores were defined as the difference between the discomfort level "before" and the larger discomfort level from "during" or "after" the surgery. These changes in body part discomfort and overall fatigue will subsequently be referred to as "*(specific body part)* discomfort" and "overall fatigue" throughout the rest of the paper.

Statistical analyses were performed using JMP Pro 17 (SAS, Cary, NC). For each dependent variable, a Shapiro-Wilk test was used to assess normality. Statistically significant differences between exoskeleton and baseline conditions were then evaluated using Paired Student *t*-tests for normally distributed data, while Wilcoxon-signed Rank tests evaluated data that violated normality. Statistical significance was defined as having a p-value ≤ 0.05. Thematic analyses were used to identify common themes from the usability evaluations.
This study was approved by this academic medical center's Institutional Review Board (IRB) before recruiting participants or collecting data. All participants consented to the study and were not compensated for participating.

Results

Demographic and Surgery Breakdown

Twelve surgeons (seven male, five female) specializing in breast (four), cardiovascular (two), gynecological (one), plastic (two), thoracic (two), and vascular/endovascular (one) surgery performed a total of 48 surgical procedures (four per surgeon); specific surgery types and their matching pairs are listed in Appendix Table I, Supplemental Digital Content 1, http://links.lww.com/SLA/F458. All surgeons were right-handed. On average, the surgical duration was 2:42 (H:M); exoskeleton surgeries lasted 2:32, and baseline surgeries lasted 2:52. These durations did not differ significantly (Student *t*-test *p*-value = 0.06), with the baseline procedure 0:20 longer on average. Surgical procedures ranged between 0:40 and 5:12.

NASA-TLX Workload

There were no statistically significant differences in perceived procedure difficulty between exoskeleton and paired baseline cases (Student *t*-test *p*-value = 0.29) or difficulty relative to initial expectations (Student *t*-test *p*-value = 0.52).

Exoskeleton procedures were scored at higher Mental and Physical Demand levels than paired baseline surgeries by 2.6 (Student *t*-test *p*-value = 0.01) and 1.7 (Student *t*-test *p*-value = 0.05) on a 20-point scale, respectively. No statistically significant differences existed in Temporal Demand, Performance, Effort, or Frustration between exoskeleton and baseline surgeries. Average reported workloads for exoskeleton and baseline surgeries are shown in Figure 2.

Body Part Discomfort/Overall Fatigue

There were statistically significant decreases in discomfort when using the exoskeleton for the neck (Student *t*-test *p*-value = 0.05), left shoulder (Wilcoxon Signed-Rank Test *p*-value < 0.001), right shoulder (Wilcoxon Signed-Rank Test *p*-value = 0.02), and left upper arm (Wilcoxon Signed-Rank Test *p*-value = 0.01). There were no differences in discomfort between the right upper arm, either wrist, upper or lower back, or overall fatigue. These results can be seen in Figure 3.

IMUs

Statistically significant decreases in mean angles were seen in the neck (Wilcoxon Signed-Rank Test *p*-value < 0.001) when using the exoskeleton compared to baseline surgeries, as seen in Figure 4. The mean angle of the neck reduced from 33.4° during baseline to 28.6° during exoskeleton surgeries, with an average difference of 4.8°. There were no statistically significant decreases in mean angles on either the left or the right arms or torso.

Changes in mean angles relative to potential discomfort can be better explained using the four risk categories[1,26,28]. Statistically significant changes in ergonomic risk were noted in the neck and torso; the exoskeleton led to significant ergonomically favorable decreases in Risk 4 (the most extreme, riskiest posture; neck Wilcoxon Signed-Rank Test *p*-value < 0.0001, torso Wilcoxon Signed-Rank Test *p*-value < 0.0001) and ergonomically favorable increases in Risk 2 (moderate risk posture; neck Student *t*-test *p*-value < 0.01, torso Student *t*-test *p*-value < 0.01) relative to baseline surgeries. There were also ergonomically favorable decreases in Risk 3 for both the neck and the torso while wearing the exoskeleton, but these findings were not statistically significant, as shown in Figure 5.

