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Use of field-based motion capture to augment observational data in ergonomic assessment of aircraft maintenance

Edwin Irwin*, Kristin Streilein

Mercer Engineering Research Center, Mercer University, Warner Robins, Ga 31088, USA

Abstract

A dramatically increasing trend in the population of aircraft painters with permanent physical limitations was identified among participants in the return-to-work program at a large aircraft maintenance facility. The increase came primarily from painters who had used a full-depth mechanical sanding depainting process. A detailed ergonomic assessment of the process was begun to elicit details of the range and types of risks faced by painters in that shop, and determine what types of mitigation might be utilized to minimize the prevalence of injury. Shoulder injuries represent the biggest area of ergonomic risk for painters. Cervical problems, hand/wrist problems, and lumbar problems make up the majority of the remainder of injuries. The extent, duration, and complexity of the risks involved in the depaint process required more data than the typical observational and psychophysical assessment tools could provide. Inertial motion capture and tool force instrumentation was implemented in combination with the typical ergonomic methods to provide more details as to the biomechanical sources of risk and how this varies throughout the depainting process. The results indicate surprisingly high normal forces on the palm sander, with rapid muscle fatigue and frequent postural substitution evident during overhead sanding. The long duration of this overhead activity, in combination with the evidence of fatigue, implicates the development of risky scapulo-humeral kinematics and end-of-range glenohumeral motion in the etiology of shoulder and cervical injuries. A mix of management and engineering strategies for mitigation resulted from the analysis.

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Keywords: Ergonomics; Motion capture

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* Corresponding author. Tel.: 1-478-953-6800; fax: 1-478-953-6815.
E-mail address: eirwin@merc-mercer.org

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1. Introduction

This project was initiated when statistics from a return-to-work program at a large aircraft maintenance facility, indicated a dramatically increasing trend of aircraft painters reporting permanent job limitations. At the end of 2011, 12% of participants in the return-to-work program were aircraft painters, accounting for approximately 5% of all aircraft painters in the facility. By June 2014, 21% of RTW participants were aircraft painters, accounting for 12% of the total number painters in the facility. Since the RTW program is voluntary and very dependent upon active recruitment efforts, there was a great deal of uncertainty whether this was a real increase in ergonomic risk for painters or simply a statistical artifact. Mercer Engineering Research Center (MERC) was asked to perform an in-depth study to determine the level of ergonomic risk faced by aircraft painters, and the specific sources of risk.

Depainting is performed at the facility primarily through chemical removal or mechanical sanding, depending on the aircraft manufacturer specifications. Sanding was judged to present the greatest ergonomic risk to aircraft painters. 50/50 sanding and scuff sanding are used for depainting large aircraft on the facility. Scuff sanding involves using a palm sander with coarse grit sand paper to roughen the surface enough to allow paint to adhere. 50/50 sanding involves use of the same sander and paper to remove all paint layers until half of the appearance is primer and half is paint. This requires significantly more dwell time to achieve with the sander than scuff sanding, and was thus targeted for further analysis.

The same sander is used for all sanding operations in the depaint area. It is a 3M model 20327 6” pneumatic random orbital palm sander. Without accessories, it weighs 2.35 lbs. The addition of 1/2” air hose, fittings, and dustbag brings the overall hand load to approximately 8 lbs.

Depainting a large aircraft, using a mix of 50/50 and scuff sanding processes, typically takes 8 days, working 3 shifts per day (nominally 24 shifts). Between 14 and 16 painter workers are programmed for each shift, though the actual number varies from 11-16 depending on staffing and absenteeism. Each shift has defined regions of responsibility on the aircraft: Day Shift is responsible for all areas of the fuselage; Swing Shift is responsible for the left side engines, and the upper and lower surfaces of the left wing and left side of the tail; Owl Shift is responsible for the right side engines, and the upper and lower surfaces of the right wing and the right side of the tail.

