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REGULAR PAPER

Pressure monitoring based identification of the EOD suit–human interface load distribution

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Abstract

Soldiers working in the field of explosive ordnance disposal (EOD) wear cumbersome personal protective equipment (PPE) that may affect their performance in the field, limit their mobility, and cause discomfort. The objective of this study was to develop a test methodology to identify the relationship between EOD suit interface loads and mission-critical performance metrics. The physical interactions between an EOD suit and human subjects were monitored using a distributed pressure sensor network to investigate the interface load distribution during EOD-related physical positions and activities. More specifically, a Med-Eng brand Model EOD 8 suit was utilized to evaluate shoulder discomfort and leg mobility restriction. Thirty-four college aged adults of varying athletic abilities completed a test course and walked on a treadmill for 2 min while wearing the EOD 8. Demographic information was collected before testing via a survey and qualitative observations were collected at the end of testing with a questionnaire. After each test course repetition, participants ranked their perceived exertion using the Borg scale. Overall, the time it took participants to complete the test course increased by 17% and participants experienced a 60% increase in perceived exertion while wearing the EOD 8. The region that experienced the most pain and discomfort was the top of the shoulders (59%) and there was a negative correlation ($r = -0.5$, $p < 0.05$) between participants' body mass index (BMI) and the max shoulder pressure. The groin protector was found to restrict hip rotation when the subject squatted to pick up an object, producing a pressure 30-times higher than without the EOD 8. These results suggest that a range of motion evaluation method for EOD suits and other protective ensemble can be successfully developed using a combination of user feedback and strategically placed pressure sensors. This study implements the largest pressure region ever recorded on the human body and is the first of its kind to investigate the movement restriction of PPE for various practical tasks.

Keywords Pressure sensing · Monitoring · Interface loads · Range of motion · Military protective equipment · Classification

1 Introduction

In the twenty-first century, the nature of warfare has evolved with the dawn of global terrorism leading to a drastic increase regarding the threat of improvised explosive devices (Barker 2011). This has consequently increased the demand for trained explosive ordnance disposal (EOD) technicians and state-of-the-art personal protective equipment (PPE). The EOD suit worn by military and civilian professionals has been subjected to a few investigations regarding blast resistance (Bass et al. 2005) and ergonomics (N. Institute of Justice 2012a), but presently little is known regarding how the weight of the suit is distributed on the body and how it impacts performance. The possible physical consequences on the human body due to prolonged field use have also not been addressed completely (Roy et al. 1976). Personal protective equipment purchased by the U.S. Army are thoroughly tested for not only primary functionality, but extended performance, ergonomics, cost effectiveness, etc. Nonetheless, there is still an opportunity for significant improvement of standardized methodologies to better

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characterize and thoroughly evaluate EOD suits to reduce harmful physical effects on the EOD technician (Nindl et al. 2013).

The EOD 8 (the "8" denoting the suit version) was developed in 1999, becoming one of the most widely utilized EOD suit models used by both military and civilians around the world for the next two decades (Bass et al. 2005). Aside from the helmet, the EOD 8 consists of three main components. The suit's outer fabric is made from an aramid weave with both hard and soft removable armor panels made from proprietary composites. The jacket is the heaviest component with flexible armor protecting both arms from the wrist to the shoulder and a torso and neck protective component providing 360-degree coverage to those areas. A large, two-piece rigid composite plate is incorporated into the jacket front to protect the pelvic, abdomen, chest and neck regions. The trousers (leg protection) provide coverage extending from the ankles to the thighs and contain an impact absorbing back protector that covers the length of the spine. Finally, the groin protector, which resembles a pair of shorts, contains a soft armor element that covers the waist, groin, and buttocks. Finally, the groin protector is a sheath containing a single, soft armor protector that wraps around the waist, groin, and buttocks. EOD suits must provide four critical protection factors: fragmentation, overpressure, heatwave, and impact (Krzystała et al. 2019). The primary mode of protection is the composite torso plate in the EOD suit which is designed to attenuate and redirect the blast (pressure) wave of an explosion around the technician (Gmitrzuk et al. 2018), while providing protection from shrapnel when combined with the soft armor and padding (Bass et al. 2005).