Usability

Surgeons responded favorably overall to usability questions about the exoskeleton, as the exoskeleton minimally interfered with surgeons' abilities to perform surgery and did not compromise their range of motion. Additionally, the exoskeleton was reported to slightly increase surgeons' physical comfort and ability to perform surgery. The results of these usability questions are reported in Table 2.

During one atypical surgical procedure, the exoskeleton restricted the surgeon's mobility during the second half of the surgery and had to be removed; the first half was completed without incident. In the survey, the surgeon reported 10 for exoskeleton interference and range of motion (greatly interfered, extremely limiting) and -4 for change in physical comfort. If this surgery were to be removed, the ranges in Table 2 for interference with surgical ability, range of motion, and changes in physical comfort would change to (0 to 4), (0 to 6), and (-1 to 5), respectively. Additionally, the surgeon performed this same procedure again with the exoskeleton but completed the entire surgery successfully.

When asked whether they would be interested in using the exoskeleton during future surgeries, surgeons responded "Yes" during 91.7% (22/24) of the surgeries. Surgeons handwrote "Maybe" during two surgeries instead of selecting the provided "yes or no" options. Favorable responses were also seen when asked whether the exoskeleton interfered with their workflow or their colleagues' workflows/surgical equipment, with surgeons reporting that the exoskeleton did not interfere during 87.5% (21/24) and 100% (23/23; one questionnaire was accidentally missed), respectively.

Discussion

In this study, we set out to prove four hypotheses: the exoskeleton, relative to baseline, would lead to I) reductions in neck discomfort, II) reductions in extreme, ergonomically unfavorable neck postures, III) overall positive usability scores with minimal interference from the exoskeleton on the surgical workflow, and IV) minimal differences in surgeons' workloads. Our data supported all four hypotheses overall.

Demographic and Surgery Breakdown

We sought to recruit an equal number of male and female surgeons and ended with seven males (58.3%) and five females (41.7%). Although there are more males than females in the surgical population[30], we oversampled female surgeons to ensure that the exoskeleton would be useable across both sex and anthropometric ranges. Additionally, we trialed the exoskeleton across six surgical subspecialties. It should be noted that the exoskeleton was only assessed during open surgeries, as these surgeries typically require a greater degree of neck flexion compared to other approaches (e.g., laparoscopic or robotic).

Hypothesis I) Body Part Discomfort and Overall Fatigue

Surgeons experienced significantly lower neck discomfort when using the exoskeleton relative to baseline. Considering the purpose of the NekSpine™ is to support the head-neck complex, this reduction was unsurprising and supported our first hypothesis regarding decreases in neck discomfort. Surgeons stated that it felt like the exoskeleton was "passively supporting" them and that they forgot they were wearing it. They also noted that after the exoskeleton's tension was disabled, they felt as if their "head was heavy."

Along with the reductions in neck discomfort, the exoskeleton significantly reduced the discomforts of the left arm, right shoulder, and left shoulder. These findings were surprising as

the exoskeleton did not support the surgeon's arms, and the effect was seen more on surgeons' left sides than right sides despite all the surgeons being right-handed. Surgeons may have been altering their operating techniques, leading to this reduced discomfort, though further inquiry is necessary. Considering the exoskeleton was not increasing surgeons' discomfort, these findings were a beneficial, yet unexplained, side-effect.

Hypothesis II) Postural Changes

Postural data objectively assessed the exoskeleton's effects. Using the exoskeleton significantly improved surgeons' neck and torso postures, as shown through the reductions in the percentage of surgical duration spent in Risk 4 (high-risk) and increases in duration spent in Risk 2 (mild risk).