The ergonomic risks anticipated in the depaint process involved a combination of body/joint postures, force application, repetition, and hand/arm vibration. Postural risks include sustained or repeated awkward body or joint postures and end-of-range postures involving soft-tissue impingement. Forces applied through these awkward postures exacerbate the biomechanical risk. Vibrations are selectively absorbed by specific joints and structures, causing both biomechanical and tissue-level risks, primarily in areas of the hands and wrists.

The injury history data collected as part of the RTW program provided an indication of the relative severity of the various risks. Twenty one of the painters participating in the RTW program (70% of participating painters) came from those working directly on the aircraft, rather than on commodity parts. The median number of injuries/illnesses they reported was 2 per person. The onset date of the latest injury for 48% of these workers is 2011 or later. Interestingly, the median age for this group of employees is roughly 12 years younger than the overall median (41 years vs 53 years). This indicates a more rapid onset of permanent physical limitation than occurred in the past.

Shoulder injuries represent the biggest area of ergonomic risk for painters. Cervical (neck) problems, hand/wrist problems, and lumbar (low back) problems make up the majority of the remainder of injuries. A more detailed look at the subset of painters participating in the RTW program who experienced shoulder injury shows that 9 of the 21 (43%) participants has experienced at least one shoulder injury, with 4 of the 21 (19%) having more than 1 shoulder injury. The combination of shoulder and cervical issues are highly related to overhead work, and are worsened by repetition and force exertion [1].

Posture and task analysis techniques are typically used to document the level of risk in cases like this. They will not provide adequate information with which to identify mitigation strategies in this case due to the extent, duration, and complexity of the risks involved in the depaint process. More detailed time-based upper extremity motion data was needed to quantify the effect of overhead work on joint risk. Wireless motion capture instrumentation was used to measure segmental motion over extended periods, with time synchronization that allowed discrimination of risky and benign joint postures.

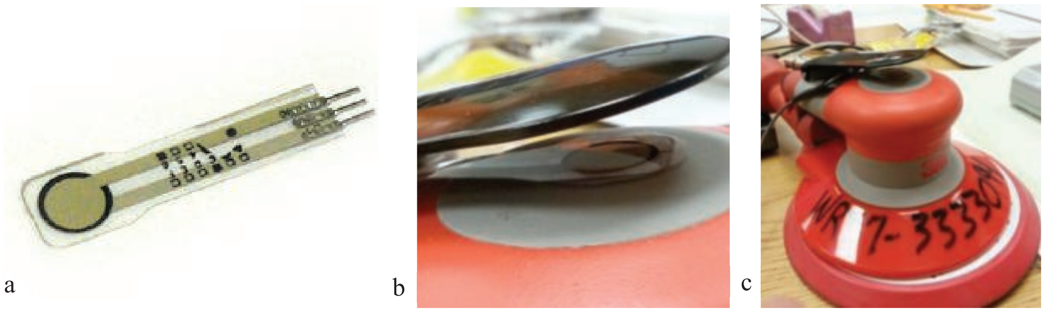

Fig. 1. Flexiforce A201 sensor (a) mounted (b) beneath the trigger of the 3M palm sander (c).

2. Methodology

Resistive film force sensors were used to measure the forces applied to the sander by painters. They were placed on the fingers of a glove and under the trigger of the sander. Experimentation showed a great deal of variability in measured force under the fingers, depending on placement of the sensors and orientation of the sander. The experiments showed that the hand assumed a typical power grip when the wrist was neutral, allowing for good finger force measurement, but not when the wrist was extended or deviated, which is more typical while working overhead. There was little variation, however, in the normal force exerted on the trigger. Therefore, the forces to be measured were limited to the normal force exerted on the trigger of the palm sander. A Tekscan Flexiforce A201 sensor was adhered to the top of the palm sander to give this measurement. It was located beneath the trigger using double-sided tape (Figure 1). A 0.25” x 0.06” circular spacer was placed beneath the 0.5” force sensor to provide repeatable force application whenever the concave surface of the trigger was pressed down to the top of the sander. The force sensor was connected to an ErgoPak wireless transmitter that communicated with a laptop computer. A Shimpo hand-held force gauge was used to validate the response linearity of the setup.

