Spacesuit Glove-Induced Hand Trauma and Analysis of Potentially Related Risk Variables

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Injuries to the hands are common among astronauts who train for extravehicular activity (EVA). When the gloves are pressurized, they restrict movement and create pressure points during tasks, sometimes resulting in pain, muscle fatigue, abrasions, and occasionally more severe injuries such as onycholysis. Glove injuries, both anecdotal and recorded, have been reported during EVA training and flight persistently through NASA's history regardless of mission or glove model. Theories as to causation such as glove-hand fit are common but often lacking in supporting evidence. Previous statistical analysis has evaluated onycholysis in the context of crew anthropometry only.

The purpose of this study was to analyze all injuries (as documented in the medical records) and available risk factor variables with the goal to determine engineering and operational controls that may reduce hand injuries due to the EVA glove in the future. A literature review and data mining study were conducted between 2012 and 2014. This study included 179 US NASA crew who trained or completed an EVA between 1981 and 2010 (crossing both Shuttle and ISS eras) and wore either the 4000 Series or Phase VI glove during Extravehicular Mobility Unit (EMU) spacesuit EVA training and flight. All injuries recorded in medical records were analyzed in their association to candidate risk factor variables. Those risk factor variables included demographic characteristics, hand anthropometry, glove fit characteristics, and training/EVA characteristics.

Utilizing literature, medical records and anecdotal causation comments recorded in crewmember injury data, investigators were able to identify several risk factors associated with increased risk of glove related injuries. Prime among them were smaller hand anthropometry, duration of individual suited exposures, and improper glove-hand fit as calculated by the difference in the anthropometry middle finger length compared to the baseline EVA glove middle finger length.

Nomenclature

A = amplitude of oscillation
a = cylinder diameter
C_p = pressure coefficient
Cx = force coefficient in the x direction
Cy = force coefficient in the y direction
c = chord
dt = time step
Fx = X component of the resultant pressure force acting on the vehicle
Fy = Y component of the resultant pressure force acting on the vehicle
f, g = generic functions

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h = height
i = time index during navigation
j = waypoint index
K = trailing-edge (TE) nondimensional angular deflection rate

I. Introduction

TO work in the harsh environment of space, astronauts must protect themselves with an Extravehicular Activity (EVA) garment, a space suit. The space suit glove is a critical element of EVA suit design, because it is the prime tool that the astronaut uses to interact with their environment. Whether in microgravity, lunar gravity or a neutral buoyancy scenario, the astronaut must use their hands extensively in order to function. Performing these EVA tasks in a pressurized suit has been known to negatively affect crewmembers' hands, resulting in signs and symptoms such as redness, muscle soreness, fatigue, pain, and injury. These types of injuries have been persistent and prevalent throughout NASA EVA history regardless of glove model.

The High Performance EVA Glove project was undertaken in order to design a more revolutionary glove that meet three goals; 1) improve performance, 2) reduce hand and lower arm related injury, and 3) increase glove durability. This glove injury data mining study was geared towards the second HPEG goal: to gain a better understanding of the injuries associated with two of the most recent EVA glove assemblies, the 4000 Series and the Phase VI, and to investigate possible injury causation mechanisms. Data was gathered for hand and lower arm related injuries that occurred during training on ground in the Weightless Environment Training Facility (WETF), the Neutral Buoyancy Laboratory (NBL), vacuum chambers, and inflight during EVA missions.

This observational retrospective case-control study was undertaken to develop the best possible report on EVA glove-hand injury during approximately 30 years of recorded US astronaut (crew) history (1981-2010) retrievable from Lifetime Surveillance of Astronaut Health (LSAH) data. An additional effort was made by investigators to assess injury risk and independent exposure variable relationships for correlation and predictability using advanced statistical analysis techniques. The ultimate intent of this endeavor was to develop a standard guideline to assess injury potential of current and future spacesuit glove assemblies.

II. Methodology

A. Information Search Methods

LSAH Injury Records

Data was requested from LSAH regarding hand and lower arm (distal upper extremity) injuries. The investigation team only requested data for US crew, and constrained the timeframe to the years of 1981 to 2010. These years coincided with the Space Shuttle and International Space Station (ISS) programs and the data would overlap two types of EVA gloves that were highlighted for this investigation; the 4000 Series and the Phase VI. Investigators chose the Shuttle era as the data mining starting point because injury data from prior programs, such as the Apollo program, were recorded with less consistency, had limited attributable causation data, and were anecdotal in most cases. In addition to including EVA flight injuries for Shuttle and ISS, investigators included all training related injuries that occurred in the NBL, the WETF, and vacuum chamber events while using the Extravehicular Mobility Unit (EMU) spacesuit. Of the 338 people who have been selected as US crewmembers as of 2014, 224 were assessed by this study as they served as active duty crewmembers between 1981 and 2010.

The following were the analysis definitions established by investigators for the standardization of the study:

- **Injury**: pain, redness, or other off-nominal diagnosed sign or symptom reported on a crewmember's distal upper extremities
- **Injury Incident**: a single event, occurrence, or case affecting a single crewmember. One recorded incident may include multiple injuries. For example, a subject could have one incident where they experienced hand pain, hand redness, fingernail redness and thumb paresthesia.

- **Injury Count**: the summation of multiple injuries within the same incident or from multiple incidents. In the example incident above, the subject would have an injury count of (2) for redness, since they noted two redness-related injuries (one injury to the fingernail, and the other to the hand).
- **Injury Incidence Rate**: the calculated number of incidents per 100 NBL events (≈ 600 hours)

Injury Cases

A broad definition of injury was used for this data mining project. Injury was defined as any issue describing off-nominal status. Injuries included any mention of redness, pain, or bruising to the area. Injury cases were defined as those injuries occurring between the fingertip (including fingernail) and the elbow that could be attributed to training or EVA flight tasks while wearing US EVA gloves. Any injuries that occurred while wearing the Orlan (Russian suit and glove) were removed from the analysis.

Injury cases were identified from several main sources: the NASA JSC Electronic medical record (EMR), post flight shuttle medical debriefs (Shuttle crew members), private medical conferences (PMC) between crewmember and crew surgeon (ISS crew members), and the Suit Symptom Surveillance Questionnaire.

The EMR was queried several different ways. An initial search of hand injuries by the International Classification of Diseases, 9th Revision (ICD 9) codes was conducted. Specific ICD 9 codes queried included:

- 703 – diseases of the nail
- 915 – superficial injury of finger
- 955 – injury to nerves of shoulder girdle and upper limb
- 959 – injury, other and unspecified
- 726.3 – epicondylitis

Following this initial query effort, a text search of documents within the EMR was conducted using the words “hand”, “wrist”, “glove”, “NBL”, or “WETF”. All injuries that were identified in the EMR by ICD 9 search or text string search were reviewed to ensure only hand/wrist/elbow injuries were included and only those injuries that could possibly be attributed to training or EVA flight were included in the analysis. Further, the SportsWare program used by the Astronaut Strength, Conditioning and Rehabilitation Specialists (ASCRs) was queried for any hand or wrist injury. This yielded no documented injuries to the hand or wrist that were attributed to the EVA glove.

Inflight injury cases were also identified from the Post Flight Shuttle Medical Debriefs and the PMCs. During the Shuttle era, private medical conferences were only conducted between the crew surgeon and the commander of the Shuttle mission. The commander would provide the crew surgeon a high-level update on the health of the crew. Minimal data was available from these private medical conferences. Individual medical conferences between individual crewmembers and crew surgeons were not performed until the mission returned to Earth. When EVAs were performed, the crew surgeons would also fill out an “EVA Pre and Post PMC checklist.” This checklist covered a variety of topics pertaining to the health of the crewmember including hand health. Data was extracted from this checklist if any information was noted regarding a potential hand injury. These individual checklists are currently stored within the Shuttle Data Archive, a large archive of Shuttle era documents that were converted from paper records to electronic format and stored virtually. Each of the checklists available within the Shuttle Data Archive was reviewed for potential hand injuries that occurred during the EVAs.

When the individual crewmembers met with their crew surgeon on the day they returned to earth (Return + 0) and again three days later (R+3), a standardized list of questions was asked of the crewmember. A data collection tool called the “Post flight Shuttle Medical Debrief” was developed to extract pertinent information from these crewmember/crew surgeon debrief transcripts or audiotapes. This debrief data is currently stored within the LSAH Command Center database. For this study, data was queried from the debrief and hand/wrist/elbow injuries were included if they were attributed to the EVA.

PMCs also occurred and still occur between the individual crew member and their respective crew surgeon throughout ISS missions to discuss the health of the crew member while on orbit. The PMC is typically performed daily for the first 5 days of flight and weekly throughout the course of the mission. A pre and post EVA PMC are typically conducted as well. After each PMC, the crew surgeons record their observations and impressions in the crew members' EMR. Before the introduction of the EMR, PMCs were recorded on paper notes or audio/video tapes. A comprehensive searchable database known as the Historic PMC tool was created to capture these pre-EMR PMCs.

Finally, the Suit Symptom Surveillance Questionnaire was used in the prospective suit symptom study from July 19, 2002 to January 16, 2004 (Strauss et al., 2005). The goal of this study was to continue to identify trends in problem areas, quantify the nature and severity, and identify attributed causes. Another goal was to analyze causal mechanisms and make recommendations to appropriate disciplines including suit engineering, astronaut training, and flight medicine. The questionnaire captured information on location of injury, characteristics of the injury such as localized or diffuse, countermeasures used, and any additional comments the suited subject volunteered. The questionnaire continued to be used following the suit symptom study in order to continue surveillance of pain and/or paresthesia symptoms related to NBL training in the EMU extra-vehicular mobility suit. However, following the end of the suit symptom study, its use was not standard across all training events. Over 1,300 suit symptom questionnaires completed between 2000 and 2010 are available in LSAH archives. For this study, each of these questionnaires was reviewed for any mentions of hand injury signs or symptoms. Any information (i.e. injury location, type of injury, and characteristics of the injury) available in the questionnaires pertaining to hand, wrist, and elbow injuries were extracted and compiled for this data mining study.

A senior epidemiologist from LSAH was responsible for reviewing all of these injury sources and compiling all injuries for the study into two separate data sets: injuries during training and injuries during EVA flight. A thorough review was conducted of all injuries to ensure that a single injury that may have been mined from several sources was not duplicated in the final datasets. This list of glove related injuries represents the full set of injuries reported from known and recognized sources. It is possible that other injury records may exist in other non-medical databases such as suit sizing notes or that crewmembers may have had injuries that were never reported.

Suit and Glove Sizing Records

Data were provided by Stinger Ghaffarian Technologies (SGT), Inc. under an agreement that they would compile and organize suit and glove sizing records, to be provided to the glove-hand injury investigation team. These data included:

- Suit Sizing for Flight and Training, Prime and Back up, by person, for both Baseline Suit and Enhanced Suit
    - Hard Upper Torso (HUT) style
    - HUT size
    - WLVTA (Water Line Vent Tube Assembly)
    - Upper Arm
    - Lower Arm
    - Sizing Rings
    - Arm Bearing Adjustment
    - Wrist Disc Adjustment
    - Lower Torso Assembly (LTA)
    - Waist
    - Leg
    - Thigh Sizing Ring
    - Leg Sizing Ring
    - Thigh Adjustment
    - Leg Adjustment
    - Boot
    - Glove Size
    - Glove Serial Number
    - Comfort Glove Size and Type

These data were compiled as a single sizing record per crewmember and was not dated. Therefore, investigators were unable to link this data to injury data and unable to use the data set. Because this project was focusing primarily on the glove, and glove usage histories were provided separately, this was not considered to be a significant detriment to the quality of the project.

- Glove Usage History by person, by training/EVA event
  - Event Date
  - Event Name
  - Wrist Disconnect Style (e.g. dual seal vs. low torque)
  - Glove Size
  - Glove Serial Number
  - Arm POGO (arm span between wrist disconnects)
  - LTA Left and Right (not used)

This data was linked by person and date with the LSAH training/EVA records

- Glove Sizing Comments and Suit Sizing Comments
  - Date
  - Activity (NBL training, Fit Checks, EVA contingencies, etc.)
  - Comments regarding suit fit or glove fit

Approximately 3,000 pages of suit fit and glove fit comments were received. Due to the enormity of the data received, the team was unable to assess these thoroughly in the timeframe allowed by the project. Assessing these comments is recommended forward work.

- Glove Sizing Sheets, one sheet for each crew member for training and EVA gloves, prime and back up
  - Includes data on glove size, serial number, glove contacts by location on hand (i.e. index finger tip, crotch between fingers 2 and 3), and final adjustment cord take-ups.
  - These data were compiled as single sizing sheets per crewmember. The original test date is noted; however, final cord adjustment take ups were not dated. Therefore, investigators were unable to link this data to injury data and unable to use the data set.

The remaining items are data investigators received related to suit sizing, but were not included in the glove injury analysis. These data either did not pertain to the glove injury analysis or were too qualitative in nature to distill into an analyzable data set.

- Custom Comfort Glove Sizing Sheets
- Comfort Padding Sizing Sheets
- Liquid cooling vent garment
  - Liquid Cooling Vent Garment
  - Mini vs. Standard
  - AVD
  - LVD
  - BLVD
  - Leg Cuff Ext Required?
- BSI Size and Extended BSI Size
- Thermal Slipper Required? If yes, size.
- TCU Top and Bottom Sizes
- Sock Data – types, sizes and notes
  - Tube Socks
  - Crew Socks
  - Thermax Liner
  - Polypro Linger
  - Woodsman Thermal
- CCA Size and notes
- CCEM Size and notes
- Mag Size
- Wristlet quantity
- Nail Hardener Use
- Shoulder Harness Use

All previously described suit sizing data were provided to LSAH by crewmember name. The data was de-identified by the senior epidemiologist (removing all references to names, dates, and missions) and linked to the other hand injury data by use of a unique Hand Injury ID code that was standard across all data sets used for this project.

Training and EVA Flight Records

Training and EVA records were provided by LSAH. A multi-year effort was conducted by LSAH between 2010 and 2014 to obtain as thorough as possible training and EVA records from historical records from the WETF and NBL. Hand written records from the WETF were transcribed by the NASA Senior EVA Operations Engineer and provided to LSAH. The EVA data (date and duration) were provided by biomedical engineers and the EVA Office. Over 12,000 records were consolidated into a single database. Variables received from LSAH included crew member id, date of training/EVA event, type of event (training or EVA), event description (i.e. NBL training, Prep and post, Payload EVA contingencies), HUT type worn (Planar vs. Pivoted), HUT size worn (i.e. medium, large, extra-large) actual event time (minutes), and estimated event time (in minutes, estimated by NBL and WETF personnel).

An event was defined as a unique exposure in the EMU suit, either by training or EVA on a particular day. If multiple glove sizes or serial numbers were reported on the same day, this constituted a new event. If multiple glove sizes or serial numbers were reported for a single day, the event for that day was split into the number of different gloves used. The time of the event was divided by the number of gloves used to estimate the time spent in each glove.

Anthropometry Records

Twenty-seven hand anthropometric measures were provided by SGT Inc. All measures were provided in inches. Ten variables were finger circumferences for all five fingers, for both the left and right hands. Ten variables were finger lengths for all five fingers for both the left and right hands. Additional anthropometric measures included hand breadth, hand circumference and hand length, for both left and right hands. The anthropometric data also included the handedness of the individual.