In the case of the neck, statistically significant improvements were observed by increasing the surgical duration spent in Risk 2 and decreasing the duration spent in Risk 4. Additionally, while not statistically significant, surgeons spent 76.2% of their baseline surgeries on average in Risk levels 3 and 4, which was reduced to 69.4% while wearing the exoskeleton. As the two highest-risk postures, both risk categories should lead to the greatest discomfort experienced and are the most crucial to mitigate. Surgeons repeatedly stated that the exoskeleton was a subtle reminder not to go to the extremes of postures. These reductions are ergonomically beneficial and may explain surgeons' subjective decreases in neck discomfort.

Torso posture also improved by reducing the duration spent in Risk 4 and increasing the duration spent in Risk 2. However, surgeons did not note any significant decreases in upper or lower back discomfort between the exoskeleton and baseline conditions despite the improvements in torso posture. More importantly, torso posture improvements meant that

although surgeons reduced their average neck flexion angle, they were not compensating with increased torso flexion.

The exoskeleton had a two-fold effect on surgeons' ergonomics: first, the exoskeleton supported surgeons' body segments, and second, the exoskeleton reminded surgeons to reduce extreme angles. The support for surgeons' heads was variable, so surgeons could calibrate it to support their heads at any operating posture they desired, even high-risk postures, theoretically reducing neck pain. Simultaneously, setting the tension established an upper limit on the degree of neck flexion allowed without fighting against the exoskeleton. Surgeons were instructed to calibrate the exoskeleton to a "comfortable" level but not necessarily favorable ergonomic postures. Despite the lack of instructions, surgeons naturally set the exoskeleton to support them at less flexed postures, and the upper limit reminded them to avoid the higher-risk postures typically assumed during baseline surgeries. While this study examines short-term effects, long-term implications may exist, such as whether the exoskeleton could be a training tool to help improve surgeons' postures even during baseline surgeries.

Hypothesis III) Usability

Although the findings of the exoskeleton's effects on discomfort and posture appeared to provide ergonomic benefits, they would be meaningless if they were considered unusable to the surgeon or if they interfered with the surgical workflow. Surgeons were overall favorable regarding the exoskeleton's usability, as reported by surgeons saying "Yes" (22/24) and "Maybe" (2/24) when asked whether they would want to use the exoskeleton again. Additionally, the exoskeleton typically did not interfere with surgeons' workflows, as there were no issues during 21 of the 24 surgeries. During the three surgeries with interference, 1) the exoskeleton's headgear pulled the surgeon's goggles upwards and had to be readjusted, 2) the surgeon could not find a

comfortable/familiar angle for the headlight while it was attached to the headgear, and 3) the surgeon noted that it took an extra three to five minutes to scrub in due to application of the exoskeleton and sensors. These issues were resolved during the surgeons' other exoskeleton surgeries, and the delay was due to the study design and not the exoskeleton itself.

Finally, surgeons were asked whether the exoskeleton interfered with their surgical colleagues or equipment. This question was accidentally missed during one surgery, but during all other surgeries, there were no instances of the exoskeleton interfering with their colleagues or surgical equipment.

Surgeons also evaluated the exoskeleton interfering with surgical ability, improvement to surgical abilities, compromises to range of motion, and changes in physical comfort. Most surgeons reported that the exoskeleton did not interfere with their surgical ability or compromise their range of motion. The exoskeleton provided slightly increased comfort and improved surgical ability. It should be noted that during one surgery, one surgeon had to remove the exoskeleton during the second half due to it restricting his mobility, which led to the surgeon answering, "greatly interfered" and "extremely limiting." These issues did not occur during the first half of this surgery or the entire second surgery and appeared to be an outlier in the exoskeleton's performance, but this instance of the exoskeleton limiting mobility is worth considering.