While vibrations and the normal force on the sander are unlikely to vary significantly, great variation was anticipated in postures, durations, joint motions, and frequency of motion among workers on each shift. It was thus decided to instrument 1 worker per shift with a motion capture system that can collect torso, shoulder, elbow, and wrist motions in 3 dimensions. A 5-sensor XSENS system was used for this purpose. Each XSENS sensor is a wireless inertial sensing system that integrates a triaxial accelerometer, a triaxial angular rate gyroscope, and a magnetometer. When a sensor is attached to a body segment, it provides complete measures of segment orientation, velocity, and acceleration with respect to a global coordinate system aligned with gravity (Z-axis) and magnetic north (X-axis). The data collection frequency for 5 sensors was 60 Hz. The sensors were placed on each worker’s dominant extremity. See Figure 2 for an illustration of how the sensors were placed.

During roll-call at the start of each shift, the workers and the supervisor in each shift were asked to identify the task(s) requiring the highest level of effort for that shift. A volunteer who would be working those tasks was recruited to wear the motion capture instrumentation and use the instrumented sander. Initial anthropometric measures were taken in order to calibrate the XSENS motions with respect to joint angles and allow calculation of joint motion.

In addition to the motion capture instrumentation, a system of time-based task requirement counts and Rapid Entire Body Assessment (REBA) scoring was used to evaluate all of the painters working on each shift. Task requirements are categories of postures, forces and movements used to perform a specific job. The frequency with which the individual requirements are used in a job determine the physical requirements of a job. These frequencies are reported as ranges of the percent of time during a standard work shift: never, infrequent (<10%), occasional (10%-33%), frequent (33%-66%), and continuous (>66%). REBA is an assessment technique developed to allow evaluators to quickly assess the riskiest postures involved in a job [4]. It is typically used to provide a single snap-shot of maximum risk among 6 segment postures (neck, trunk, legs, upper arms, lower arms, and wrists), with magnifiers for force/load and grip coupling, giving a total of 8 data points per posture.

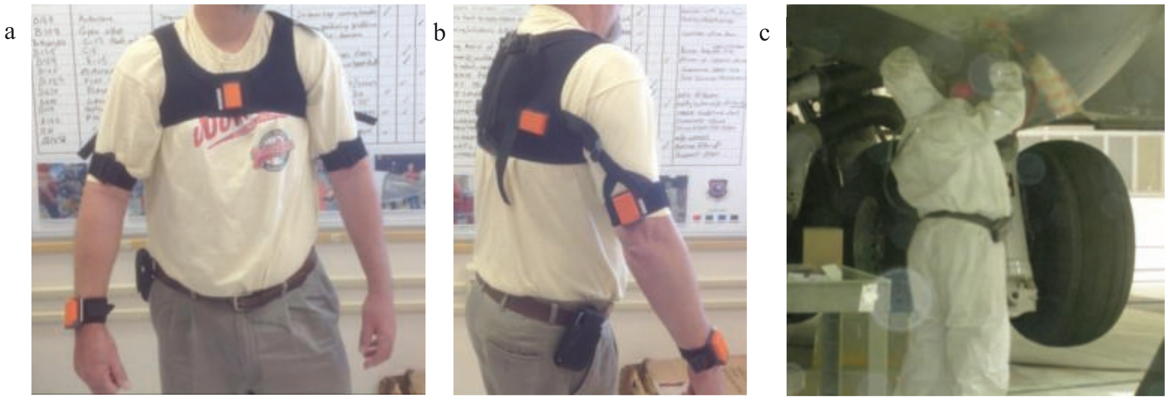

Fig. 2. XSENS sensors mounted on body segments (hand sensor not shown) (a & b) and under PPE (white lights on back, upper arm, and forearm)(c).