Anthropometric measures for the entire body were also provided (however, none of the full body anthropometric measures were used in analysis). Where appropriate, measures were provided for both the left and right sides. All measures provided included height, cervical height, mid shoulder height, acromion height, axilla height, iliocristale height, crotch height, tibial height, arm reach, abdominal extension to wall, instep height, foot length, foot breadth, shoe size, shoe width, vertical trunk diameter, expanded chest, inter-acromion distance, chest breadth, hip breadth, bideltoid breadth, inter scye distance, inter fingertip distance, inter wrist distance, inter-stylion distance, inter elbow distance, abducted acromion stylion length, acromion stylion length, acromion radiale length, sleeve inseam length, lower arm length, neck circumference, shoulder circumference, chest circumference, biceps circumference, biceps flexed circumference, elbow circumference, waist circumference, thigh circumference, vertical trunk circumference, head length, head breadth, bitragion coronal arc, bitragion inion arc, sagittal arch, head circumference, weight, and any abnormalities.

B. Data Evaluation

As of 2014, a total of 338 US crew have been selected by NASA since the inception of the space program in 1959. Of these, 224 had documented training in the WETF and or NBL between 1981 and 2010. One hundred eighty-five crewmembers (regardless of EVA training or flight exposure) had anthropometric data that was provided to the team by SGT, Inc. Of the 185 crew with anthropometric data, six did not have any training or EVA records, so the effective sample for analysis was 179. Only the individuals who participated in EVA flight or training in those years bound by the study were included in these analyses. Ninety-six of the 179 participated in EVA flight missions in those corresponding years and all 179 participated in at least one training event. If crewmembers were recorded to have viable injury data from flight or training exposure, but were not identifiable in the records, they were included where possible in the Descriptive Analysis but not the Risk Variable Analysis (statistical analysis) portion as they would need to be identified in order to match correctly with their anthropometry and glove sizing information.

Additionally, these numbers of US crewmembers do not include international partner crews or a special class of space flyer known as payload specialists who trained and flew on specific missions for specific purposes. Payload specialists were not uniformly tracked by NASA Space Medicine in the same way that the crew were.

Dependent Variables

Injury was the dependent variable of interest. Two functions of injury were used in analysis: 1) if an injury occurred (yes or no) and 2) time to first injury (in years). Use of two dependent variables allows for exploration of what factors were related to both an injury occurring and what factors were related to the time it took for a crewmember to report their first injury. A subset analysis of onycholysis injuries was also conducted.

Independent Exposure Variables

Candidate independent exposure variables were analyzed in their relationship to the injury outcome. These include several variable types: demographic variables, hand anthropometry, glove variables, and time.

Demographic variables included sex and age.

Anthropometric measures considered for analysis included finger circumferences and lengths for all five fingers, hand breadth, hand circumference and hand length, for both left and right hands.

Glove variables included glove model (4000 Series vs. Phase VI) and glove sizing variables. There was a large proportion of glove sizing data missing. Of 12,026 training and EVA events analyzed, glove data was missing from 3,328 events. If a glove model could be deduced from what was worn previous to and following a missing event, the glove model was replaced. This was able to be completed for 2500 of the 3300 missing glove models. Because glove sizing measurements are very specific to a particular glove, it was not feasible to use standard replacement methods to impute; therefore any analyses that used glove sizing measurements had a reduced sample size. Further, each glove model has many different unique sizes and serial numbers. Because of the large number of glove sizes reported (n=138) relative to the total number of injuries used in analysis (n=184), individual glove sizes as they related to injury could not be modeled. However, each glove size is based on measurements of certain anthropometric characteristics of the hand. These sizing measurements were then related to the specific anthropometric characteristics of the crew member to identify a “delta” between the sizing of the glove and the anthropometry of the crewmember. The Phase VI glove size is translated to four measurements per hand: hand circumference, hand length, middle finger length and middle finger circumference. Series 4000 glove size is based only on two measurements per hand, middle finger length and hand circumference. Because of the high correlations between the deltas for left and right hands on each measure ($r > 0.7$), only the delta between the glove size and the anthropometry for the dominant hand was used in the regression models. In cases where the glove sizing was unknown, this delta could not be included for analysis.

Time was modeled in several different ways in the analyses. First, the duration of individual EVA or NBL event was included in the analyses. This time variable is highly skewed with the majority of training events being estimated at 360 minutes or 6 hours by the NBL staff who provided the training data. Even so, there were a large number of missing training times (there were no missing EVA times). The training time was imputed based on the crewmembers other training times. An average of all training times that were available for each crewmember was computed. This average was imputed for the missing times.

Other time variables included time to first injury that was modeled as the outcome in survival analysis. The total number of events (suited training and EVA) that occurred prior to an injury (over the crew’s entire career) was modeled as an independent exposure variable in the survival analyses. The number of events that occurred in the month prior to the injury was modeled in both the logistic regression and survival analysis.

Table 1 displays descriptive statistics for each of these independent exposure variables.

Table 1: Descriptive characteristics of crewmember sample and EVA and training events for years 1981-2010

	EVA (n=96 crewmembers)	**Training (n=179 crewmembers)**
	N (%)	N (%)
Sex		
Male	86 (89.6)	142 (79.3)
Female	10 (10.4)	37 (20.7)
Handedness[1]		
Right-handed	70 (83.3)	151 (84.4)
Left-handed	14 (16.7)	28 (15.6)
Reporting Any Injury	50 (52.1)	44 (24.6)
Reporting Delamination Injury[2]	4 (4.2)[2]	17 (9.5)
	Mean ± SD (Range)	Mean ± SD (Range)
Age @ 1st Training	37.5 ± 4.4 (<30 – >48)	39.0 ± 4.9 (<30 – >50)
Total Career Events (Training or EVA)	98.7 ± 54.1 (<15 - >300)	53.9 ± 51.5 (<10 - >300)
Total Estimated Career Time in hours (Training or EVA)	465 ± 285 (<35 - >1300)	253 ± 278 (<10 - >1000)
	EVA (n=322 events)	**Training (n=11,704 events)**
	N (%)	N (%)
Glove Model Worn[3]		
Phase VI	196 (68.8)	5255 (48.1)
Series 4000	89 (31.2)	5671 (51.9)
Reporting Any Injury on a given EVA	96 (29.8)	88 (0.75)
Reporting Delamination Injury	4 (1.2)[2]	27 (0.23)
	Mean ± SD (Range)	Mean ± SD (Range)
Duration of an Event	271.8 ± 98.6 (< 175 - >500)	268.6 ± 98.6 (<25 - > 400)
Delta: Glove Size and Anthropometry for Middle Finger Length[4]	0.024 ± 0.169 (-0.390-0.453)	0.062 ± 0.193 (-0.524-0.815)
Delta: Glove Size and Anthropometry for Hand Circumference[4]	1.088 ± 0.512 (0.029-2.069)	0.753 ± 0.604 (-1.386-2.891)

[1] 12 crewmembers that performed an EVA are missing all anthropometric data.
[2] Included all fingernail related injuries that occurred during EVA in the risk analysis due to potential discrepancies in injury nomenclature. See Section 4.2.2.1 for further details.
[3] n=285 glove model for EVA, n=10,926 glove model for training
[4] n=185 Delta for EVA, n=6893 Delta for training

Control Variables

Two variables were used as control variables in the statistical models: Training between 2002 and 2004 and EVA vs. Training. A variable was created to identify training that was completed between 2002 and 2004. Due to the prospective suit symptom study (Strauss et al., 2005) and the Shoulder Injury Tiger Team Research Study (Williams and Johnson, 2003) being conducted during this time frame, injuries were reported at a much higher rate than other time frames. Because of the reporting differences during 2002 to 2004 and other time periods, an indicator variable signifying that the training occurred during this period is included to control for these reporting differences.

Analyses were stratified by the type of event the crewmember was participating in, training or EVA. This allows understanding of independent exposure variables as they relate to each type of event. In the onycholysis analysis, EVA or training event is used as an independent exposure variable due to the low number of onycholysis injuries reported during EVA.

Statistical Analysis

All statistical analyses were performed using SAS 9.3 (SAS Institute, Cary, NC). This exploratory analysis seeks to understand factors that are related to hand injuries during training and EVA. To that end, each analysis includes a "Full Model" with all candidate predictor variables and a "Parsimonious Model" that includes only those independent exposure variables statistically significant at less than the 0.15 level. The 0.15 was chosen over the typical 0.05 level because exploratory analysis does not want to exclude variables that may be important but the analysis does not have the power to detect at the typical 0.05 statistical significance level.

Principal Components Analysis (PCA)

The purpose of a principal component analysis (PCA) is to create a new, reduced set of factors from a large number of observed variables. This is usually done because the large number of observed variables are highly correlated with one another; these high correlations are a sign of high redundancy within the data. Most analysis methods cannot support this 'multicollinearity' (defined as many highly correlated variables in one statistical model). Goals of PCA include identifying how different variables work together, reduce the dimensionality of the data (decrease number of variables), and decrease redundancy in the data.

Due to the low number of injuries in comparison to the large number of EVAs and training events the potential for each of 26 anthropometric measurements to be associated with injury is low. Also, the individual anthropometric measurements are highly correlated among each other (correlations ≥ 0.5) predicting a high likelihood that the statistical model would not converge. Therefore, the individual anthropometric measurements were combined, based on a PCA, to create fewer variables that would be used in subsequent regression analyses. Based on the large number of anthropometric variables of the hand (13 for each hand = 26 potential variables) PCA was performed in order to either 1) identify the most important anthropometric variables or 2) combine anthropometric variables into a smaller number of variables to be used for analysis. This analysis is based on the linear combinations of the observed variables and produces a smaller set of factors from the observed variables.

Initially, anthropometric variables were standardized along a z-distribution for the sample of crew members with anthropometric data, so that each anthropometric variable would be given equal weight in the PCA. This standardization was also conducted in order to normalize any differences in variance within any given anthropometric measure (those variables with larger variances would be given more emphasis within the PCA). The most important new factors are the ones with the most variance explained by the eigenvalues produced by the analysis.

Logistic Regression

The relationship between the outcomes of overall injury (yes or no) or onycholysis injury (yes or no) and candidate independent variables was analyzed using logistic regression analyses, a type of analysis used for a binary outcome. Repeated observations within the same individual were adjusted by using generalized estimating equations in fitting the underlying logistic regression model. Results from logistic regression analyses included parameter estimates and odds ratios for each variable included in the model. The odds ratio for each independent variable gives the likelihood of having an injury given increases or decreases in that variable, while controlling for all other variables in the model. An odds ratio of 1.0 signifies there is no greater or lesser odds of injury based on the level of the independent exposure variable. As the odds ratio increases, the odds of injury increase based on increasing levels of an independent exposure variable. As the odds ratio decreases below 1.0, the odds of injury decrease with increasing levels of an independent exposure variable. The logistic regression models initially included all candidate independent variables. A final, more parsimonious model included only those variables that are statistically significantly related to the outcome of injury at less than 0.15 level.

Survival Analysis

The relationship between the outcomes of time to first injury (any type) or onycholysis injury and candidate independent variables was analyzed using Cox proportional hazards regression. Cox proportional hazards regression models the time to a particular event, in this case injury. The results are compared across each independent exposure variable. The time to injury (also known as survival time, hence, survival analysis) was calculated from the day of injury minus the day that training commenced for each crewmember. If a crewmember never reported an injury, they were "censored" in the analysis at the time of their last training or EVA event. Results from the Cox regressions included parameter estimates and hazard ratios for each independent variable included in the model. The hazard ratio informs if the rate of injury is higher or lower for each variable.

III. Results and Discussion

Scope of this Section

It should be noted that the scope of this section of the report, which is considerable in length, is intended primarily for those readers with an interest in reviewing the detailed statistical methods and results, as well as corresponding discussion and analysis. The authors consider this section vital to document for posterity; however it is not suitable for all readers. Those that wish to view a summary of results and interpretations may choose to skip this section and begin reading at Section IV: Summary and Discussion.

Limitations and Constraints

Investigators cast a wide net between 1981 and 2010 to catch the most data available for glove induced injuries. Even with this in mind, injury data was not consistently recorded over time or by standard diagnosis severity methods. For example different flight surgeons may have reported the same type of injury as different diagnoses (i.e. pain versus trauma). This is a known limitation of data mining: using medical records for purposes other than why they were originally collected. Using data mined from the medical records for the purposes of this research led to unexpected findings, primarily within the training data. Injury data was recorded with high levels of injury fidelity (includes low severity and high severity injuries) for some years and low levels of fidelity or underreporting (largely high severity injuries) for others. As a result, literature searches and statistical analyses for injuries are based only on the reported results of the data mining effort.

A. Injury Descriptive Analysis

The first step taken to understand the injury data from the LSAH systems was to perform a descriptive analysis. This simply meant configuring the data into tables and figures that displayed the information in an easily discernable manner. Results of the descriptive analysis effort helped investigators decide how to drive the statistical injury analysis later on in the study.

Training Injuries

Few training data injury records exist prior to the onset of training in the NBL. Historically, training is known to have been conducted in the WETF, but very little data exists pertaining to hand related injury in that training location. In total there were 94 incidents found related to hand injury, and four were considered non-applicable. Two of the incidents were considered non-applicable because the injuries were not directly caused by EVA training, and two additional incidents were removed from the dataset because they occurred after 2010.

Of the remaining 90 incidents, 82 occurred in the NBL, 2 in the WETF and 6 in unknown locations. Training event lengths varied depending on the objectives of the training, but the most common training length for the NBL setting was 6 hours.

Side of body distributions indicate that 51% of the total injuries affected both right and left sides, 29% affected the right side only, 17% affected the left side only, and in 3% of incidents, the affected side was unknown. Regardless of body side affected, the 90 known training incidents were shown to be distributed across multiple body locations between the elbows and the fingertips of the affected individuals. Eleven incidents were shown to be applicable to the elbow, forearm, or hand in general. A majority of the remaining 79 incidents were specific to the exact hand part. To simplify description of these injuries occurring to specific hand regions, locations on the hand were numbered as seen in Figure 1.

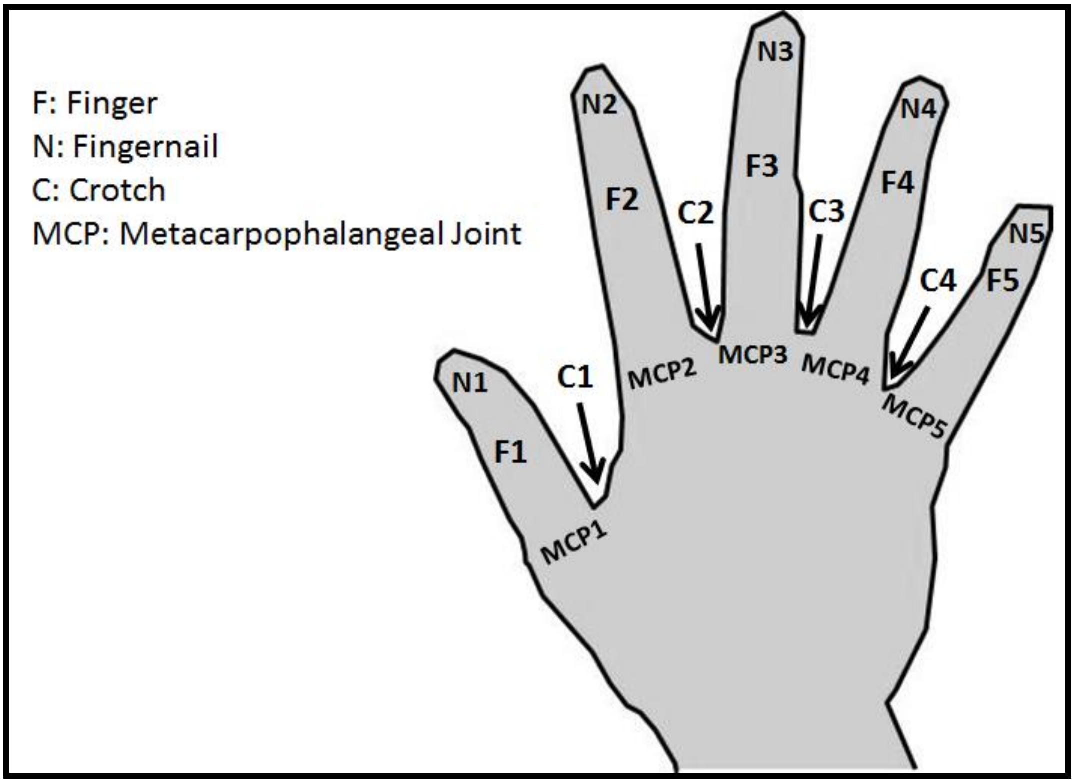


Figure 1: Hand location key

Examples of injury distribution patterns can be seen in Figure 2 below. Finger 1 (thumb), finger crotches 1 (between thumb and index finger) and 4 (between ring and little fingers), fingernail 3 (middle finger), and metacarpophalangeal joint (MCP) 2 (index finger) were more highly affected than other areas of the hand.