Hypothesis IV) NASA-TLX Workload

The exoskeleton increased surgeons' Mental and Physical Demands but did not affect the other workloads. The lack of significant differences between exoskeleton and baseline cases when comparing procedure difficulty suggests that the exoskeleton may have contributed to this workload instead of inherent differences in case difficulty. The novelty of the exoskeleton may

explain this increase in these demands and having to adjust to atypical, albeit improved, postures. This increase in Mental Demand may indicate a potential learning curve, which was out of the scope of this study as surgeons only performed two exoskeleton surgeries, though assessing the change in Mental Demand in a longitudinal study would be worth considering.

Surgeons also reported higher Physical Demands during exoskeleton cases despite their reported decreases in discomfort and improvements in posture while wearing the exoskeleton. The learning curve may again explain this increase in Physical Demand as surgeons had to operate in unfamiliar postures. Although these postures were improved, these novel postures could have felt more physically demanding to the surgeons due to the lack of familiarity.

Limitations and Conclusion

There are plans to incorporate additional participants, such as residents and fellows from additional institutions, in a subsequent study, but this study itself is limited by the small, voluntary sample size from a single institution, which may affect its generalizability. The individual characteristics of each surgeon may have also affected the results, such as varying operative volume and schedules. Paired Student *t*-tests were used to mitigate these additional factors, though their effects may have still been present. Additionally, the exoskeleton was only assessed during a select number of procedures, most notably only during open surgeries, so these results may not be generalizable to other approaches like laparoscopic, microscopic, or robotic; however, some surgeons did express interest in using the exoskeleton during these untested approaches. Finally, participants volunteered to participate and were not blinded to the effects of the exoskeleton, creating the possibility of a self-selection bias and placebo effect. Despite these possibilities, our objective postural data indicate that actual differences could be measured separately from and corroborating with the subjective questionnaire results.

In conclusion, this study evaluated the effectiveness of the NekSpine™ in reducing surgeons' neck discomfort, improving postures, and its overall favorable usability results. While this exoskeleton is not expected to be a solution to solve every surgical ergonomic issue, it appears to be a step in the right direction in potentially alleviating neck discomfort and may be beneficial in reducing long-term injuries and improving surgical ergonomics.

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Figure 1a: The NekSpine™ Exoskeleton

Figure 1b: Surgeon (on the right) wearing the NekSpine™ exoskeleton during open surgery

Figure 1: The NekSpine™ Exoskeleton

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Figure 1a: The NekSpine™ Exoskeleton

Figure 1b: Surgeon (on right) wearing the NekSpine™ exoskeleton during open surgery

Figure 2: Average Changes in Workloads During Exoskeleton and Baseline Surgeries

** indicates p-value ≤ 0.05, ** indicates p-value ≤ 0.01, *** indicates p-value ≤ 0.001*

Workloads were evaluated on a 0 to 20 scale, with 0 being minimal workloads (i.e., very low mental demand) and 20 being maximal workloads (i.e., very high mental demand). Performance scores were inverted in this figure, meaning 0 meant failure and 20 meant perfection.

The error bar shows the standard deviation of the average workload score.