The posture and task requirements of each painter were evaluated every 8 minutes during the shift. The requirements and the 8 REBA digits were logged on a data collection sheet for later scoring in order to minimize the time required for data collection. This allowed the evaluator to document requirements and postures for each of the task areas over the course of the entire shift at a rate of 6-7 per hour. In addition to task requirements and REBA, the instrumented worker was evaluated for his level of perceived exertion using a Borg CR-10 assessment scale before and during the shift. This allowed for a validation of the measured forces exerted while sanding overhead [8]. Data was collected on Owl Shift of process day 2 and two ensuing Day Shifts (day 3 and day 6). These were chosen in order to capture a wide variety of posture and positioning requirements, early enough in the scope of the depainting process that the data would not be skewed by accumulated fatigue.

3. Results

3.1. Postural risk

As anticipated, postural risks were significant, and varied among workers on each shift. Table 1 shows the range of REBA scores and task areas for each evaluated shift. Scores of 3 or lower are low risk. Scores between 4 and 7 are medium risk. Scores of 8 or more are high risk. As can be seen from this table, 30% of the tasks evaluated involved high-risk postures, primarily due to extensive overhead reach with one or both arms, excessive cervical extension, and high wrist flexion and deviation.

Table 1. REBA scores for workers in different areas and shifts. Yellow highlights show high risk tasks.

Task	Shift	Duration (hrs)	# Workers	REBA
Drop-down Panels	Owl shift (process day2)	4	4	9
Horizontal Stabilizer		4	4	5
Slats		4	2	7
Aft MLG Fairing	Day shift (process day 3)	4	2	9
Top of MLG Pod		4	1	5
Side Fuselage		4	2	5
Removed Parts		1	1	4
Under Tail		4	2	9
Nose	Day shift (process day 6)	4	1	10
LAIRCM		4	1	7
Fwd MLG Fairing		4	3	6
Belly		4	4	8
Aft MLG Fairing		4	1	6
Top Fuselage		4	2	5
Spotter	All 3 Shifts	4	1-2/shift	3

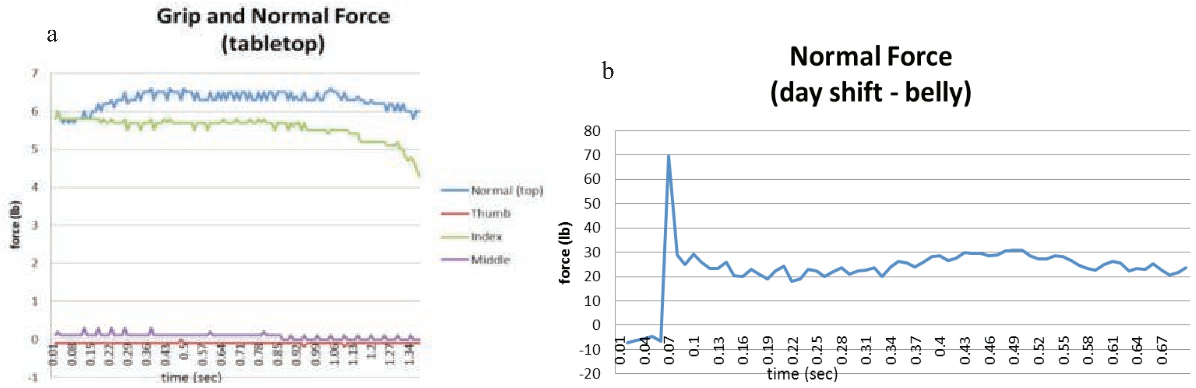

Fig. 3. (a) Grip and normal force using instrumented sander and glove, sanding on tabletop; (b) Normal force exerted on palm sander used while sanding overhead on belly of aircraft.