The Explosive Ordinance Disposal 8 (EOD 8) is a full body protection suit (see Fig. 1) that is utilized by military personnel and police around the world to diffuse/neutralize Improvised Explosive Devices (IEDs). The EOD suit protects the technician wearing it from shockwave, pressure wave, heat, and shrapnel. The blast resistance of these suits has been thoroughly tested and evaluated, but not much is known with regards to the ergonomics of the suit. This includes, but is not limited to, range of motion, cognitive function, comfort, and general maneuverability. The goal of the research that was performed was to determine how pressure hotspots due to human to suit contact effect the performance of the test subjects. This data would then be utilized to develop a pressure-based method of quantifying the interfacial loads of the EOD suit throughout various regions of the body. With this evaluation method it would be possible to not only compare the ergonomics of different EOD suits, but the data could also be used to influence the design of future EOD suits as well.

The user adapting their movement strategy while encumbered is a phenomenon that has been observed in previous work for other PPE applications (Wettenschwiler et al. 2015a). The prevailing theory is that the user will change their strategy (Wettenschwiler et al. 2015a). Currently, there

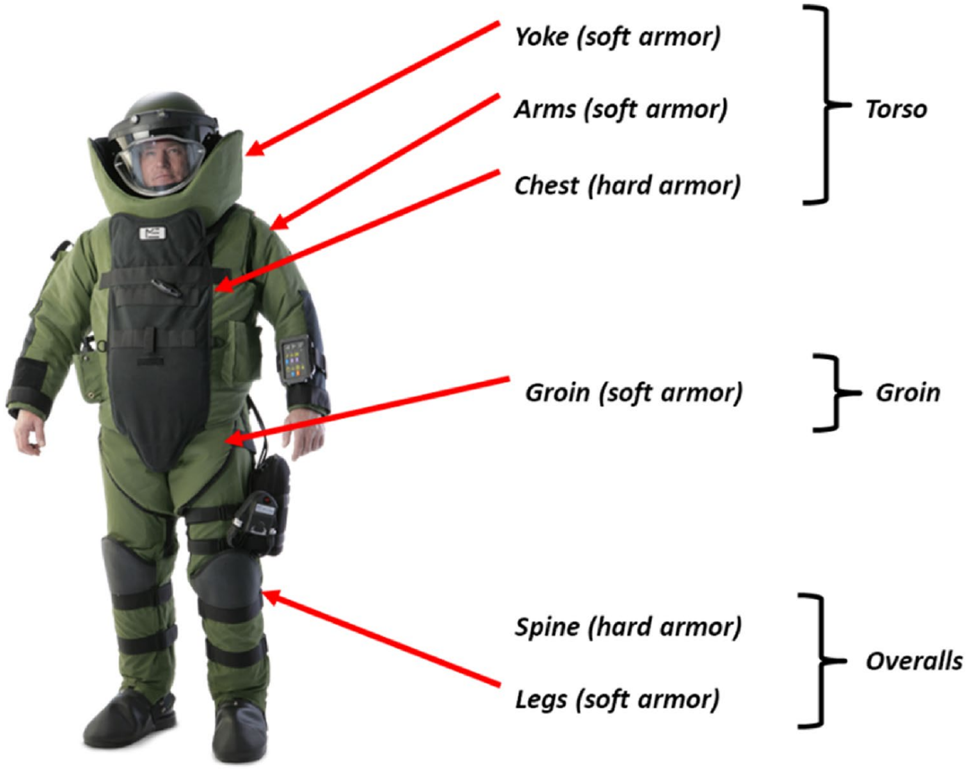


Fig. 1 Diagram outlining the main protection components of the EOD 8

is little documented on this subject for EOD suits while there is extensive research regarding more ubiquitous tactical style body armor vests (Lenton et al. 2018). The NIJ Bomb Suit Standard delineates range of motion and qualitative performance of EOD suits. The NIJ standard test course consists of a walking portion, climbing over a guard rail, ascending stairs, and a timed dexterity and mobility test (N. Institute of Justice 2012b). Only observations would be taken from this test course procedure, but there is limited amount of quantitative data with the exception of accelerometer (Brusey et al. 2009), heart rate, and core temperature (Stewart et al. 2011). The ergonomics portion of the National Institute of Justice 0117.01 standard requires the maximum angular rotation of each joint to be measured in flexion, extension, and abduction with a goniometer. Similar techniques were used to evaluate the range of motion for firefighter protective ensemble and similar conclusions were made regarding the need for a standardized method of evaluating the ergonomics of PPE (Coca et al. 2010). In Brusey et al. (2009), postural activity monitoring using accelerometers was conducted to identify non-compensable heat stress (UHS). Brusey et al. (2009) monitored posture position for both static and dynamic conditions and used a classifier to distinguish the tasks based on patterns in the accelerometer data (Brusey et al. 2009). Other studies have observed heat illness by having subjects ingest a core temperature sensor while wearing a heart rate monitor (Stewart et al. 2011). Combining the test course and the classification process could potentially yield a methodology of evaluating EOD suit mobility in an obstacle course environment. To accomplish this, pressure sensors can be used to record data from areas of contact between the suit and the wearer (Wettenschwiler et al. 2015b). This includes the kneecaps, the shoulders, and the lower back. With the pressure data, it can be determined how the load of the EOD suit is distributed from a static standing position to various dynamic movements such as walking (Zhou et al. 2017).