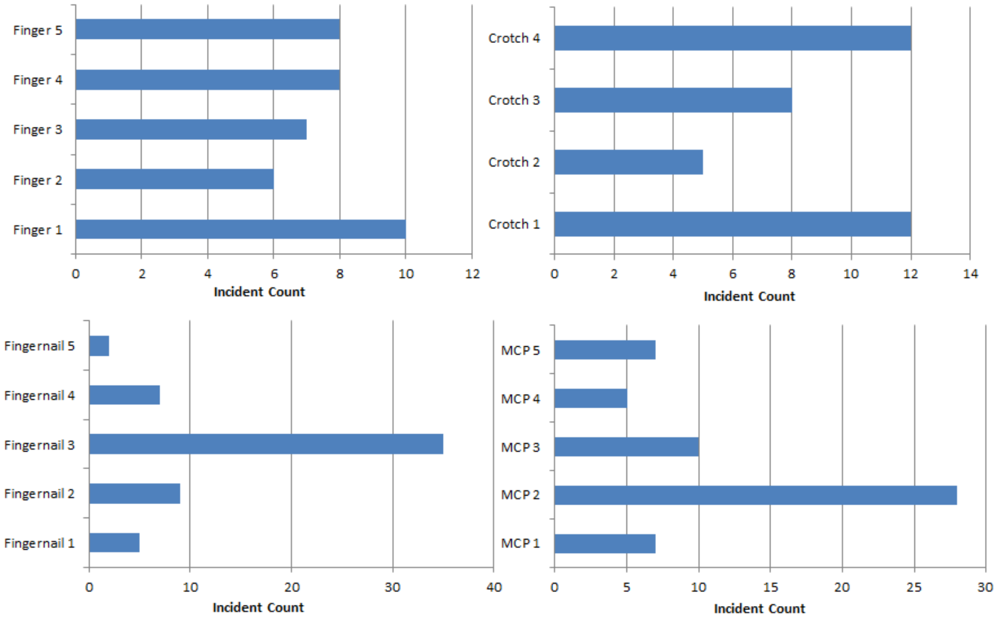
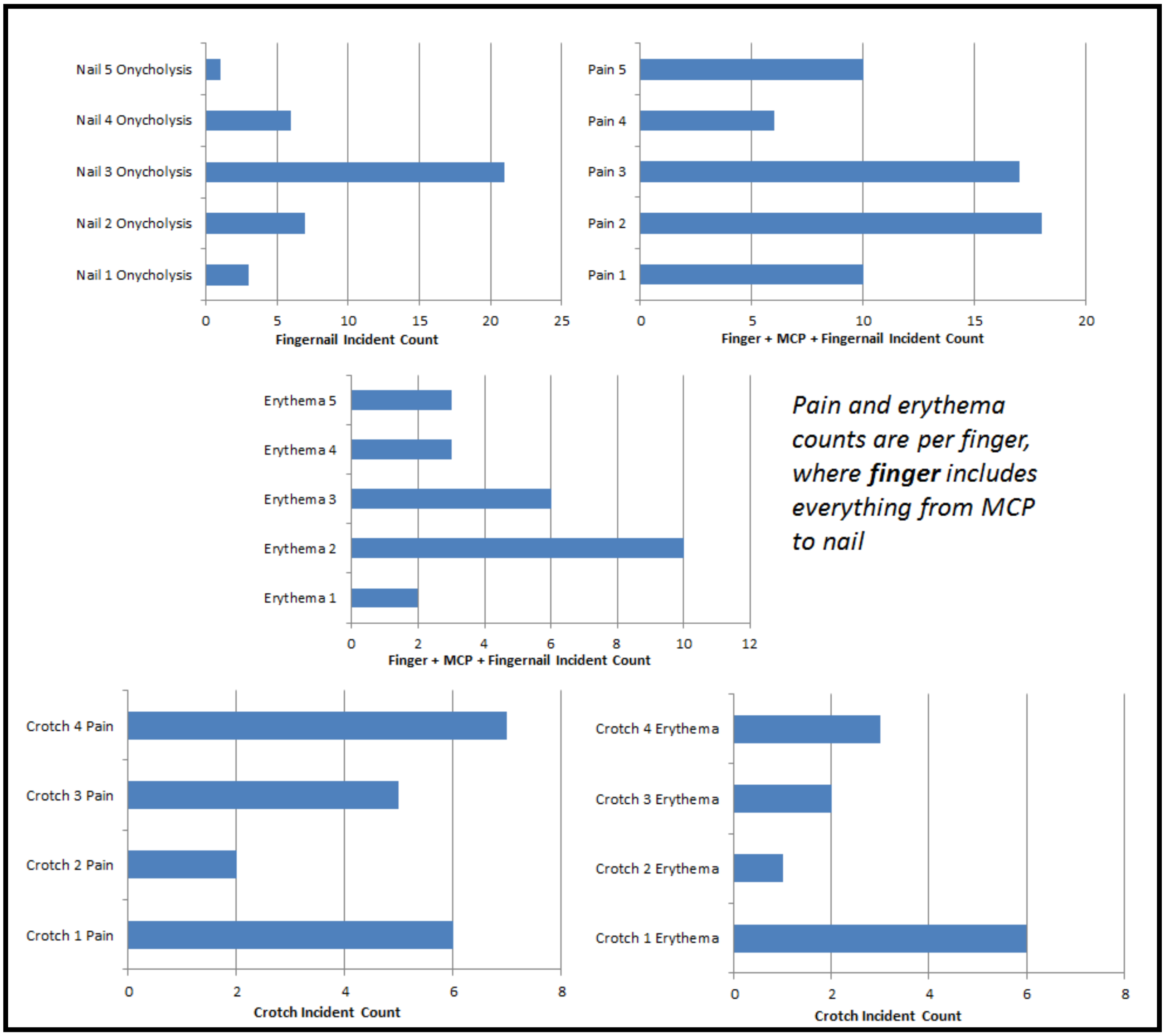


Figure 2: Number of training incidents for finger and hand locations

By combining the three most common injury types of pain, erythema, and onycholysis with finger and hand location, investigators were able to discern more specific findings. Fingernail 3 (on the middle finger) had more than 20 individual onycholysis injuries, making it the finger most affected by this injury type. For general pain and erythema injury types, finger 2 (index) followed by finger 3 (middle) were reported more often than any other finger of the hand. Pain affected finger crotch 4 (between ring and little fingers) more than the other crotch locations, and erythema was reported most on finger crotch 1 (between thumb and index finger).



Pain and erythema counts are per finger, where ***finger*** *includes everything from MCP to nail*

Figure 3: Onycholysis, pain, and erythema training injuries reported to specific hand locations

Figure 4 displays the distribution of known training injury counts for the different types of injuries from the 90 incidents. Of the 14 types of injuries recorded, approximately 76% of this injury distribution was recorded as pain, erythema, or onycholysis. A body part distribution identifies that the fingernail and the MCP are the most affected hand locations, with close to 40 injuries each. These are followed by the finger crotch (28), the finger in general (11), fingertip (10), hand in general (6), and others areas with fewer injuries.

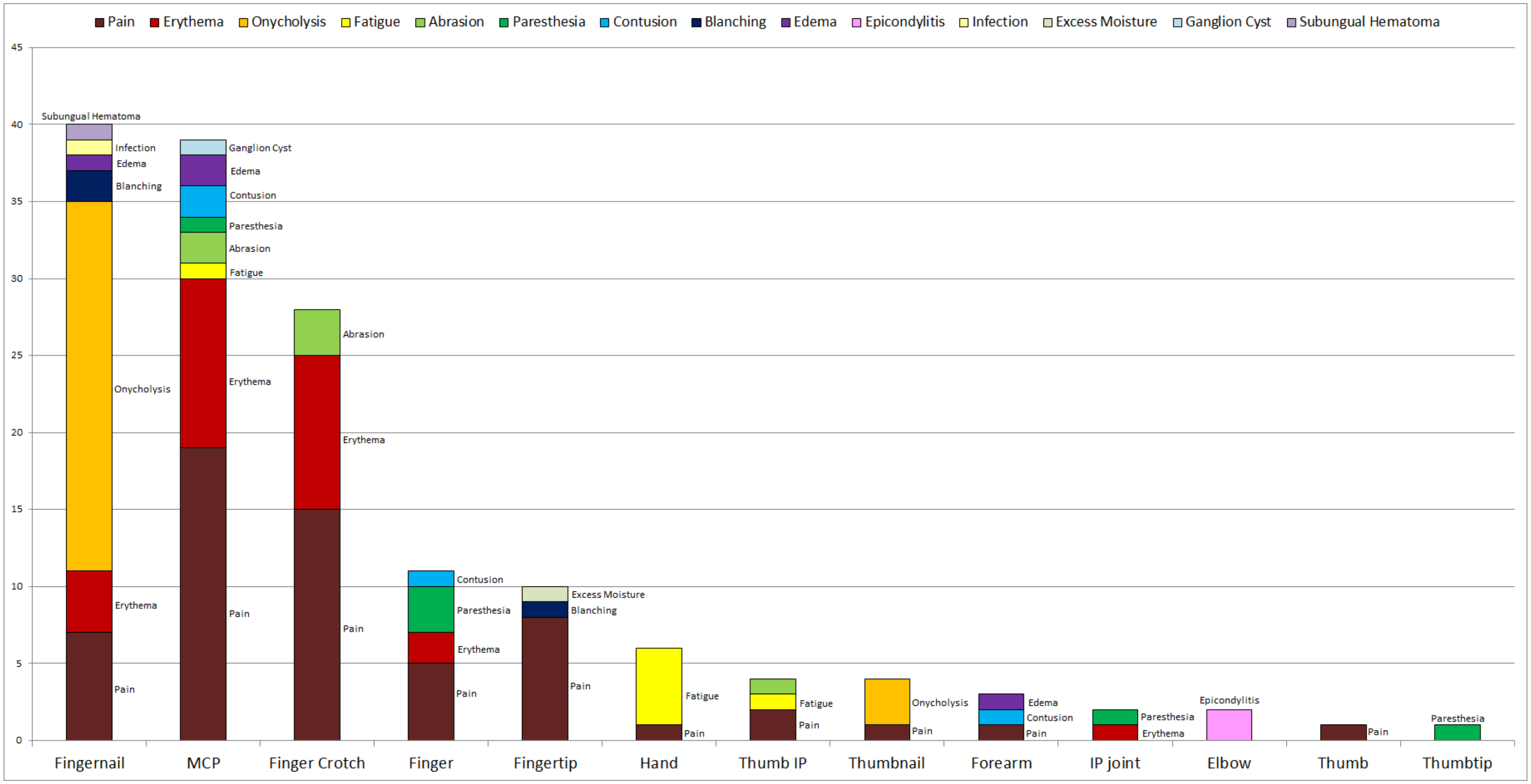


Figure 4: Training injury type by body part

Training Injury Reporting Disparity

Training events varied between an average of 2 and 6 hours depending on the nature of the event. The most common event length was 6 hours. The 6 hour per training event estimate was used to calculate the annual incident rate for the training injuries as shown in Figure 5.

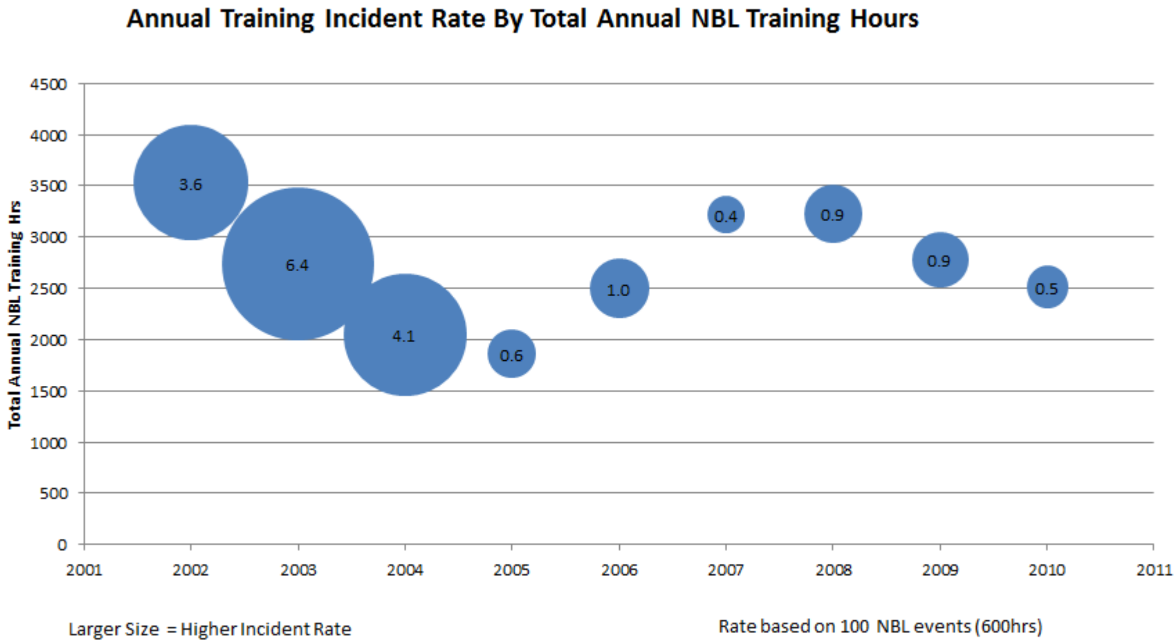


Figure 5: Annual incident rates by annual total training time for training distal upper extremity injuries between 2002 and 2010

Higher incident rates were noted to occur between 2002 and 2004 with 3.6, 6.4, and 4.1 injuries per 100 NBL events respectively. The following years had incident rates of 1.0 or less, and incident rates were shown to be independent of the total annual NBL training exposure. This finding, as well as the sheer number of injury incidents that were reported in 2002-2004, raised concerns over a possible reporting difference over the training time period being reviewed.