The percent of time these workers are expected to assume overhead postures, estimated by the task requirement data was significant as well, involving 60% of the tasks performed to depaint the aircraft. The measured amount of time spent sanding during the continuous period programmed for sanding during each shift was approximately 50%. This would normally fall into the frequent category. However, the amount of work time programmed for each shift (4.6 charged hours) is only 58% of the shift, pushing the rated task requirement into the occasional category. This means there is much less rest time in the work-rest cycle than would be available if the work was actually spread over the entire 8-hour shift. The risk of MSD is thus more similar to a frequent task with the same stressors.

3.2. Force exertion

The forces exerted on the top of the sander were higher than anticipated. Tests in the lab using only table-top sanding showed 6-7 lbf exerted on the trigger (Figure 3). A comparison graph in the same figure of the normal force exerted by a painter sanding the belly of the aircraft shows 3-4 times this effort is required. Borg ratings from this worker ranged from 3 to 5 (moderate effort to moderately heavy effort), which was consistent with this level of force exertion.

The amount of force the painters exert on the sander are not high enough to directly cause overloading and trauma to the joints of the upper extremity. However, if the loading increases the rapidity of muscular fatigue, it can cause muscle substitutions that lead to adverse joint postures and increased joint risk.

3.3. Joint risk

The risk of musculoskeletal injury of the shoulder increases with the amount of time spent working overhead, the amount of repetitive motion of the shoulder, the amount of fatigue in the shoulder complex during overhead work, and the frequency of shoulder flexion and/or abduction near the physiological limits, particularly with internal rotation of the upper arm (which increases the risk of rotator cuff tendon impingement). XSENS motion capture instrumentation was used to measure the extent of the upper extremity postures used by painters, as well as the time and frequency characteristics of this data.

The XSENS sensors collect data on the orientation of the local coordinate systems of the inertial measurement units (IMU) with respect to a fixed global coordinate system based on gravity and magnetic north. The IMUs are connected wirelessly to a controller interfaced to a computer. The controller synchronizes all of the IMUs, and collects data from them at discrete time periods (frames) at the sample rate. In this case, the sample rate was 60 Hz, so each frame represents data collected from all IMUs every 0.017 seconds.

The orientation around each of the coordinate axes can be described using a sequence of Euler rotations, common to aviation, namely roll (rotation around X), pitch (rotation around Y), and yaw (rotation around Z). Thus, with the IMUs mounted on the worker as shown in Figure 2, elevation of the upper arm above horizontal gives a pitch value greater than 0. Likewise, rotation of the upper arm around its long axis from neutral (palm forward) to internally rotated (palm backward) changes the roll value from roughly -140 degrees to -90 degrees.

Table 2 shows the total amount of IMU data collected over each of the three shifts, Owl (day 2), Day (day 3), and Day (day 6). The total amount of measurement time was between 30 minutes and 1 hour at the start of each shift, once the sanding process was begun. The measured time spent sanding and the percentage of time sanding only reflect the amount of time the painter was sanding with his dominant hand, since that was the extremity that had been instrumented. The average continuous sanding column is an average of how long the painters held their sanders against the aircraft before lowering them to rest, switch hands, or perform other tasks, such as changing the sanding paper. This was measured by detecting the elevation of the upper arms or forearms (if the upper arm sensor failed) relative to the thorax. An example graph of the measured pitch of the upper arm during overhead sanding can be seen in Figure 4.

Table 2. Data collection times and working times (SD = standard deviation).

	Measurement Time (min)	Overhead Sanding Time (min)	% Overhead Sanding (dominant hand only)	Avg. Continuous Sanding (sec)
Owl (day 2)	36	13	36%	22.9 (SD=9.4)
Day (day 3)	53	25	47%	41.1 (SD =14.1)
Day (day 6)	43	10	24%	23.7 (SD =16.8)

Maximum grip forces of the instrumented painters were measured using a Jamar grip dynamometer. This gave an estimated maximum voluntary contraction (MVC) value of 130 lbf. Using these values with the measured normal force on the sander, the expected percent of MVC was calculated to be approximately 20%. At this level, sustained exertion at the shoulder should allow endurance of about 300 seconds (5 minutes) before rest or switching arms, based on adapted Rohmert curves published by Law and Avin [5]. That the average continuous sanding time was less than 50 seconds was very surprising, given the expected endurance of 300 seconds. In fact, among all of the measured sanding times, none lasted longer than 62 seconds. This indicates a level of discomfort resulting from the combination of muscular fatigue, postural impingement, and vibration.