The purpose of this study was to quantify the resistance exerted on the user's body by the EOD suit and how the user adapts to complete various tasks that require differing ranges of movement. Previous studies related to analyzing soldier performance regarding body armor and backpack weight have measured the pressure exerted on the shoulders and waists of subjects (Lenton et al. 2018). A Load Distribution System (LDS) was analyzed by taking human subject data from both standing and marching soldiers to determine if there existed any improved measure of comfortability (Lenton et al. 2018). In this study, a similar methodology was applied. Additional dynamic tasks that were classified utilizing the pressure recorded at the knees as a reference were added (Zhou et al. 2016). Specifically, this study proposed an experimental methodology for investigating the restriction and discomfort of EOD suits with respect to pressure at the interface of the human body and the suit. The collected pressure data can then be combined with subjective rankings of exertion, demographic data, and anecdotal qualitative analysis from the participants after wearing the EOD suit. Using a combination of qualitative and quantitative analysis would help locate and measure the severity of restriction, discomfort, and pain with respect to EOD suits. This evaluation method could be utilized by designers/evaluators to refine the development of future EOD suits and other fields that require cumbersome or mission critical Personal Protective Equipment (PPE). With the implementation of pressure sensors on the body, it is possible to determine changes that could be made to the EOD suit to increase range of motion or decrease load concentrations. A notable coincidence justifying the successful approach presented in this paper was the removal of the groin protector from the EOD 10, which is the latest version of the MedEng EOD suit (used as an example system/suit to demonstrate the approach) that is widely used. The groin protector was a source of significant restriction with regards to hip rotation in the journal paper. This restriction appeared in the data as a significant increase in pressure (40 × increase) in the quads region when the subjects were overcoming the hurdle, squatting, and climbing up stairs. In the post-test questionnaire 11% of subjects reported the groin as the second largest source of discomfort while completing the test course. By actively tracking the pressure hot spots on the body, the PPE can be updated to compensate. This pressure sensor methodology has the potential to evaluate the ROM of PPE required in other fields such as firefighter ensembles, space suits, body armors, etc. The pressure data gleaned from different obstacle course tasks when combined with user feedback could be used to influence the design of future protective suits.

2 Methodology

2.1 Test participants and instrumentation

Thirty-four subjects were recruited from a subject pool primarily consisting of college aged adults (20–38 years) with varying levels of physical fitness. One subject had prior experience of wearing the EOD suit in the U.S. Army and only two subjects were female. There was no clear variation in the data between these three exceptions and the other subjects. All subjects provided their consent to participate in this study within compliance of the National Institutes of Health (NIH). This study was approved by the Institutional Review Board of the University of Massachusetts Lowell (# 19-023). Before any physical testing, subjects were asked to complete a 10-min anonymous (a subject number was assigned and used in place of birth name) survey to compile demographic information.