A review of the three most common injury types between 2002 and 2010 found that onycholysis was consistently reported over time with incident reporting ranging from one to six per year (Figure 6). Pain and erythema incidents however, were shown to be at their height in recording only between 2002 and 2004, falling to less than four per year afterwards (Figure 7). Further historical examination by investigators revealed that during the 2002 to 2004 timeframe there was an increased push for awareness and recording for any injuries resulting from EVA training (Strauss et al., 2005; Williams and Johnson, 2003). Following these investigations, there were several additional countermeasures made available to the crew including nail hardener/polish, bandages over fingernails, and a greater attention to nail hygiene, particularly keeping the nails trimmed short. The time frame 2002-2004 differs from 2005-2010 in injury incident rates, but the extent to which this difference is attributable to reporting methods versus countermeasure development is unknown. At this time, we hypothesize that the difference in pain and erythema reporting are mostly caused by injury recording methods and that the reduction in onycholysis rates could be attributed to both countermeasure development and inconsistent injury recording methods.

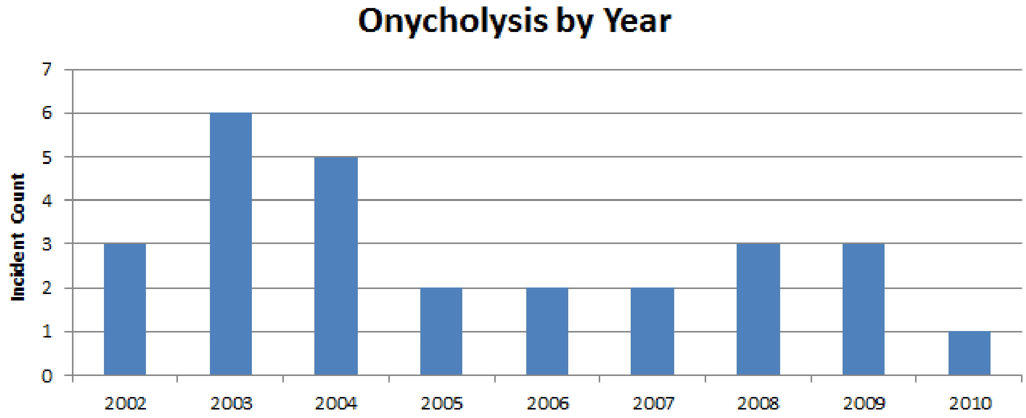


Figure 6: Onycholysis training distal upper extremity incidents between 2002 and 2010

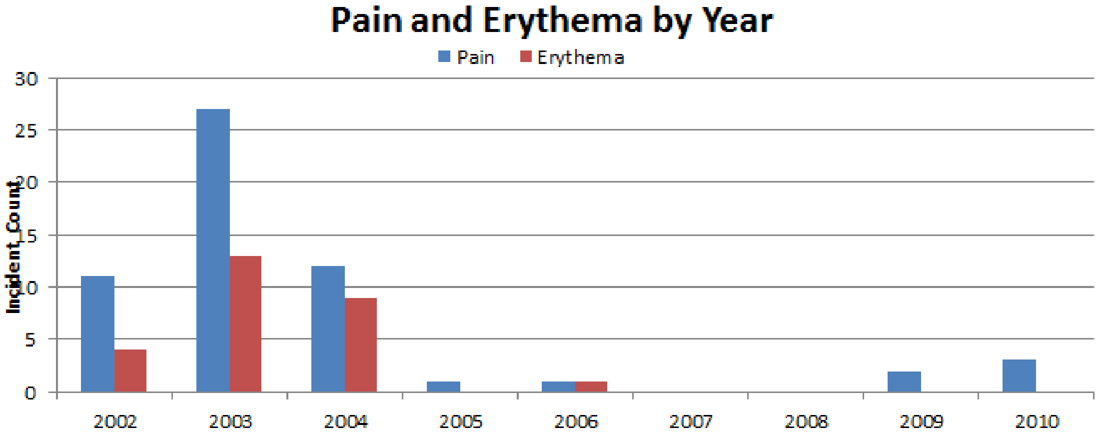


Figure 7: Pain and erythema training distal upper extremity incidents between 2002 and 2010

With 69% of the data being reported in the indicated time range of 2002 to 2004, several precautions (controls) were taken by investigators during the correlation and predictor statistical analyses to prevent this disparity from affecting the significance of the analysis results. Details of these controls are discussed more in the Methodology section on Control Variables and in the Results section Scope of this Section

It should be noted that the scope of this section of the report, which is considerable in length, is intended primarily for those readers with an interest in reviewing the detailed statistical methods and results, as well as corresponding discussion and analysis. The authors consider this section vital to document for posterity; however it is not suitable for all readers. Those that wish to view a summary of results and interpretations may choose to skip this section and begin reading at Section IV: Summary and Discussion.
Limitations and Constraints. This inter-year reporting discrepancy was only indicated for the training data and not the EVA flight related data.

EVA Injuries

EVA flight incidents recorded between 1981 and 2010 occurred during both Shuttle (1981 – 2011) and ISS (2000 – present) EVA programs. There were 124 incidents found related to the distal upper extremity, eighteen of which were considered non-applicable, leaving 106. A total of 6 incidents were omitted for occurring after 2010. Five incidents were removed because the injury was not defined, and another incident was removed because it was not considered an injury, merely a comment about the gloves. Two more incidents were removed because they occurred in the Orlan spacesuit, and another incident was removed for occurring in a launch, entry, and abort (LEA) suit versus an EVA suit. One of the remaining incidents was removed due to its location (not on the distal upper extremity), and another was omitted because it was a weightlifting injury, and not due to the suit. Finally, one incident was removed because it was determined to be a repeat of another incident listing.

The affected side of the body was not known for a significant portion of the incidents (40%). Where the body side was recorded, 32% of the total injuries affected both right and left sides, 15% right side only, and 13% for left side only.

Injuries occurred to numerous body locations between the elbows and the fingertips of the affected individuals (26% non-specifically to the 'hand' and 19% to the generic location of 'finger'). In general, EVA flight incidents had less specificity in assigning an explicit body part. For example, an injury might normally be listed as occurring to the index MCP in training, but would be recorded as occurring non-specifically to a 'finger MCP' in the EVA data (Figure 8).

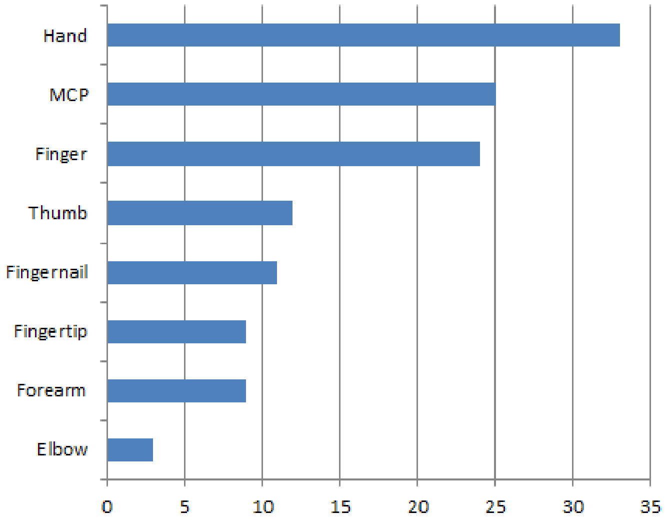


Figure 8: EVA flight injury count for distal upper extremity locations

There were a total of 126 EVA flight injuries amongst the 106 incidents. The three most common injury types for EVA flight included fatigue (soreness or cramping), abrasion, and paresthesia (Figure 9). While not commonly considered as an injury, dry skin was included as it was a resulting sign recorded from the EVAs. This sign is similar to that of excess hand moisture which was unique to the training environment, yet is not necessarily a type of injury. Both of these were included so that all signs and symptoms recorded in the data were assessed.

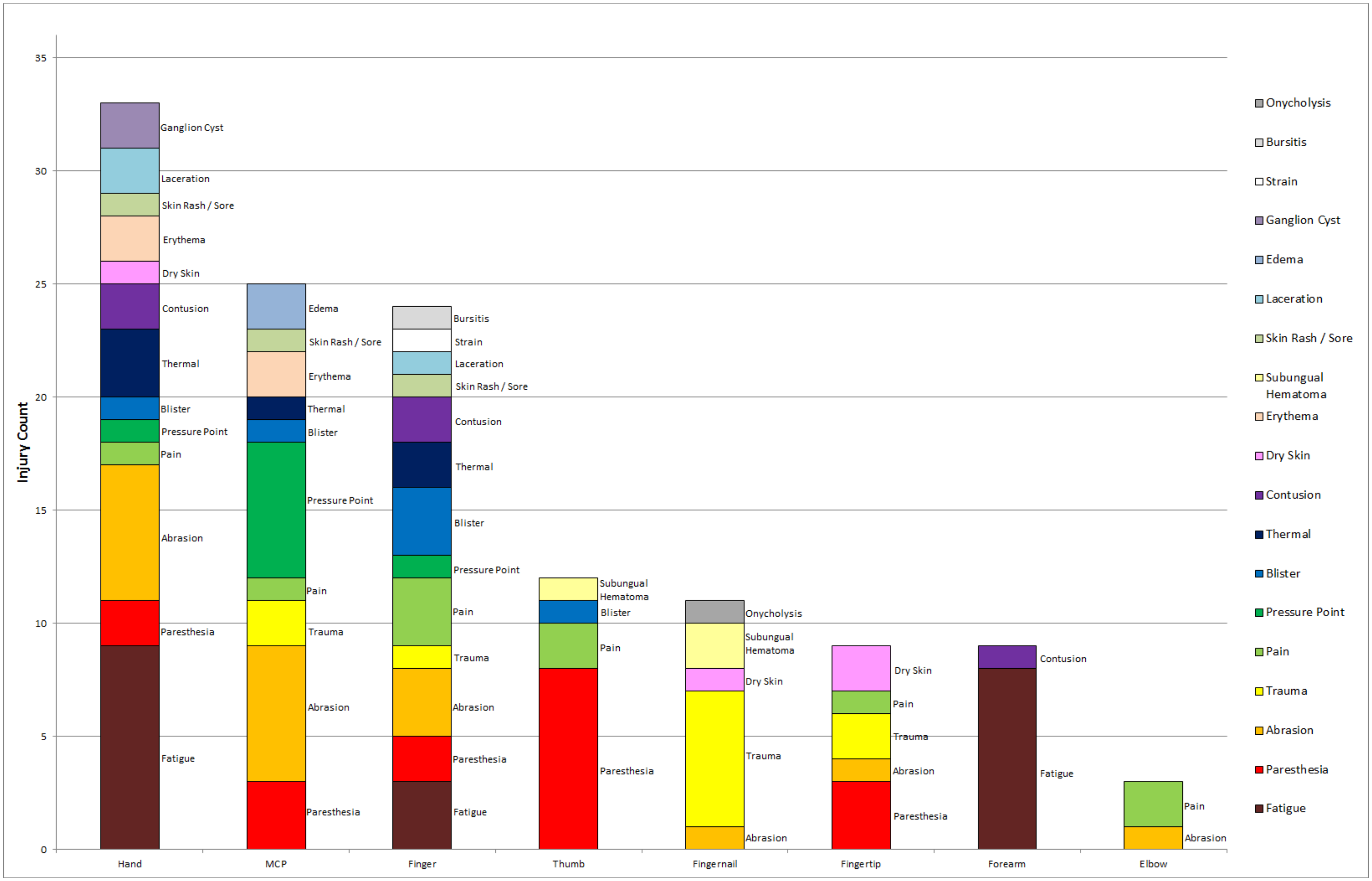


Figure 9: EVA flight injury type by body part

EVA Injury - Fingernail Injury Nomenclature Reporting

One injury term that was found in EVA flight data but not in the training data was "trauma". This injury type is a generic physical injury. Trauma is a dominant injury for EVA flight as it is listed as the 4th most common injury type. Investigators believe that delayed diagnosis circumstances in flight may have led flight doctors to use trauma as a diagnosis label, rather than calling out a more specific injury. In particular, there were 6 cases of fingernail trauma recorded. More specific fingernail injuries such as subungual hematoma and onycholysis were minimally reported (3 and 1 injury respectively). Because there is minimal detail, it may be possible that these three types of injuries may be one in the same or at least related to each other. An example of this hypothesis is shown in Table 2 where subjects with known onycholysis or non-specific 'nail damage' diagnoses from training exposure were also diagnosed with fingernail trauma injuries during flight.

Table 2: Within subject EVA flight versus training comparison for fingernail injury type

Crewmember	EVA Flight	Training
A	Nail bed trauma	Onycholysis
B	Torn fingernail	Onycholysis
C	Fingernail bed damage tip trauma	Pain and damage to nails
D	Middle nail problem 'as before'	Onycholysis
E	Nail/fingertip trauma	Onycholysis

Training Injuries vs. EVA Injuries

Of the 23 different types of injuries and injury mechanisms reported in the LSAH data, 19 were reported during EVA flight and 14 were reported during training. Although several of the injury types are common to both environmental conditions (Figure 10), there was not complete overlap. The variation in injury types reported may be due to training injuries being diagnosed by flight doctors or with doctors present, while EVA flight injuries were reported by crewmembers from orbit or after landing. Additionally, it is unknown as of the time of this report, how much gravity and water impedance contribute towards injury development while performing training activities underwater such as in the WETF or NBL.

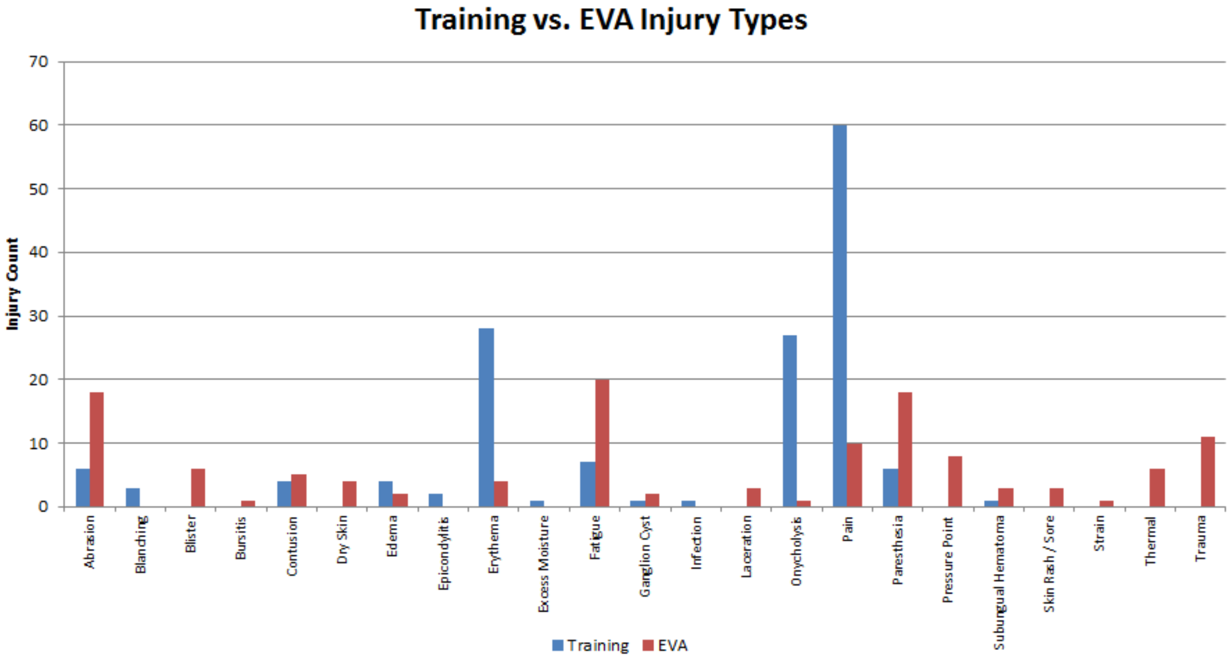


Figure 10: EVA flight and training comparison by injury type

Injury Recurrence

Recurrence of the same injury was something that the investigator team expected based on anecdotal reports from crewmembers describing consistent problems such as onycholysis, but the vast majority of crewmembers only reported 1-2 injury incidents. Figure 11 below displays that a number of crew reported multiple injury incidents in their EVA flight and training careers. For example, 14 individuals had at least two EVA injury incidents. Further analysis would need to be done to understand if these recurrences were specific to a particular type of injury, a particular body location, or a particular type of crewmember. This chart also does not provide any data about time between injuries, and could possibly include cases where one injury was chronic and recorded in successive training events.