It should be noted that the Owl 2 and Day 3 painters worked areas directly overhead, while the Day 6 painter was sanding a crew entry door, which involved sanding more at waist and chest level than above the head. For the Day 6 painter, therefore, the data analysis program was modified to collect sanding times at head-height (humerus elevation of -5 degrees) and above. The 24% sanding time for this painter thus does not reflect slothful working, but only the amount of work performed above shoulder height with his dominant extremity.

A functional indicator of muscular fatigue is a change in the frequency of extremity motions. As muscles fatigue, they tetanize, making the motion of the joints they control smaller and less fluid. A Fast-Fourier Transform (FFT) was performed on the elevation data of the upper arm for each period of continuous overhead sanding in order to identify the impact of muscle fatigue. A graph of the FFT results for the Day 3 painter can be seen on the left side of Figure 5. Three FFTs were included in each graph (starting, middle, and end) in order to identify a shift in frequency and magnitude over time. The impact of fatigue is evident in the graphs. In the early periods of sanding,

Fig. 4. Graph of upper arm elevation during 6 minutes of sanding drop-down panels overhead. The circled areas are continuous period of overhead sanding.

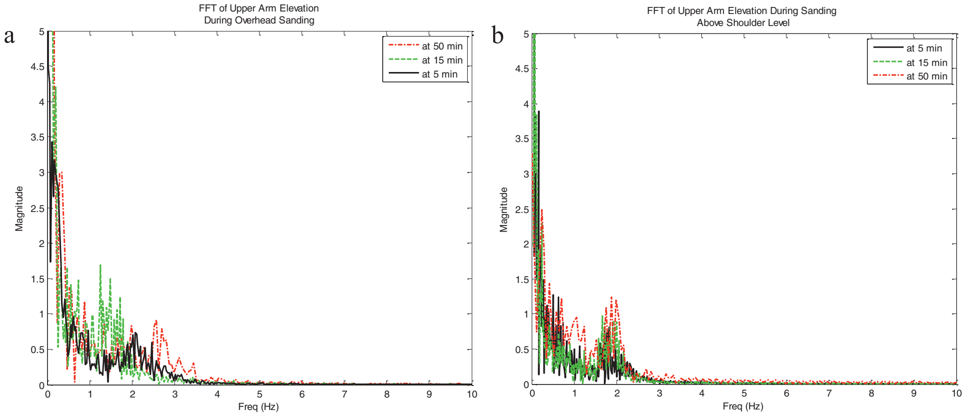

Fig. 5. (a) FFT from the Day 3 painter. Note the shift in spectral energy from 0.5 Hz to 2.0 Hz. (b) FFT from Day 6. There is no frequency shift evident here.

the majority of the energy is found below 0.5 Hz. This represents fluid motion. As work continues, the energy shifts to 1.5 Hz and then 2 Hz, which is evidence of jerkier motion with smaller displacement. This trend was consistent with the Owl 2 painter as well.

Since the Day 6 painter primarily used a different set of muscles that can generate more force than those used for overhead work, comparing his frequency shift to that of the overhead workers provides evidence for the impact of vibration on muscular endurance. The graph of his FFTs (right side of Figure 5) shows no significant shift in energy along the frequency spectrum, indicating muscular fatigue did not impact the length of his continuous sanding time periods. Likewise, joint impingement was less of a factor, since his posture was maintained closer to a neutral range than the others.