A total of three EOD 8 suits were provided in the sizes medium-small (132.41 N), medium (149.61 N), and large (172.85 N). The suit size for subjects were determined by the height and weight of the subjects. Reference Table 1 below for the jacket weight by size. The weight was calculated by allowing the deadweight of the jacket to settle on a force plate, then 10 force data points (N) were collected at random intervals and averaged to yield the final weights for the three different torso sizes. The helmet was excluded from this experiment. The suits were air-dried, washed, and sanitized after each use.

The pressure sensors (pads) used in this study included four novel™ pliance® and one novel™ elastens® pad sensors that were sourced by the team at the US Army Combat Capabilities Development Command Soldier Center (CCDC) and UMass Lowell Structural Dynamics and Acoustic Systems Laboratory (SDASL). The pliance® sensor pad works with capacitive transducers in a matrix configuration. The elasticity of the sensor permits perfect conformability to three-dimensional deformations. The pressure transducing elements contain a proprietary elastomer manufactured by novel™. Restoring force, range of force, threshold, hysteresis, temperature effect, frequency response, and other characteristics are determined during the manufacturing process. This makes it possible to adapt the sensor characteristic to different measuring needs. Each pliance® pad was 17 × 45 cm with an 8 × 32 sensor matrix for a total of 256 recordable data probes (each pad consists of pressure sensors similar to pixels of a camera) and a resolution of 0.34 sensors per square centimeter. The effective pressure range of the sensors was 2 to 240 kPa with an accuracy of ± 5% according to the manufacturer. The signal from the sensor was collected by two synchronized pliance® xf-32 units and that signal was transmitted to two separate laptops with Bluetooth receivers. The sensors were zeroed (calibrated) by laying them flat on a table while recording for 30 s. Once the subject was wearing the EOD suit, the sensors were re-zeroed by loading the previous zero in the proprietary software.

Table 1 The recorded dead weight of the EOD jacket for three different sizes

	EOD 8 size		
	Large suit (N)	Medium suit (N)	Small suit (N)
	176	149.6	132.8
	173.8	149.7	132.6
	173.3	149.6	132.2
	172.6	149.4	132.1
	172.8	150.2	133.4
	172.6	149.8	132
	172.4	149.4	132.2
	172.2	149.3	132.4
	171.8	149.1	132
	171	150	132.4
Average weight	172.85	149.61	132.41