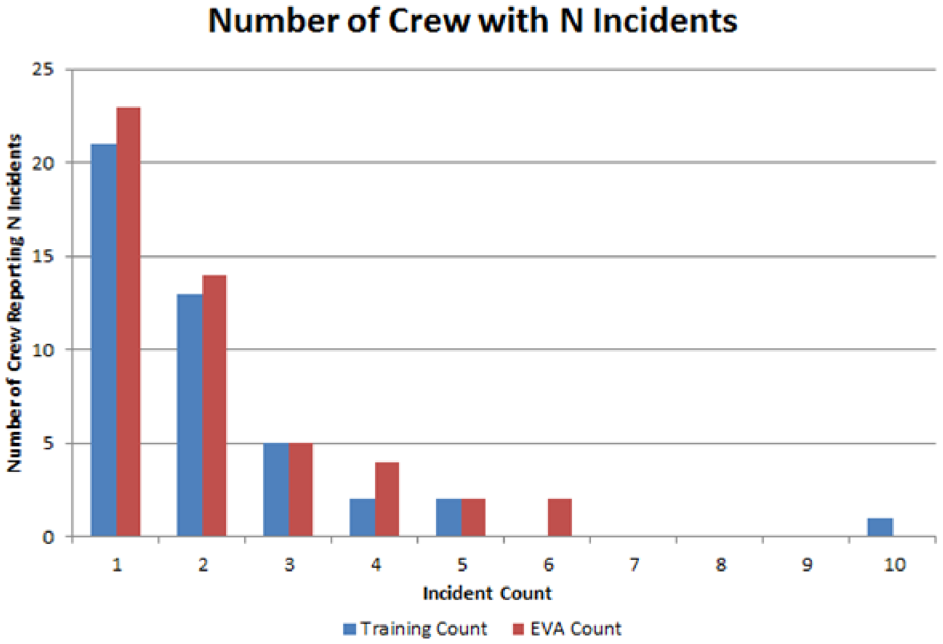


Figure 11: Number of crew who reported N injury incidents over the course of their career

Injury Distribution over Time

For training injuries in particular, it is possible to place the injuries on a scale of career training time, to determine where injuries fall within their training career. This helped indicate which crewmembers had multiple injuries recurring in a closely packed series of events and which crewmembers had injuries spaced sporadically throughout their training careers (Figure 12). It can be seen from the graph that some crewmembers had recurring injuries back to back (e.g. Hand Injury ID 201), whereas other crewmembers could go a significant number of training hours before reporting another incident (e.g. Hand Injury ID 145). To note, a majority of this data was collected in the 2002-2004 timeframe, as represented by data points with circular markers on the graph. Data points outside of the 2002-2004 timeframe are represented by plus signs.

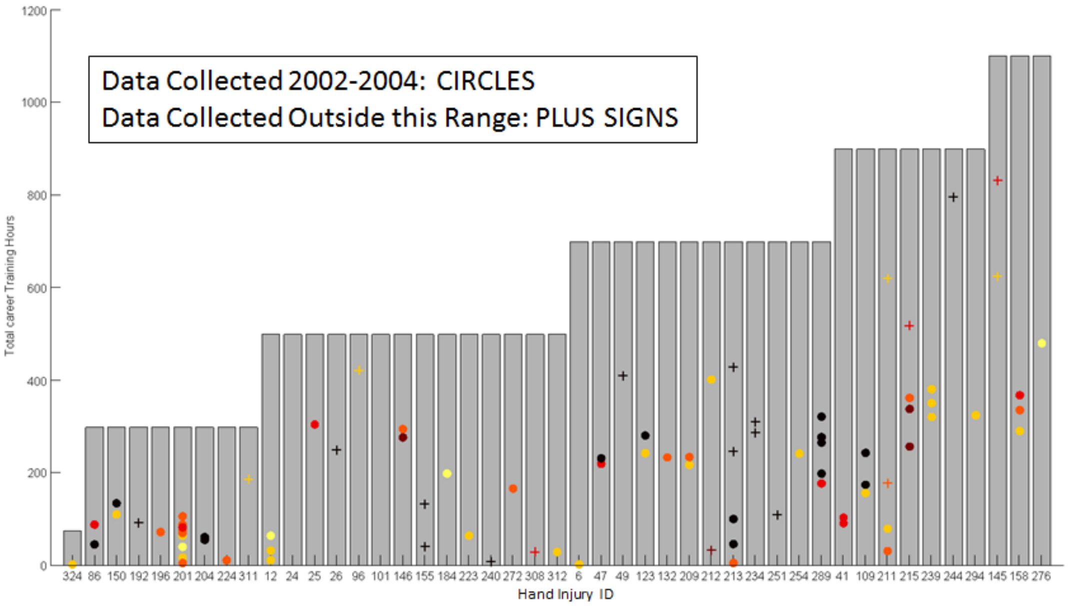


Figure 12: Distribution of training incidents on a timescale of total career training hours

Injuries can also be placed along a time scale based on when they occurred chronologically in the years 1981-2010 (Figure 13). Once again, the training data is skewed by the fact that it was primarily collected in the years 2002-2004. Sixty-nine percent of total injuries were reported in this time period, and only 2 injuries were reported before 2002.

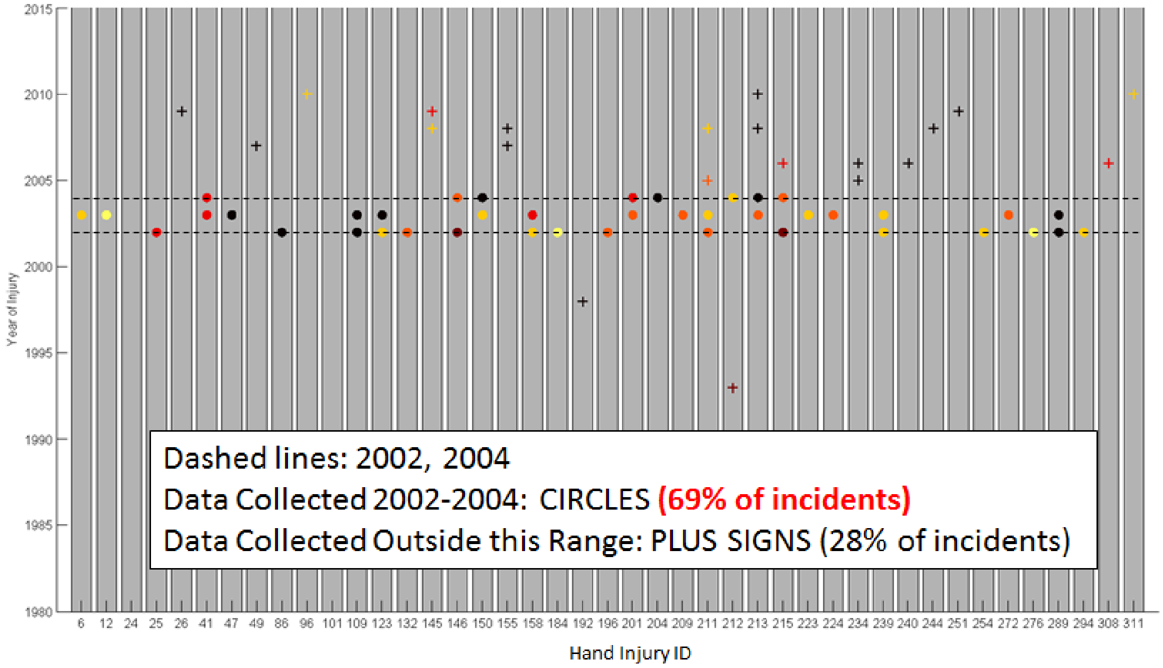


Figure 13: Training injuries by year

EVA injuries were distributed much more randomly across the time period from 1981-2010, as seen in Figure 14. Again, data points from 2002-2004 are represented by circular dots, and data points outside this time period are represented with plus signs. To note, exact dates of injury were not available due to the possibility of attributability, so actual EVAs occurred within 1-2 years of the year plotted on the chart. Also, there were some years around the

Challenger (January 1986) and Columbia (February 2003) events where EVAs did not occur. Note that the Columbia event gap is not called out in the chart as it happens to coincide and overlap with the 2002-2004 time period of indicated in the chart by the dashed lines.

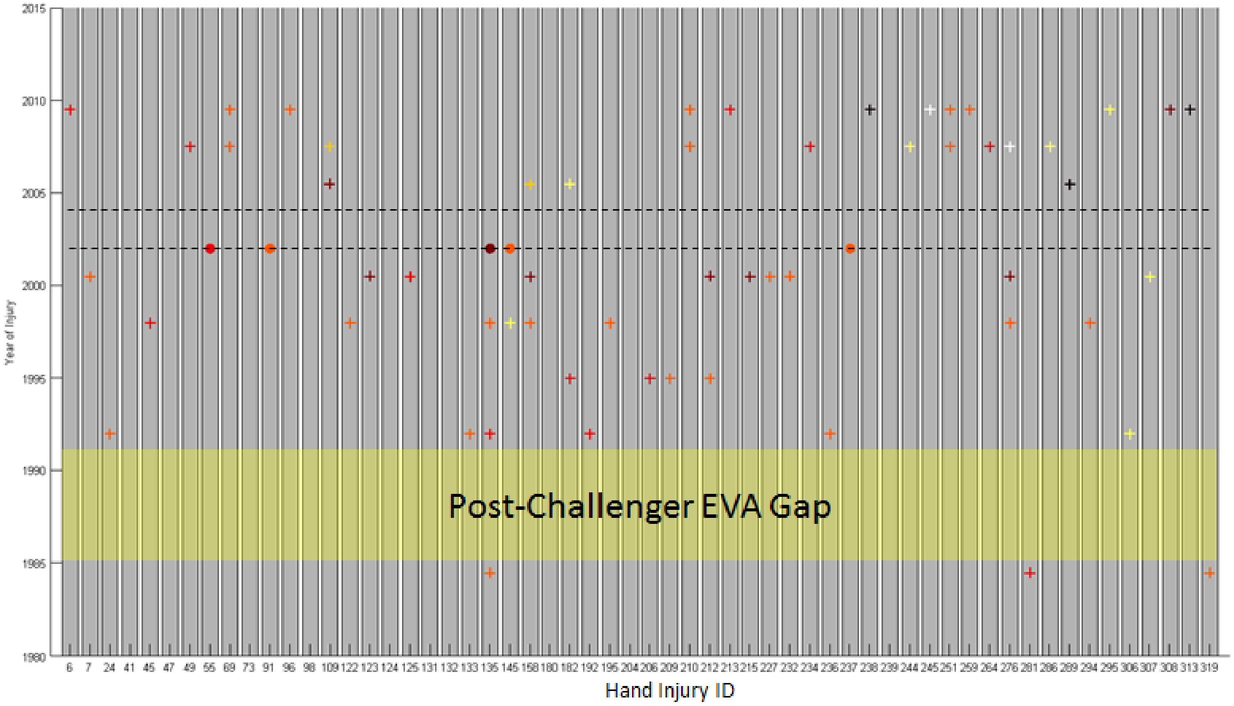


Figure 14: EVA Injuries by Year

Injury vs. Glove Model

Two main glove models were evaluated in this study: the 4000 Series and Phase VI EVA loves. Initially, there was a large proportion of glove sizing data missing. Of 12,026 training and EVA events analyzed, glove data was missing from 3,328 events. If a glove model could be deduced from what was worn previous to and following a missing event, the glove model was replaced. For EVA, 106 EVA incidents were found and 96 of those were occurred during unique EVAs (several times multiple injuries were reported during a single EVA). Twenty-seven injuries (28.1%) were reported while using the 4000 Series, 61 (63.5%) were reported in the Phase VI, and 8 (8.3%) were unknown (these were mainly from the period 2000-2001 as the transition between Series 4000 and Phase VI was occurring). For the 90 reported training incidents, 88 occurred during unique training events. Four events (4.5%) were reported in the Series 4000, and 84 (95.5%) were reported in the Phase VI glove.

B. Principal Components Analysis (PCA)

The purpose of a PCA is to create a new, reduced set of factors from a large number of observed variables; this analysis was conducted to reduce the number of observed anthropometric measures (n=26) that are highly correlated among each other. Therefore, the individual anthropometric measurements were combined, based on the PCA, to create fewer independent exposure variables that would be used in subsequent regression analyses.

The PCA found that a single variable comprised of weighted values of each of the 26 anthropometric variables explains 62.7% of the variance that the original 26 variables did. A second variable would explain an additional 14% of the variance and a third variable would explain a combined total of 80.4% of the variance the original twenty six variables did.

Table 3 displays the percent variance explained by the first three eigenvalues of the principal components analysis. The first principal component explains 62.7% of variance in all the anthropometric variables, the second principal component explains 14.0% and the third principal component explains 3.7% and those three variables together explain approximately 80% of the variance that the 26 original anthropometric variables explained. However, only the first principal component was retained for further analysis. This was due to the fact that the eigenvectors in Anthropometric Principal Components 2 and 3 are both positive and negative, adding increases of certain anthropometric variables and decreases of others to the weight of the variable (Table 4).

Explanation of these principal component variables within a multivariate regression model would become difficult. However, the eigenvector weights for Anthropometric Principal Component 1 are all in the same direction (positive). Further, the eigenvector weights for each of the twenty-six anthropometric variables are all similar in magnitude, meaning they all factor together to create a cohesive single factor. In order to calculate a final score for each crewmember for Anthropometric Principal Component 1, each eigenvector weight was multiplied by the corresponding Z-score value for each anthropometric measure. All products of the anthropometric measures and eigenvector weights were then summed into a single value for each crewmember.