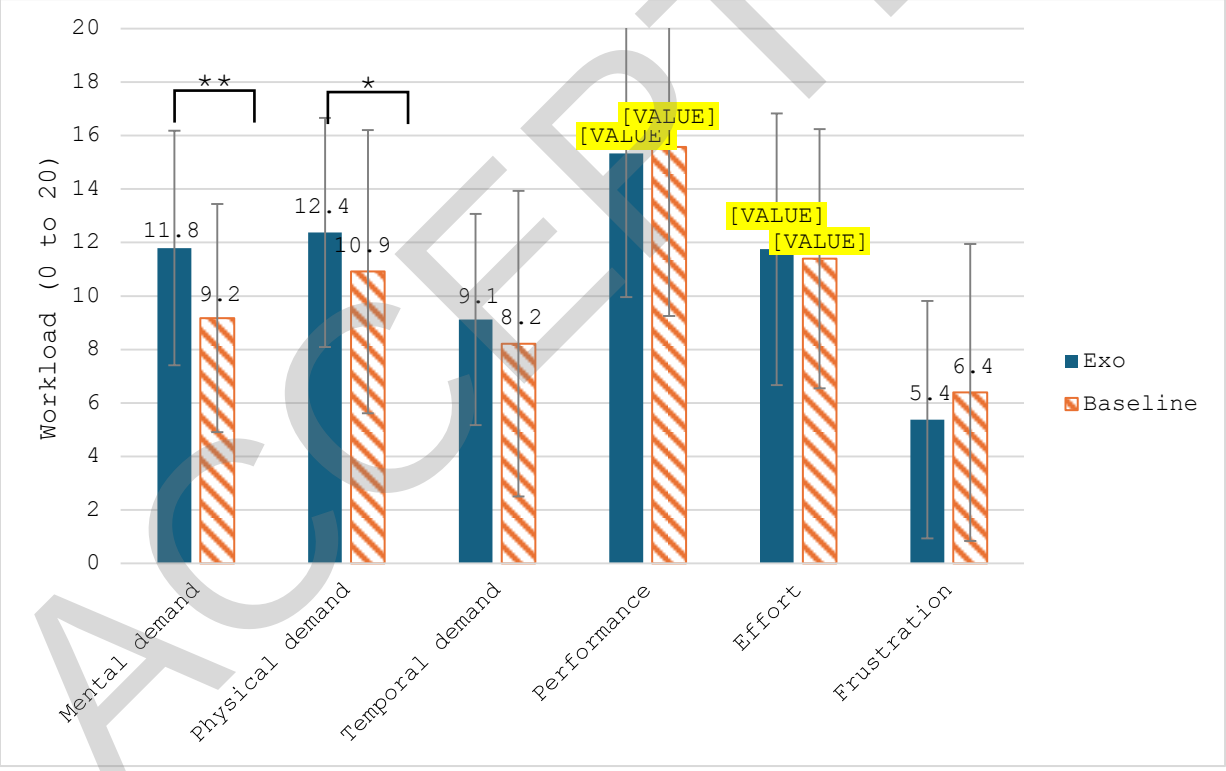

Figure 3: Average Changes in Discomfort by Body Part and Overall Fatigue During Exoskeleton and Baseline Cases

Surgeons evaluated pain on a 0 to 10 scale, with 0 = no pain and 10 = extreme pain; differences between the beginning of the surgery and during/after were calculated. Positive meant an increase in pain from before to during/after; negative meant a decrease in pain from before to during/after

** indicates p-value ≤ 0.05, ** indicates p-value ≤ 0.01, *** indicates p-value ≤ 0.001*

The error bar shows the standard deviation of the average workload score.