A significant concern with muscular fatigue over extended periods of sustained work is the risk of change in muscular recruitment creating adverse joint motions [6]. Internal rotation of the shoulder during overhead work is of particular concern, since that presents the greatest risk of rotator cuff injury [3]. This type of motion is most often seen during painting when the elbow is directed laterally from the body while working directly overhead. Figure 6 shows a graph of the upper arm pitch and roll for the Owl 2 painter sanding the drop-down panel. This graph shows clear indication of potential rotator cuff tendon impingement. The increased number of these indicators toward the end of the time record shows the effect of adverse muscular recruitment due to fatigue.

4. Discussion

Working for sustained periods with hands overhead is a known risk factor for musculoskeletal injury of the shoulder and neck [7]. No threshold limit values have been developed to guide employers in limiting exposure to risk due to this source. Thus, the National Institute of Occupational Safety and Health (NIOSH) recommends employers determine the best options for reducing the risk of injury, based on the trade space of cost and effectiveness that each option offers [2]. The options can be classified as administrative, process, or engineering controls.

Overhead posture is a basic requirement when working on a large aircraft. Administrative controls for reducing postural risk, primarily self-pacing and task area assignment changes on request, are commonly used by production managers in all the paint areas. There are limitations to the benefits offered by administrative controls, however. Too much interruption to the flow of work can quickly decrease overall productivity. As with any type of risk control, the efficacy of administrative controls should be systematically and quantitatively assessed.

Some type of process and/or engineering controls, in addition to administrative controls, will almost certainly be needed to mitigate the increased injury rate. The rapid initiation of muscular fatigue and discomfort in the shoulder during overhead sanding presents a significant challenge for mitigation with administrative controls alone. The

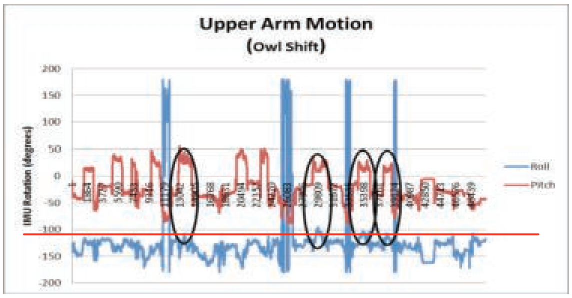

Fig. 6. Circled areas show instances when the upper arm is internally rotated during overhead work (high risk of rotator cuff tendon impingement). The horizontal red line indicates internal rotation of approximately 40 degrees (IMU roll approaches 90 degrees). Note the increased frequency of potential impingement during the last half of the measurement period.

requirement to remove all paint layers down to the original primer during 50/50 sanding makes it necessary for the painters to sustain the sanding in small areas over extended periods of time. The small, repetitive motions of the shoulder required for this effort cause the use of adverse joint kinematics by the end of the first hour of sanding, even though the painters stop and switch hands frequently to rest their extremities.

Process controls that eliminate 50/50 sanding would have the most beneficial effect on reducing risk. Manufacturer technical orders for this particular aircraft originally lead the facility to use mechanical versus chemical depaint process, however, making the feasibility of this type of risk control questionable.

Engineering controls must offer postural and vibratory decoupling, or increase the paint removal rate without increasing the force or vibration load on the painter. If, for example, removal rate is chosen as the only mitigation strategy, it would have to be increased enough to strip as much in one hour (when adverse kinematics become common) as is programmed to be done in 4.6 hours, an increase of 460%. This is unlikely to be realizable. A servo-controlled sanding system was previously developed and was evaluated by the depaint workers. It might reduce the overhead sanding stresses, but it was not favourably accepted by painters at the time, according to management reports. There is also some question whether it would be effective in a 50/50 sanding operation. An engineering assessment of the effectiveness of engineering controls such as this, with attention to worker opinions as well as upstream effects on the production chain would be critical to determining its feasibility.

The ergonomic analysis described in this paper was vastly more detailed, and was more costly, than typical industrial ergonomic evaluations. The results, however—particularly those from the motion capture data—provided the granularity needed to frame a multi-factorial mitigation approach involving administrative, process, and engineering controls. The cost savings in reduced trial-and-error mitigation and in more efficient targeting of mitigation will more than pay for the added expense.

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