Table 3: PCA Eigenvalues and variance explained

	Eigenvalue	**Proportion of Variance Explained**	**Cumulative Variance Explained**
Anthropometric Principal Component-1	16.304	0.627	0.627
Anthropometric Principal Component-2	3.649	0.140	0.767
Anthropometric Principal Component-3	0.956	0.037	0.804

Table 4: Eigenvector weight for each anthropometric variable contained within each candidate principal component variable

	Anthropometric Principal Component-1	Anthropometric Principal Component-2	Anthropometric Principal Component-3
Hand Breadth Left	0.208	-0.120	-0.250
Hand Breadth Right	0.198	-0.121	-0.296
Hand Circumference Left	0.187	-0.130	-0.297
Hand Circumference Right	0.208	-0.163	-0.195
Hand Length Left	0.202	0.116	0.001
Hand Length Right	0.197	0.131	-0.009
Index Circumference Left	0.210	-0.196	0.110
Index Circumference Right	0.202	-0.192	0.164
Index Length Left	0.175	0.243	0.028
Index Length Right	0.162	0.293	0.096
Little Circumference Left	0.208	-0.206	-0.015
Little Circumference Right	0.204	-0.198	0.060
Little Length Left	0.182	0.240	-0.280
Little Length Right	0.181	0.238	-0.206
Middle Circumference Left	0.218	-0.156	0.178
Middle Circumference Right	0.218	-0.168	0.136
Middle Length Left	0.196	0.240	-0.040
Middle Length Right	0.192	0.259	0.056
Ring Circumference Left	0.216	-0.150	0.108
Ring Circumference Right	0.217	-0.175	0.106
Ring Length Left	0.195	0.220	-0.179
Ring Length Right	0.181	0.244	-0.177
Thumb Circumference Left	0.213	-0.165	0.060
Thumb Circumference Right	0.202	-0.146	0.070
Thumb Length Left	0.143	0.219	0.515
Thumb Length Right	0.161	0.214	0.368

C. Risk Variable Analysis

Two main types of analyses were used for this project: logistic regression for analyzing the independent exposure variables associated with the increased odds of injury and Cox regression for analyzing time to the first injury and independent exposure variables associated with that time to first injury (review of the candidate independent exposure variables can be found in Statistical Analysis section 0). Each type of analysis was also conducted for the outcome of onycholysis only.

Logistic Regression for All Injuries

Logistic regression analyses were conducted to study the relationships between candidate independent exposure variables and the outcome of injury (yes or no) during either suited training or EVA flight. Table 5 displays the full logistic regression model showing each independent exposure variable as it relates to the odds of injury being reported during training. The full model was made more parsimonious by iterating the model with a backwards, step-wise approach to remove the variables with the least statistical significance. Table 6 displays the final logistic regression model for training events. Significant independent exposure variables (at the ≤ 0.15 level) that were retained in the model included handedness, glove model, time of training event (in hours), and training between 2002 and 2004.

As expected, the control variable of Training between 2002 and 2004 is highly significant with an odds ratio of 8.9. This variable controls for the effect of increased injury reporting occurring during this period. The other effects that are statistically significant (or not) have been controlled for this effect.

Table 5: Parameter estimates for injury during Training Full Model (all potential independent exposure variables included)

	Estimate	Standard Error	p-value	Odds Ratio (95% Confidence Interval)
Intercept	-10.368	1.591	<0.001	
Sex	0.917	0.644	0.154	2.502 (0.709-8.832)
Age	0.018	0.036	0.619	1.018 (0.949-1.091)
Handedness	0.844	0.387	0.029*	2.325 (1.088-4.966)
Anthropometric Principal Component-1	0.036	0.067	0.588	1.037 (0.910-1.182)
Glove Model	1.078	0.635	0.089*	2.938 (0.847-10.192)
Duration of Training Event (hours)	0.507	0.188	0.007*	1.660 (1.149-2.399)
Number of Training/EVA Events in Past Month	-0.003	0.060	0.962	0.997 (0.887-1.122)
Delta: Glove Size and Anthropometry for Middle Finger Length	0.227	0.743	0.761	1.254 (0.292-5.383)
Delta: Glove Size and Anthropometry for Hand Circumference	0.129	0.303	0.670	1.138 (0.629-2.060)
Training 2002 - 2004	2.173	0.299	<0.001*	8.781 (4.888-15.775)

* Represents significance at the $p \leq 0.15$ level

Table 6: Parameter estimates for injury during Training Reduced Model (only independent exposure variables significant at ≤ 0.15 level included)

	Estimate	Standard Error	p-value	Odds Ratio (95% Confidence Interval)
Intercept	-9.823	1.063	<0.001	
Handedness	0.829	0.442	0.061*	2.290 (0.963-5.444)
Glove Model	1.387	0.560	0.013*	4.001 (1.336-11.980)
Duration of Training Event (hours)	0.529	0.188	0.005*	1.697 (1.741-2.453)
Training 2002-2004	2.186	0.301	<0.001*	8.903 (4.935-16.063)

* Represents significance at the $p \leq 0.15$ level

For handedness, the odds of reporting an injury increase by 2.3 times for left-handed individuals compared with right-handed individuals. Previous research found a similar result with left-handers having nearly two times increased odds of all types of injury, and specifically, accident-related injury (Coren, 1989). This is hypothesized to be due to that the fact that most everyday tools and machinery are biased towards right hand use. In order to adapt, left handed individuals must work with their non-dominant and less proficient hand as well as adapt body posture (Porac and Coren, 1981).

One important caveat was that aside from what was done in the Descriptive Analysis phase (see Training Injuries and EVA Injuries sections), the data was not analyzed statistically for side of body affected. It is unknown if injury may be related to the side of the body that was injured (do injuries occur more on dominant vs. non-dominant side and are left handed individuals more likely to report injuries on the left side of the body or the right side of the body). Analyzing by injury side may dampen the effect of dominant handedness.

Glove model was also significantly related to the odds of reporting an injury. The odds of reporting any injury increased 4 times when using a Phase VI glove compared with a Series 4000 glove. However, the analysis team identified multiple confounding factors that may account for these results. Namely:

1) Although the enhanced reporting period from 2002-2004 was controlled for in the analysis, comparison of injury data from after this period against before this period indicates that crewmembers may have become more comfortable with reporting injuries and continued doing so, even after the 2002-2004 study was completed. As the Phase VI glove was dominant during this time, it could account for the results showing the Phase VI to be more injurious than the 4000 Series glove.
2) The implementation of the Phase VI glove resulted in a reduction of the LCVG vent tube length from the wrist to the upper arm. This has been theorized as a potential contributor to injury due to increased levels of humidity in the glove cavity. It was not possible to separate this factor from the glove model variable and therefore, is a possible contributor to consider with these results.
3) Lastly, it is possible that a unique design feature and/or sizing methodology employed with the Phase VI glove makes it inherently more injurious during use than the 4000 Series glove. Unfortunately, given the varying reporting rates through time it is not possible to know how much the Phase VI glove alone is responsible for this correlation. In fact, it is possible that the Phase VI glove is no more injurious than the 4000 Series (or less) and the differences in reporting rates through time account for the results presented.

It should be noted that if the increased reporting rates in 2005-2010 are partially or fully responsible for these results, the conclusion would be that injuries during the 4000 Series glove era were vastly under-reported.

Next, the duration of a training event was significantly related to the odds of reporting an injury. The odds of injury increased by 70% for every additional hour that the length of each training event increased. For instance, the odds of injury increased 70% if the training event is 2 hours compared with one hour. Logically, as the time spent working with the hands in the pressurized suit increased, so did the odds of reporting an injury. An important caveat on duration of an event is that a large proportion (5,112 of 11,668 = 43.8%) of the training events were estimated by WETF and NBL staff with a time of six hours, so the distribution of duration was highly skewed (mean = 4.48 hours, range = 0.4 hours to 7.25 hours). Enhanced reporting of this duration of a training event may provide an opportunity to implement better operation controls for event duration that might lead to reducing injury.

Of note, sex was nearly significant at the ≤ 0.15 level in the full model. However, it was not retained in the parsimonious model because the level of significance approached one as other candidate independent exposure variables were removed from the model. Other independent exposure variables that were not significantly related to odds of reporting an injury include Anthropometric Principal Component 1, the number of training or EVA events that occurred in the previous month, and the differences in glove sizing and anthropometry for both the middle finger and hand circumference. This is of note because individual anthropometry measures (hand circumference, etc.) have been found to be related to injury in previous research (Opperman et al., 2010). It is possible that while one of the 26 anthropometric measurements of the hand is statistically significant, when all anthropometry is taken together as a single entity, as was done in this research, there is no association between hand size and odds of injury. To compare to previous literature, an additional logistic regression model including hand circumference of the dominant hand instead of the Anthropometric Principal Component 1 variable was performed. Hand circumference was not found to be significantly related to the odds of reporting injury in this sample (OR = 1.159, p=0.71).

Table 7 displays the full logistic regression model showing each candidate independent exposure variables and their relationship to injuries reported during EVA flight. Ninety-six crewmembers participated in 322 EVA events over the study years 1981-2010 and injuries were reported on 96 of the 322 EVAs. The full model was made more parsimonious by iterating with a backwards, step-wise approach to remove the variables with the least statistical significance. Table 8 displays the final logistic regression model for injuries reported during EVA. For EVA, the only variable that is statistically significant at the 0.15 level is the Anthropometric Principal Component 1 variable. Figure 15 displays the predicted probability of injury based on differing levels of the Anthropometric Principal Component 1 variable. This shows that as the hand increases in size, the probability of injury decreases across time. Conversely, as the hand decreases in size, the probability of reporting an injury increases. This is in direct contradiction with previous research by Opperman (2010) that states an increase in hand circumference is related to an increase in the odds of onycholysis injury. While the outcome for this analysis was any injury (not just onycholysis), post-hoc analyses were conducted in order to assess the impact of hand circumference (for dominant hand) on odds of injury. When hand circumference was included in the model instead of the Anthropometric Principal Component 1 variable, the odds ratio was 0.612 (p=0.07), showing that larger hand circumference was associated with a smaller odds of injury (or inversely, a smaller hand circumference was associated with a larger odds of injury).

In addition, post-hoc analyses were conducted to further investigate this discrepancy on hand circumference between the two analyses. The first, which only looked at Phase VI gloves, which facilitated additional sizing measures (delta between anthropometry and glove middle finger; delta between anthropometry and glove hand length). Most results were very similar, and most notably, hand circumference was never a significant risk factor to injury. The second post-hoc analysis performed was an attempt to replicate the Opperman analysis to the extent possible given the available data set. These results are presented in later sections analyzing onycholoysis specifically, as this section is speaking to injuries in general.

No other independent exposure variable reached statistical significance. This may be because a different set of exposure variables are associated with the EVA event as compared to the training events. These other factors may consist of mission-related factors not taken into account such as mission duration and frequency of EVA events on the mission. Investigators attempted to capture the frequency of EVA events that occurred prior to the injury (number of training/EVA events in the past month), but the total number of EVAs performed on a mission or the total EVA time on a mission was not captured, but rather the duration of a single EVA event.

Table 7: Parameter estimates for injury during EVA Flight Full Model (all potential independent exposure variables included)

	Estimate	Standard Error	p-value	Odds Ratio (95% Confidence Interval)
Intercept	-1.847	3.668	0.615	
Sex	-0.667	1.131	0.556	0.514 (0.056-4.7131)
Age	0.053	0.072	0.458	1.055 (0.917-1.214)
Handedness	0.526	0.739	0.476	1.693 (0.398-7.198)
Anthropometric Principal Component-1	-0.211	0.128	0.099*	0.810 (0.630-1.041)
Glove Model	-0.037	0.675	0.957	0.964 (0.257-3.616)
Duration of EVA (hours)	-0.066	0.252	0.793	0.936 (0.571-1.534)
Number of Training/EVA events past month	-0.012	0.102	0.910	0.986 (0.810-1.207)
Delta: Glove Size and Anthropometry for Middle Finger Length	-0.915	1.497	0.541	0.401 (0.021-7.531)
Delta: Glove Size and Anthropometry for Hand Circumference	-0.208	0.456	0.648	0.812 (0.332-1.985)
Training 2002 to 2004	0.429	0.516	0.405	1.536 (0.559-4.220)

* Represents significance at the $p \leq 0.15$ level

Table 8: Parameter estimates for injury during EVA Flight Reduced Model (only statistically significant independent exposure variables at the ≤ 0.15 level)

	Estimate	Standard Error	p-value	Odds Ratio (95% Confidence Interval)
Intercept	-0.694	0.174	<0.001	
Anthropometric Principal Component-1	-0.081	0.053	0.126*	0.922 (0.831-1.023)

* Represents significance at the $p \leq 0.15$ level

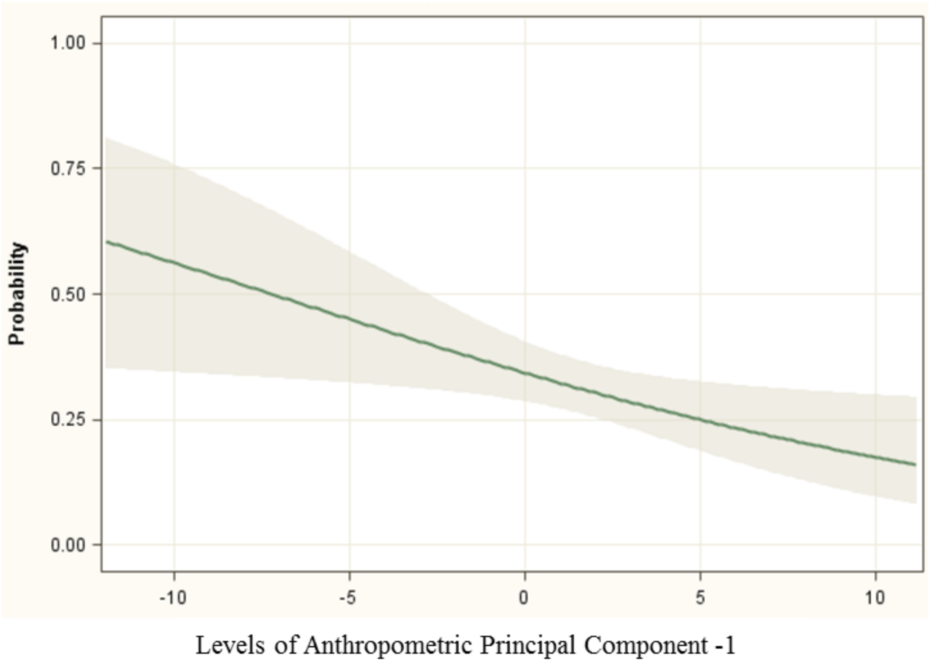


Figure 15: Predicted probabilities of Injury (y-axis) based on normalized levels of the score of Anthropometric Principal Component 1 (x-axis) and 95% confidence interval (shaded area)

There were several notable differences between the independent exposure variables found to be related to training events and those found to be related to EVA flight events. These differences included duration of event being related to injury reporting during training events but not EVA events; glove model being related to injury reporting during training events, but not EVA events; handedness being related to injury reporting during training events but not EVA events; and Anthropometric Principal Component 1 being related to injury during EVA events, but not training events. This lack of consistency between independent exposure variables related to EVA flight and training injury risk most likely indicates that these exposure events have different risk profiles or different injury reporting standards between them.

Survival Analysis for Time to First Injury (All Injuries)

The next outcome studied was time to first reported injury. This outcome was modeled using Cox proportional hazards regression (also known as survival analysis).

Table 9 shows all parameter estimates and hazard ratios for each candidate independent exposure variable and its relationship to the outcome of time to first injury. Non-significant variables were removed in a backwards, step-wise fashion starting with those variables with the least statistical significance (largest p-value). Table 10 displays the independent exposure variables that were significant at the ≤ 0.15 level in the final parsimonious model. Significant variables included age, Anthropometric Principal Component 1, time of training event (hours), number of prior training events, the delta for glove size and anthropometry for middle finger length, and training between 2002 and 2004.

Based on the hazard ratios, those crewmembers who were younger reported injury at a faster rate than those who were older (HR = 0.768). For every additional year in age, the rate of reporting an injury decreased by 23%. Along the same lines, crewmembers who performed fewer training and EVA events reported injury at a faster rate than those who had more previous events (HR = 0.974). This shows that crewmembers who are at the beginning of their career (hence, younger) report injuries at a faster rate, possibly because they have not become fully accustomed to use of the pressurized suit and may still be going through sizing adjustments.

As with other statistical models, the duration of a training event was statistically significant. The longer the duration of the event, the faster the rate of injury reporting (HR=2.368). For every hour increase in duration of the training event, injury was reported at a 2.4 times faster rate.