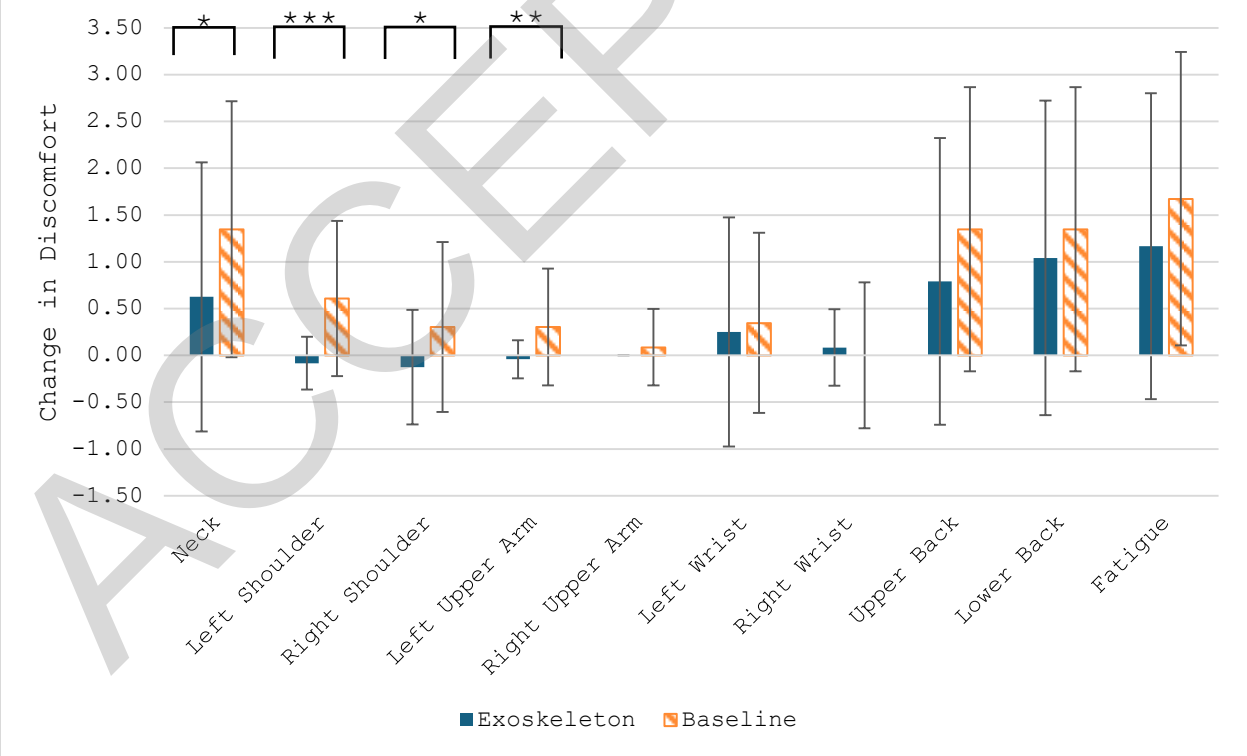

Figure 4: Average Changes in Postural Angles During Exoskeleton and Baseline Surgeries

** indicates p-value ≤ 0.05, ** indicates p-value ≤ 0.01, *** indicates p-value ≤ 0.001*

The error bar shows the standard deviation of the average workload score.

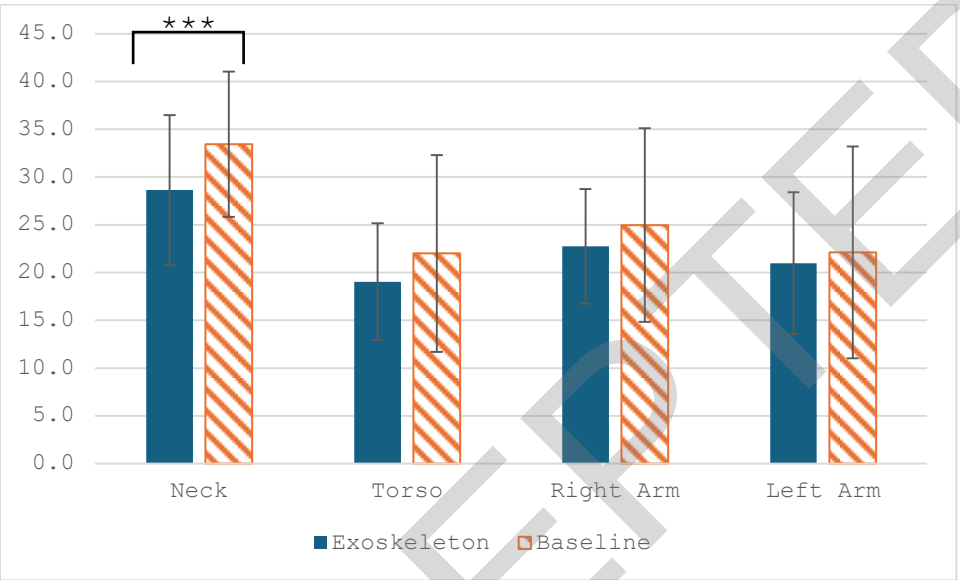

Figure 5a: Percentage of Surgery in High-Risk Neck Postures	Figure 5b: Percentage of Surgery in High-Risk Torso Postures
Figure 5c: Percentage of Surgery in High-Risk Left Shoulder Postures	Figure 5d: Percentage of Surgery in High-Risk Right Shoulder Postures