Additionally, crew members with larger anthropometry reported injuries at a 21% faster rate than those with smaller anthropometry (HR=1.208). This differs from the results of the logistic regression analysis. One reason that may be is that the outcome of each type of analysis differs, logistic regression studying the overall odds of injury occurring versus survival analysis that analyzes the time to first injury when it does occur. Those who have larger anthropometric measures report injuries at an earlier time in their career. However, those crewmembers with larger anthropometry have lower odds of reporting any injury over the entire course of their career.

Finally, the difference (delta) between glove size and anthropometry, for every inch increase in the difference, injury was reported at a 5 times faster rate. Because a one-inch difference in sizing and anthropometry is viewed as very large, and the largest absolute range for this data set was 1.403 inches between the smallest delta and the largest delta for gloves worn during training (range = -0.549 to 0.854), the magnitude of the delta was reduced to 1/10 of inch. For every 1/10 inch increase in the difference between sizing and anthropometry, injury was reported at an 18% faster rate (OR=1.180). This is a potential indicator that poor suit or glove sizing may contribute to injuries occurring at a faster rate. The fact that this is statistically relevant in the context of time to first injury but not increased odds of injury overall is logical when coupled with the fact that optimal suit and glove sizing is often dialed in over a period of time early in a crewmembers training. More experienced crewmembers have had their sizing tweaked many times based on hours of experience, while less experienced crewmembers may still be in the process of finding their optimal fit. In addition, this could indicate that achieving adequate glove sizing through the use of large finger takeups may contribute to injury and may not be recommended.

Those independent exposure variables found to not be related to time to first injury included sex, handedness, glove model, number of training/EVA events in the past month, delta between glove sizing and anthropometry for hand circumference.

Table 9: Parameter estimates for time to injury for Training – Full Model (all potential independent exposure variables included)

	Parameter Estimate	Standard Error	p-value	Hazard Ratio (95% Confidence Interval)
Training 2002-2004	1.421	0.376	0.001*	4.139 (1.979 – 8.657)
Sex	-0.747	0.726	0.304	0.474 (0.114 – 1.967)
Age	-0.280	0.058	<0.001*	0.756 (0.674 – 0.847)
Handedness	-0.092	0.519	0.860	0.913 (0.330 – 2.523)
Anthropometric Principal Component-1	0.133	0.071	0.060*	1.142 (0.994 – 1.311)
Glove Model	-0.929	0.840	0.269	0.395 (0.076 – 2.049)
Duration of Training event (hours)	1.067	0.377	0.005*	2.907 (1.390 – 6.081)
Total Number of Prior Events (EVA or Training)	-0.030	0.006	<0.001*	0.971 (0.958 – 0.983)
Number of Training/EVA events past month	0.048	0.128	0.705	1.050 (0.817 – 1.349)
Delta: Glove Size and Anthropometry for Middle Finger Length	1.321	1.050	0.208	3.748 (0.479 – 29.333)
Delta: Glove Size and Anthropometry for Hand Circumference	-0.263	0.428	0.539	0.769 (0.333 – 1.779)

* Represents significance at the $p \leq 0.15$ level

Table 10: Parameter Estimates for Time to Injury for Training – parsimonious model (only independent exposure variables significant at ≤0.15 level)

	Parameter Estimate	Standard Error	p-value	Hazard Ratio (95% Confidence Interval)
Age	-0.274	0.052	<0.001*	0.760 (0.686 - 0.842)
Anthropometric Principal Component-1	0.189	0.049	0.001*	1.208 (1.098 - 1.330)
Duration of Training event (hours)	0.862	0.330	0.009*	2.368 (1.241 - 4.517)
Total Number of Prior Events (EVA or Training)	-0.026	0.006	<0.001*	0.974 (0.963 - 0.985)
Delta: Glove Size and Anthropometry for Middle Finger Length	1.653	0.999	0.098*	5.222 (0.737 - 36.999)
Training 2002-2004	1.415	0.369	0.001*	4.117 (1.996 - 8.491)

* Represents significance at the $p \leq 0.15$ level

Time to first reported injury was also modeled for EVA events only. Ninety-six crewmembers participated in 322 EVA events over the study years 1981-2010 and fifty of those crewmembers reported at least one injury during any of their EVA events. Table 11 represents all the parameter estimates and hazard ratios for the proposed full model for time to reporting an injury following EVA with all candidate independent exposure variables. Non-significant variables were removed in a step-wise fashion starting with those variables with the least statistical significance (largest p-value). Table 12 displays the independent variables that were significant at the ≤ 0.15 level in the parsimonious model. Significant independent exposure variables retained in the final model included sex, glove model, time of EVA (hours) and the delta for glove size and anthropometry for middle finger length.

Sex was found to be significantly related to the time to first injury meaning that men report injuries at a faster rate for EVA events (HR = 0.094) than women. This may be due to the greater number of men who performed an EVA over the course of the Shuttle and ISS missions. Of the 322 US person-EVAs performed between 1981 and 2010, 296 (91.9%) were performed by men. Thus, the likelihood of men reporting an injury at any time is greatly increased.

Injuries were reported at a faster rate for those who wore wear a 4000 Series glove compared to those who wore Phase VI (HR=0.116) during the EVA. Of the 322 person-EVAs that were performed between 1981 and 2010, 89 wore Series 4000 gloves, 196 wore Phase VI gloves and 37 were unknown. The Series 4000 model of glove was worn primarily in flight during the 1980s and early 1990s. Programmatically, the elapsed time between the beginning of a crewmember's training and any EVA was shorter during this time period. The average time between first training event and EVA was 5.64 years for those who wore 4000 Series during EVAs (range = 0.88 to 17.28 years), whereas, the mean time between first training and EVA for those who wore Phase VI was 8.25 years (range = 1.74 to 20.62 years). Therefore, it is probable that this result does not indicate a protective factor for the Phase VI over the 4000 Series, but simply a correlation with reduced time from training to EVA.

The length of time for the EVA event was significantly related to the time to reporting first injury (HR=1.611). For every hour increase in EVA length, injury was reported at a 61% faster rate. This means that the longer the EVA, the sooner the injury was reported.

The total number of career events (regardless if those were EVA or training) that occurred prior to the event the crewmember was injured on was inversely related to the time to reporting first injury (HR=0.940). This means that those crewmembers with fewer EVA and training events reported injury at a faster rate than those crewmembers with more EVA and training events. This seems counterintuitive, but may be due to the fact that crewmembers who have had fewer events are earlier in their careers and have had less time to become accustomed to glove fit. Contrary to this finding, the number of events (regardless of EVA or training) that occurred in the calendar month previous was not an indicator or increased time to injury reporting.

Finally, injuries were reported at a nearly 28 times faster rate for each one inch increase in the difference between glove size and the anthropometric measure of the length of the middle finger of the dominant hand (HR=27.890). The actual average difference between glove sizing and the anthropometry of the middle finger for EVA events was 0.0196 inches (range = -0.3900 to 0.3652 inches). Further, a one-inch difference in sizing and anthropometry is viewed as very large, so the magnitude of the delta was reduced to 1/10 of an inch. For every 1/10 inch increase in the difference between sizing and anthropometry, injury was reported at a nearly 40% faster rate (OR=1.395). While the variable is statistically significant at the ≤ 0.15 level, the confidence interval is very wide, probably due to the small sample size of injuries during EVA. Another point of consideration may be that only the exact glove worn during the particular EVA in which an injury was reported was analyzed. If a different glove size was worn in previous EVAs in the same mission, this could have been a precipitating factor in the injury, but not taken into account by this analysis.

Other independent exposure variables that were found not to be related to time to injury for EVA events included age, handedness, Anthropometric Principal Component 1, number or events that occurred in the month prior, and the delta between glove sizing and anthropometry for hand circumference.

Table 11: Parameter estimates for time to injury for <u>EVA Flight</u> – Full Model (all potential independent exposure variables included)

	Parameter Estimate	Standard Error	p-value	Hazard Ratio (95% Confidence Interval)
Sex	-1.991	1.262	0.115	0.137 (0.012-1.619)
Age	-0.015	0.082	0.857	0.985 (0.840-1.156)
Handedness	0.135	0.727	0.853	1.144 (0.275-4.756)

Anthropometric Principal Component -1	0.113	0.117	0.334	1.119 (0.890-1.408)
Glove Model	-3.227	1.310	0.014*	0.040 (0.003-0.517)
Duration of EVA event (hours)	0.510	0.312	0.102*	1.666 (0.903-3.073)
Total Number of Prior Events (EVA or Training)	-0.062	0.015	<0.001*	0.939 (0.913-0.967)
Number of Training/EVA events past month	-0.190	0.228	0.406	0.827 (0.529-1.294)
Delta: Glove Size and Anthropometry for Middle Finger Length	4.569	2.008	0.023*	96.404 (1.884-4933.76)
Delta: Glove Size and Anthropometry for Hand Circumference	0.585	0.677	0.388	1.795 (0.476-6.767)

* Represents significance at the $p \leq 0.15$ level

Table 12: Parameter estimates for time to injury for EVA Flight –Parsimonious Model (only independent exposure variables significant at ≤0.15 level)

	Parameter Estimate	**Standard Error**	**p-value**	**Hazard Ratio (95% Confidence Interval)**
Sex	-2.369	0.860	0.006*	0.094 (0.017-0.505)
Glove Model	-2.153	0.929	0.020*	0.116 (0.019-0.717)
Duration of EVA event (hours)	0.477	0.295	0.106*	1.611 (0.903-2.872)
Total Number of Prior Events (EVA or Training)	-0.062	0.014	<0.001*	0.940 (0.915-0.965)
Delta: Glove Size and Anthropometry for Middle Finger Length	3.328	1.613	0.039*	27.890 (1.181-658.741)

* Represents significance at the $p \leq 0.15$ level

There were several notable similarities and differences between the independent exposure variables found to be related to time to training events and those found to be related to time to EVA flight events. The similarities included duration of event, number of career events prior to injury, and the difference between the glove sizing and anthropometry. Differences included glove model being related to time to first injury for EVA only. The Anthropometric Principal Component 1 variable was related to time to injury for training events only. Further, age was related to time to first injury, but only for training events.

Logistic Regression Analysis for Onycholysis Injury

The next outcome studied was whether or not an onycholysis injury was reported following training or EVA event. Due to the low numbers of crew reporting onycholysis or nail injuries during EVA, this analysis was not able to be stratified by EVA or training. However, EVA or training was included as dichotomous variable in the analysis in order to control for any effect EVA or training may have had. Table 13 displays the full logistic regression model showing the variables related to onycholysis injuries reported during training. The full model was made more parsimonious by iterating the models with a backwards, step-wise approach to remove the variables with the least statistical significance. Significant independent exposure variables (at the ≤ 0.15 level) that were retained in the parsimonious model included sex, age, glove model, time of Training/EVA event (hours), the delta for glove size and anthropometry for middle finger length, training vs. EVA, and training 2002-2004 (Table 14).

Table 13: Parameter estimates for onycholysis injury Full Model (all potential independent exposure variables included)

Parameter	Parameter Estimate	Standard Error	p-value	Odds Ratio (95% Confidence Interval)
Intercept	-13.247	2.186	<0.001	
Sex	0.841	1.047	0.422	2.318 (0.298-18.045)
Age	0.063	0.046	0.174	1.065 (0.973-1.166)
Handedness	0.510	0.691	0.460	1.666 (0.430-6.448)
Anthropometric Principal Component-1	-0.002	0.116	0.986	0.998 (0.796-1.252)
Glove Model	1.921	1.226	0.117*	6.827 (0.618-75.444)
Duration of Training/EVA event (hours)	0.449	0.309	0.146*	1.567 (0.855-2.871)
Number of Training/EVA events past month	-0.112	0.117	0.336	0.894 (0.712-1.123)
Delta: Glove Size and Anthropometry for Middle Finger Length	2.065	1.018	0.043*	7.789 (1.073-58.001)
Delta: Glove Size and Anthropometry for Hand Circumference	0.352	0.598	0.556	1.422 (0.440-4.596)
Training or EVA?	0.966	0.620	0.119	2.627 (0.780-8.852)
Training 2002-2004	1.273	0.392	0.001*	3.573 (1.658-7.699)

* Represents significance at the $p \leq 0.15$ level

Table 14: Parameter estimates for onycholysis injury Reduced Model (only independent exposure variables significant at ≤ 0.15 level included)

Parameter	Parameter Estimate	Standard Error	p-value	Odds Ratio (95% Confidence Interval)
Intercept	-13.194	2.365	<0.001	
Sex	0.964	0.493	0.051*	2.622 (0.997-6.894)
Age	0.063	0.042	0.131*	1.065 (0.981-1.156)
Glove Model	2.144	1.114	0.054*	8.535 (0.961-75.811)
Duration of Training/EVA event (hours)	0.451	0.309	0.144*	1.570 (0.857-2.875)
Delta: Glove Size and Anthropometry for Middle Finger Length	2.042	1.191	0.087*	7.709 (0.746-79.623)
Training or EVA?	0.928	0.611	0.129*	2.529 (0.763-8.381)
Training 2002-2004	1.272	0.398	0.001*	3.566 (1.633-7.786)

* Represents significance at the $p \leq 0.15$ level

Women have a 2.62 times greater odds of reporting a onycholysis injury than men. Other results showed men had a greater risk of any injury. There is evidence in the general dermatology literature that delamination may occur more often in women than men. Reasons cited for this difference may include exposure to nail cosmetics, strong soaps, and overaggressive care of the nails (Daniel, et al., 2011).

This analysis also found that there is a 65% greater odds of reporting an onycholysis injury for every year increase in age. This is the opposite result as was found in the all-injury survival analysis that showed as age increased the time to reporting of first injury slowed. This may be because onycholysis injuries may occur slowly over many training events, thus reporting may occur later in training and later in age.

It was also found that there is a 8.5 times greater odds of reporting onycholysis injury when the crewmember was wearing Phase VI gloves compared with when they were wearing 4000 Series gloves. However, the analysis team identified multiple confounding factors that may account for these results. Namely:

1) Although the enhanced reporting period from 2002-2004 was controlled for in the analysis, comparison of injury data from after this period against before this period indicates that crewmembers may have become more comfortable with reporting injuries and continued doing so, even after the 2002-2004 study was completed. As the Phase VI glove was dominant during this time, it could account for the results showing the Phase VI to be more injurious than the 4000 Series glove.
2) The implementation of the Phase VI glove resulted in a reduction of the LCVG vent tube length from the wrist to the upper arm. This has been theorized as a potential contributor to injury due to increased levels of humidity in the glove cavity. It was not possible to separate this factor from the glove model variable and therefore, is a possible contributor to consider with these results.
3) Lastly, it is possible that a unique design feature and/or sizing methodology employed with the Phase VI glove makes it inherently more injurious during use than the 4000 Series glove. Unfortunately, given the varying reporting rates through time it is not possible to know how much the Phase VI glove alone is responsible for this correlation. In fact, it is possible that the Phase VI glove is no more injurious than the 4000 Series (or less) and the differences in reporting rates through time account for the results presented.

It should be noted that if the increased reporting rates in 2005-2010 are partially or fully responsible for these results, the conclusion would be that injuries during the 4000 Series glove era were vastly under-reported.

Duration of a training or EVA event was also found to be statistically significantly related to reporting of a onycholysis injury. For every hour increase in the duration of the event, there was a 57% increase in the odds of reporting an onycholysis injury. This is consistent with most of the other analyses in that as the duration increases, so does the likelihood of reporting an injury. Further, moisture is known to play a role in the development of onycholysis. As an event increases in length, it is thought the amount of moisture accumulating in the glove due to perspiration may also increase.