Figure 5: Average Percentage of Surgery Duration in High-Risk Postures

** indicates p-value ≤ 0.05, ** indicates p-value ≤ 0.01, *** indicates p-value ≤ 0.001*

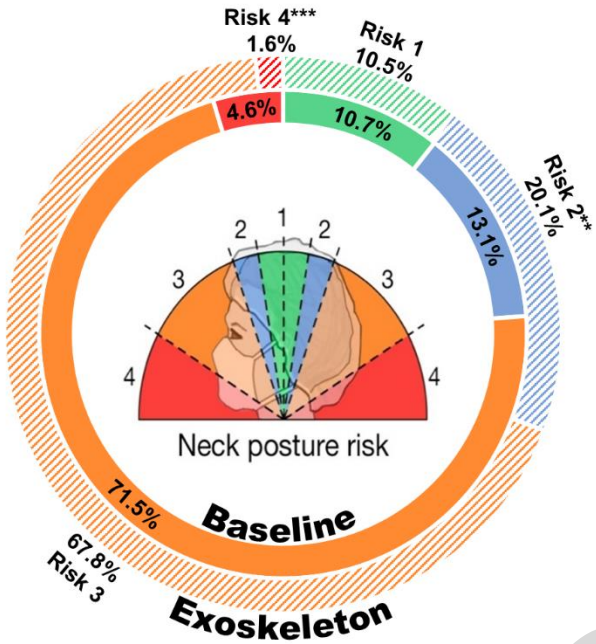

Figure 5a: Percentage of Surgery in High-Risk Neck Postures

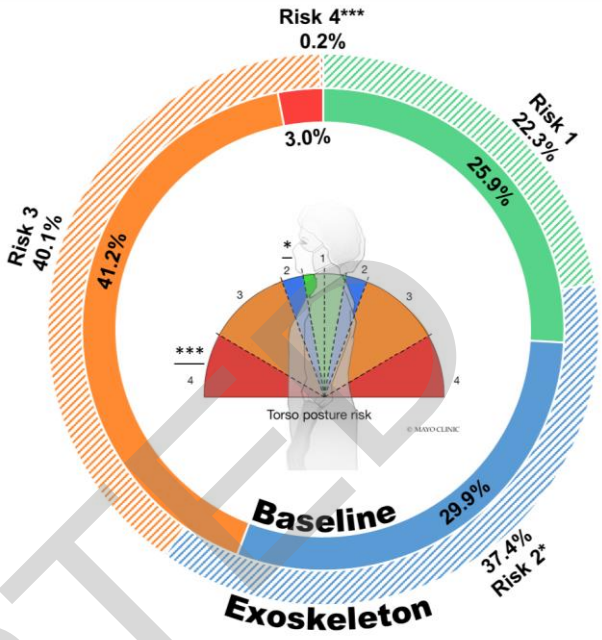

Figure 5b: Percentage of Surgery in High-Risk Torso Postures

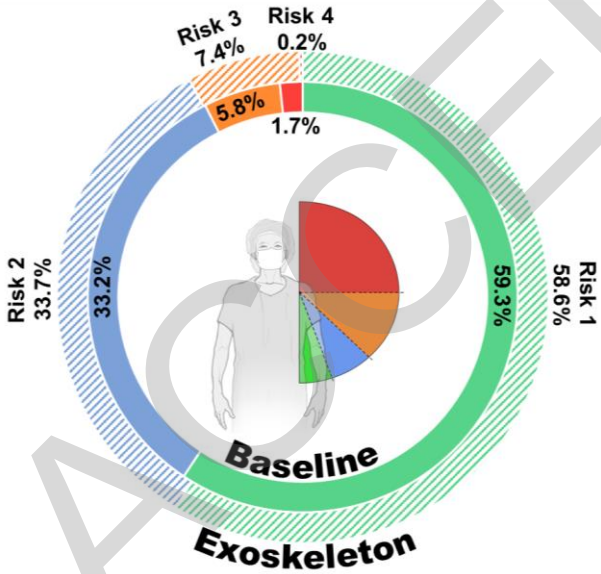

Figure 5c: Percentage of Surgery in High-Risk Left Shoulder Postures

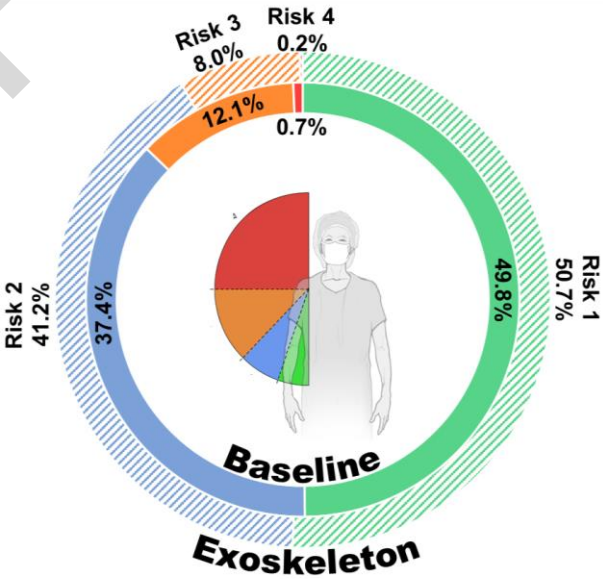

Figure 5d: Percentage of Surgery in High-Risk Right Shoulder Postures

Table 1: List of Dependent Variables

Difficulty/Workload Metrics	Discomfort/Fatigue Metrics	Posture Metrics
Difficulty based on procedure type Difficulty based on patient factors NASA-TLX Workload (0 to 20 scale) • Mental Demand • Physical Demand • Temporal Demand • Performance • Effort • Frustration Usability (exoskeleton trials only; Borg CR-10 Scale) • Did the exoskeleton interfere with your ability to perform surgery? • Did the exoskeleton improve your ability to perform surgery? • Was your range of motion compromised? • Did the use of the exoskeleton increase your physical comfort when performing surgical procedures? Usability (exoskeleton trials only; binary questions) • Given