Finally, this research showed there was a 7.7 times greater odds of reporting onycholysis for every inch increase in the delta between glove size and the anthropometry of middle finger length. Since a one inch difference in sizing and anthropometry is viewed as very large, the magnitude of the delta was reduced to 1/10 of an inch. For every 1/10 inch increase in the difference between sizing and anthropometry, the odds of reporting any injury increased by 23% (OR=1.227). This may be counterintuitive due to the fact that onycholysis injuries have been theorized to be caused by mechanical stressors from the glove on the fingernail and/or fingertip. This analysis seems to indicate increased risk of onycholysis as the glove finger gets longer than the finger itself or that poor glove fit itself may be an issue. Therefore, further investigation into this and other variables contributing to increased onycholysis risk is warranted. In addition, this could indicate that achieving adequate glove sizing through the use of large finger takeups may contribute to injury and may not be recommended.

The two control variables, Training versus EVA and Training between 2002 and 2004, were both significant as would be expected. More onycholysis injuries were reported during training than during EVA and more onycholysis injuries were reported during the years 2002 – 2004 than other years.

Handedness, Anthropometric Principal Component 1, and the number of events in the past month were not significantly related to an increased risk of reporting an onycholysis injury. The fact that anthropometry was not related to injury was in direct contradiction of previous reports that increased hand circumference was related to increased risk of onycholysis (Opperman, 2010). When a model replacing the Anthropometric Principal Component 1 variable with the more specific hand circumference of the dominant hand was conducted, it was found there was no relationship (OR=1.386, p=.611) between hand circumference and onycholysis injuries.

In addition, post-hoc analyses were conducted to further investigate this discrepancy on hand circumference between the two analyses. The first, which only looked at Phase VI gloves, which facilitated additional sizing measures (delta between anthropometry and glove middle finger; delta between anthropometry and glove hand length). Most results were very similar, and most notably, hand circumference was never a significant risk factor to injury. The second post-hoc analysis performed was an attempt to replicate the Opperman analysis to the extent possible given the available data set. Here, only right-handed males were evaluted, and instead of using a principal components analysis each individual anthropometric measure was analyzed as a discrete independent variable. Again, the results indicate that there is not a statistically relevant correlation between hand circumference and onycholysis (odds ratio of 2.325, 95% confidence interval of 0.662-8.165, p=0.188). Interestingly enough, in this analysis the results show a correlation between onycholysis and larger index circumference (OR = 48.1 (1.5-999); p=0.028) and middle circumference (OR = 69.8 (1.14-999); p=0.043). Even more intereting, these are the two fingernails most commonly reported with injuries. Regardless, we were not able to corroborate previous analysis indicating that larger hand circumferences are a risk to onycholysis.

Survival Analysis for Time to Onycholysis Injury

The next outcome studied was the time until onycholysis injury. Due to the low numbers of crew reporting onycholysis or nail injuries during EVA, this analysis was not able to be stratified by EVA or training. However, EVA or training was included as a dichotomous variable in the analysis in order to control for any effect the type of event may have had. Further, the variable glove model was not able to be estimated in the Cox regression, probably due to the low number of onycholysis injuries occurring in the 4000 Series glove.

Table 15 displays the full survival analysis models showing the independent exposure variables as they relate to onycholysis injuries. The full model was made more parsimonious by iterating the models with a backwards, step-wise approach to remove the variables with the least statistical significance. Significant independent exposure variables (at the ≤ 0.15 level) that were retained in the model included age, Anthropometric Principal Component 1, time of Training/EVA event (hours), total number of prior events (training or EVA), the delta for glove size and anthropometry for middle finger length, and training 2002-2004 (Table 16)

Table 15: Parameter estimates for time to first onycholysis injury – Full model (all potential independent exposure variables included)

Parameter	Parameter Estimate	Standard Error	p-value	Hazard Ratio (95% Confidence Interval)
Sex	-0.147	1.275	0.908	0.863 (0.071-10.513)
Age	-0.251	0.096	0.009	0.778 (0.645-0.939)
Handedness	-0.896	0.985	0.363	0.408 (0.059-2.812)
Anthropometric Principal Component-1	0.186	0.122	0.126	1.205 (0.949-1.530)
Duration of Training/EVA event (hours)	0.887	0.334	0.008	2.427 (1.260-4.675)
Total Number of Prior Events (EVA or Training)	-0.034	0.011	0.002	0.966 (0.946-0.988)
Number of Training/EVA events past month	0.082	0.212	0.700	1.085 (0.717-1.643)
Delta: Glove Size and Anthropometry for Middle Finger Length	3.946	1.814	0.030	51.731 (1.477-1812.352)
Delta: Glove Size and Anthropometry for Hand Circumference	-0.117	0.743	0.875	0.890 (0.208-3.816)
Training 2002-2004	1.447	0.606	0.017	4.252 (1.297-13.935)

* Represents significance at the $p \leq 0.15$ level

Table 16: Parameter estimates for time to first onycholysis injury – Parsimonious Model (only independent exposure variables significant at ≤0.15 level)

Parameter	Parameter Estimate	Standard Error	p-value	Hazard Ratio (95% Confidence Interval)
Age	-0.269	0.084	<0.001	0.764 (0.648-0.900)
Anthropometric Principal Component-1	0.207	0.077	0.007	1.230 (1.058-1.431)
Time of Training/EVA Event (hours)	0.863	0.299	0.004	2.370 (1.319-4.260)
Total Number of Prior Events (EVA or Training)	-0.029	0.008	<0.001	0.971 (0.955-0.988)
Delta: Glove Size and Anthropometry for Middle Finger Length	4.690	1.695	0.006	108.871 (3.928-3017.190)
Training 2002-2004	1.453	0.581	0.012	4.275 (1.369-13.348)

* Represents significance at the $p \leq 0.15$ level

For age, for every year increase in age, there is a 24% reduction in rate of onycholysis injury (HR = 0.76), or those crewmembers who are younger are more likely to report an onycholysis injury faster. This is contrary to the result found for age and the association with reporting any onycholysis injury; the odds of reporting an onycholysis injury increased as the crewmember aged. This again, may be due to the fact that poor glove fit during early suited events may influence an increased rate of injury reporting at an earlier age. Further, as crewmembers advance in their career, and get older and increase training, the overall risk of onycholysis may increase. As with other analyses, the number of career events prior to injury was statistically significantly related to the time to injury. For every one more event completed prior to the event the crewmember was injured on, there was a 3% decrease (HR=0.971) in the rate of onycholysis reporting.

Additionally, crew members with larger anthropometry reported onycholysis injuries at a 23% faster rate than those with smaller anthropometry. This is similar to the result found for time to any injury, those who have larger anthropometry report injuries of any type, and specifically onycholysis at a faster rate than those with smaller anthropometry.

There is a 2.37 times faster rate of onycholysis reported for every hour increase in the duration of the event, whether it be EVA or training. As with most other analyses performed, this one also showed that as the duration of a training or EVA event increased, onycholysis injuries were reported at a faster rate.

There is more than a 100 times greater rate of reporting onycholysis for every inch increase in the delta between glove size and the anthropometry of middle finger length. Since a one-inch difference in sizing and anthropometry is viewed as very large, the magnitude of the delta was reduced to 1/10 of an inch. For every 1/10 inch increase in the difference between sizing and anthropometry, injury was reported at a nearly 60% faster rate (HR=1.598). This may be counterintuitive due to the fact that onycholysis injuries have been theorized to be caused by mechanical stressors on the fingernail and/or fingertip. This analysis seems to indicate increased risk of onycholysis as the glove finger gets longer than the finger itself or that poor glove fit itself may be an issue. Therefore, further investigation into this and other variables contributing to increased onycholysis risk is warranted. In addition, this could indicate that achieving adequate glove sizing through the use of large finger takeups may contribute to injury and may not be recommended.

IV. Summary and Conclusion

This literature review and data mining study was conducted between 2012 and 2014. The study was bound by events occurring between 1981 and 2010, crossing both the Shuttle and ISS eras. Only US NASA crew were investigated regarding 4000 Series and Phase VI glove models utilized during Extravehicular Mobility Unit (EMU) spacesuit EVA training and flight.

Utilizing both literature and anecdotal causation comments recorded in crewmember injury data, investigators were able to identify several types of risks associated to the 23 type of injuries indicated in the study. These risks can be generalized to force based, task based, environment based, and individually based. A large majority of the risks identified point to force against the body (such as axial or shear loading, sustained and/or constricting forces). Task related risks include those that require exposure to repetitive motions and/or overexertion. Environmental variables also could be causational factors, such as fluid shifting due to microgravity or inverted work, moisture accumulation or extreme temperatures. Lastly, individual factors such as allergic reactions to chemicals or material can act as an injury factor. As force related and task related variables were not assessed by this study, further future work assessing and quantifying these risks, will need to be performed. With that, there were many significant findings as a result of this study. These key findings were divided into three primary categories:

- Glove Injury Descriptive Statistics
- Glove Injury Reporting Methods
- Glove Injury Risk Causation Analysis

A. Glove Injury Descriptive Statistics

1. EVAs were performed by 96 crewmembers during the 322 EVAs that occurred through the investigation period of 1981 to 2010. There was a report of at least one injury during 96 (29.8%) of these 322 EVAs. Further, 50 of the 96 crewmembers (52.1%) who participated in an EVA reported at least one injury.
2. Most reported injuries were from only 1-2 individual incidents. This may indicate that most reported injuries were not chronic or cumulative problems with frequent recurrence, but due to injury data recording inconsistencies over time, there is not enough evidence available to support that chronic/cumulative injury is or is not a considerable risk. Future follow-up correlation studies will need to be performed to confirm this.

3. Injury types reported differed between training and flight exposures. This could be due to actual differences between the exposure events, but more likely indicates a need for standard injury type nomenclature and reporting timeframes.
4. Training injury locations were most commonly reported at the fingernail, MCP joint or finger crotch with pain, erythema (redness), and onycholysis the most common reported injuries.
5. EVA flight injury locations were most commonly reported at the hand, MCP joint or finger with fatigue, abrasion, and paresthesia the most commonly reported injuries.

B. Glove Injury Reporting Methods

1. Injuries were tracked with different methods over time. Moving forward, there needs to be one standard approach to reporting all suit related injuries regardless of exposure type (EVA flight or training) or suit/glove model.
2. Terms used to describe the injury types were not standardized. Investigators had to group injuries into one large category, and other than onycholysis, no other injury type was investigated separately. Future work should look to investigate other specific injury types.
3. Body part locations were inconsistently labeled, and oftentimes reports were too general citing only the hand or finger as the injury location. Standardized locations including specific finger, joint, or crotch should be used for glove related injuries.
4. There was no use of an injury severity scale for recorded injuries. Without severity information, all injuries had to be treated with equal severity. Also, there was limited information on the duration or persistence of an injury, therefore, investigators could not estimate a severity scale.
5. Suit sizing information was not available consistently per exposure. If engineering design solutions are to be used to mitigate glove related injury, then a record of relevant suit and glove sizing metrics needs to be included with every EVA training or flight event.
6. Injury data were stored in multiple databases and had to be consolidated. If it is to be studied as an occupational exposure, suit related injury data should be clearly identified from other medical data in a crewmembers' medical record. In addition to currently implemented countermeasures, suit related injuries should be mitigated using engineering and operational controls wherever possible.

C. Glove Injury Risk Causation Analysis

1. Likelihood of reporting an injury during training was related to handedness, glove model, duration of the training event and whether the training occurred in the years 2002-2004. Ergonomic task analysis including an evaluation of handedness bias in EVA training classes should be considered. Also, since many of the training event durations were estimated, this should be rectified with an exact recording of suited exposure duration. While this is specific to training, EVA flight recording should also be treated the same.
2. Likelihood of reporting an injury during inflight EVA was related only to the Anthropometric Principal Component 1 (hand size). This indicates that crew with smaller hand anthropometry were at higher risk for reporting an injury. While there are no clear recommendations from this finding, it supports general recommendations for optimizing fit and possibly controlling for and reducing hand intensive tasks and EVA durations for crew with smaller hand anthropometry.
3. Likelihood of reporting an injury earlier in career during training increased with Anthropometric Principal Component 1 (hand size), duration of the training event, and the delta between glove size and anthropometry for middle finger length and decreased with higher age and total number of prior events. Of all of these factors, the most striking finding was how the delta between glove size and middle finger length increased the risk early in a career. This indicates the need to optimize glove sizing as soon as possible in a crewmembers' career and to not substitute a poorly fitted glove. In addition, this could indicate that achieving adequate glove sizing through the use of large finger takeups may contribute to injury and may not be recommended.
4. Likelihood of reporting an injury earlier in career during inflight EVA increased with exposure event duration and the delta between glove size and middle finger length. Again, this points towards shorter exposures decreasing risk and the need to optimize glove sizing early in a crewmembers' career. In addition, this could indicate that achieving adequate glove sizing through the use of large finger takeups may contribute to injury and may not be recommended.

5. Likelihood of reporting an onycholysis (fingernail delamination) injury increased with age, duration of the training or EVA event, delta between glove size and middle finger length and being female. This again points to the need for shorter exposures and optimal glove sizing.
6. Likelihood of reporting a onycholysis injury earlier in one's career increased with Anthropometric Principal Component 1 (hand size), duration of training or EVA event, and the delta between glove size and middle finger length. In this case, it was the larger handed crewmembers who reported injury earlier, but it still points to shorter exposure and optimal glove fit as important controls.
7. Another interesting find was specific to glove model, indicating that Phase VI gloves could possibly influence the likelihood of developing onycholysis specific injuries versus wearing the 4000 Series glove. To note, there were changes made to the design of the EMU vent tube length where the vent tube was reduced from the wrist to the upper arm around the same time period as the Phase VI implementation. This may contribute in some way to glove related environmental changes in the EVA glove. In addition, reporting differences between the two periods of time these gloves were in use may be a significant contributor as well.
8. A previous study by Opperman et al. (2010) found an increased risk of onycholysis injury with greater hand circumference. Substituting hand circumference for Anthropometric Principal Component 1 in any of the statistical analyses found hand circumference to be a non-significant factor. Further post-hoc analyses to replicate the Oppermann analysis to the extent possible given the available data set found the same results.

D. Future Work

1. NASA should implement a suited injury data collection standard across all EVA training and flight to allow for future causation analysis studies. This data collection standard should clearly define injury, assess severity, and elucidate recurrence/chronicity. A prospective pilot phase of this project would allow for validation of the findings of this current research. Specific follow-up studies can refine the risk quantities to allow for more specific risk thresholds for glove size, age, event exposure time, and event exposure frequency. Additionally, this will also allow for investigators to better assess the acute versus cumulative risk towards these injuries.
2. Additional quantification of the cause-effect risk factors outside of this data mining study, such as those specific to the environment in the glove (forces on the body, moisture, temperature, etc.), should be examined to determine how they contribute to injury. These studies will help understand the glove environment as it relates to injury; this understanding could help provide better operational controls and lead to improved designs for the EVA glove.
3. Approximately 3,000 pages of suit fit and glove fit comments were received. Due to the enormity of the data received, the team was unable to assess these thoroughly in the timeframe allowed by the project. Potentially, additional risk factor data and injury information may be derived from these comments. As these records were mainly provided in a non-queriable format, these comments should be digitized and assessed towards injury risk in a follow-up study.

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