the choice, would you want to use the exoskeleton in future surgical procedures? • Did wearing the	Changes in Discomfort/Overall Fatigue (Borg CR-10 Scale) • Neck • Left Shoulder • Right Shoulder • Left Upper Arm • Right Upper Arm • Left Wrist/Hand • Right Wrist/Hand • Upper Back • Lower Back • Overall Fatigue	Mean angle (degrees) • Neck • Torso • Right Upper Arm • Left Upper Arm Duration in Risky Postures 1-4 (%) • Neck • Torso • Right Upper Arm • Left Upper Arm

exoskeleton interfere with your normal workflow in any way? • Did the exoskeleton interfere with surgical equipment or the work of your colleagues?		

Table 2: Exoskeleton Usability Questions

	Average (Standard Deviation)	Range	IQR
Did the exoskeleton interfere with your ability to perform surgery? *(0 = no interference, 10 = greatly interfered)*	1.3 (2.2)	(0, 10)	(0, 1.25)
Did the exoskeleton improve your ability to perform surgery? *(0 = no improvement, 10 = great improvement)*	3.7 (2.6)	(0, 8)	(1, 5.25)
Was your range of motion compromised? *(0 = no limitation, 10 = extremely limiting)*	1.5 (2.5)	(0, 10)	(0, 2)
Did the use of the exoskeleton increase your physical comfort when performing surgical procedures? *(-5 = decreased comfort, 0 = no change, 5 = increased comfort)*	1.6 (1.9)	(-4, 5)	(0, 3)