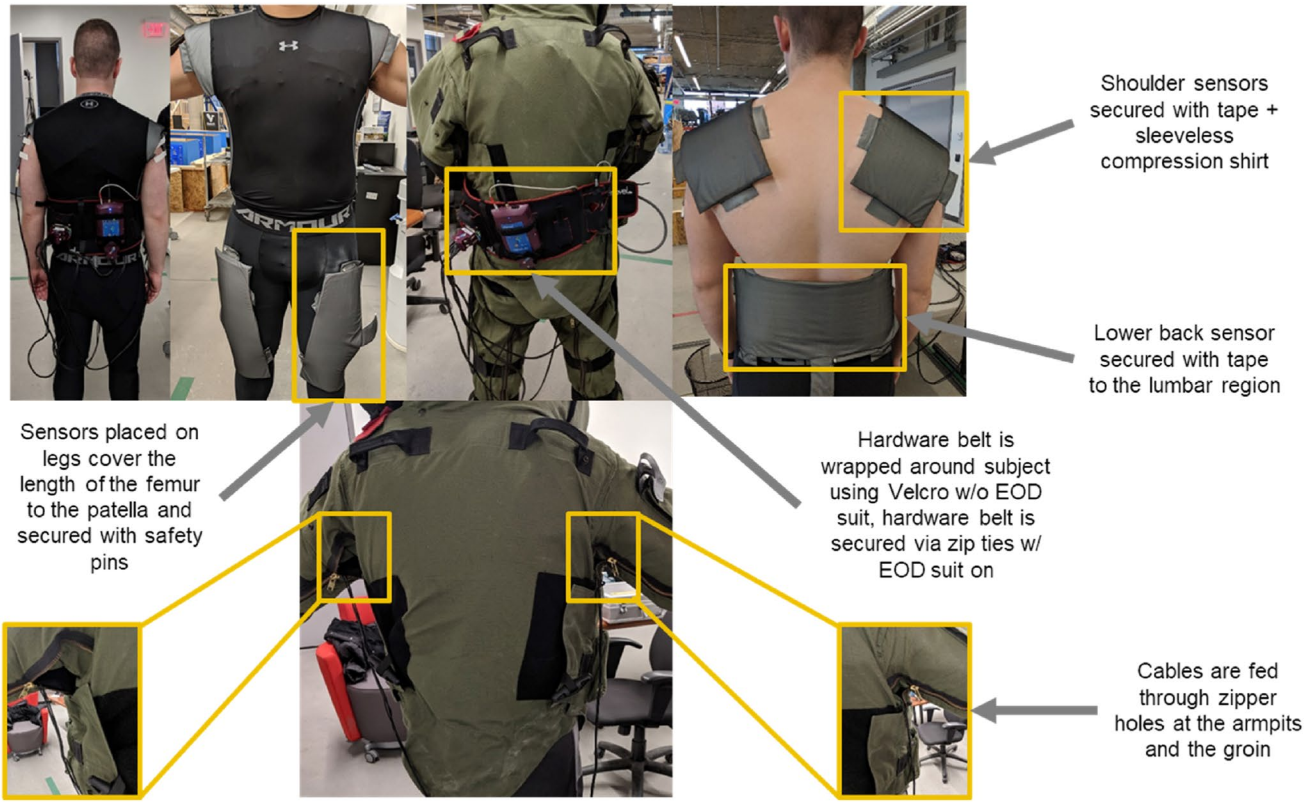
The shoulder sensors were taped (3M™ Micropore®) to the subjects' bare skin on the pectorals and trapezius regions (see Fig. 1). The lower back sensor was secured in the lumbar region of the spine via tape, with the length of the sensor spanning from the right oblique to the left oblique. A sleeveless compression shirt was then used to further secure the shoulder and lower back sensors onto the body. For the legs, the sensors were attached via safety pins to compression pants. The cables from the shoulders ran down the biceps and out the armpits, the cables from the legs protruded from the back of the knees. The hardware was secured using a Velcro belt and a string bag that was pinned to not interfere with the shoulder sensor pads. The leg sensor covered from the length of the femur all the way past the patella. In Fig. 1 the layout of the sensor pads under the EOD suit is shown. To determine if the sensors had been placed properly, the tops of the shoulders and the kneecap regions were palpated for bone landmarks (Lenton et al. 2018). The center portion of the shoulder sensor would show the clavicle, acromion, and the scapula when palpated. For the legs, the patella had to be visible on the lower third partition of the sensor.

When putting the EOD suit on the subject, the trousers were put on first, the groin protector second, and then the jacket. Once the suit was on, the straps were adjusted for a secure fit and a basic joint mobility test was conducted to ensure that all limbs had equivalent motion. The subject would raise each leg, one at a time, with the knee bent to compare leg mobility. For arm mobility, the subject would make two fists, stick their elbows out, and flex their arms into their chest. If this test was passed, the subject would point their index and middle finger then attempt to touch their temples with both fingers while keeping their elbows out.

2.2 Experimental approach

A test course was developed with consideration of the NIJ standard and consisted of five tasks: walking 30 m, shuffling 30 m, clearing a 2.5 ft. hurdle (approx. height of a guardrail or common waist-height obstacle), picking up and walking with a crate containing 20 lbs. up and over a 15 degree incline/decline then placing the crate down, and ascending/descending three steps of stairs in that exact order. Each subject would complete this test course five times both with and without the EOD suit being worn. The test course and its associated tasks are illustrated and labeled in order in Figs. 2 and 3.

A 5-s pause of static standing was inserted before and after each repetition of the test course. A 5-s pause



Shoulder sensors secured with tape + sleeveless compression shirt

Lower back sensor secured with tape to the lumbar region

Sensors placed on legs cover the length of the femur to the patella and secured with safety pins

Hardware belt is wrapped around subject using Velcro w/o EOD suit, hardware belt is secured via zip ties w/ EOD suit on

Cables are fed through zipper holes at the armpits and the groin

Fig. 2 Outline of sensor attachment and placement under the EOD suit

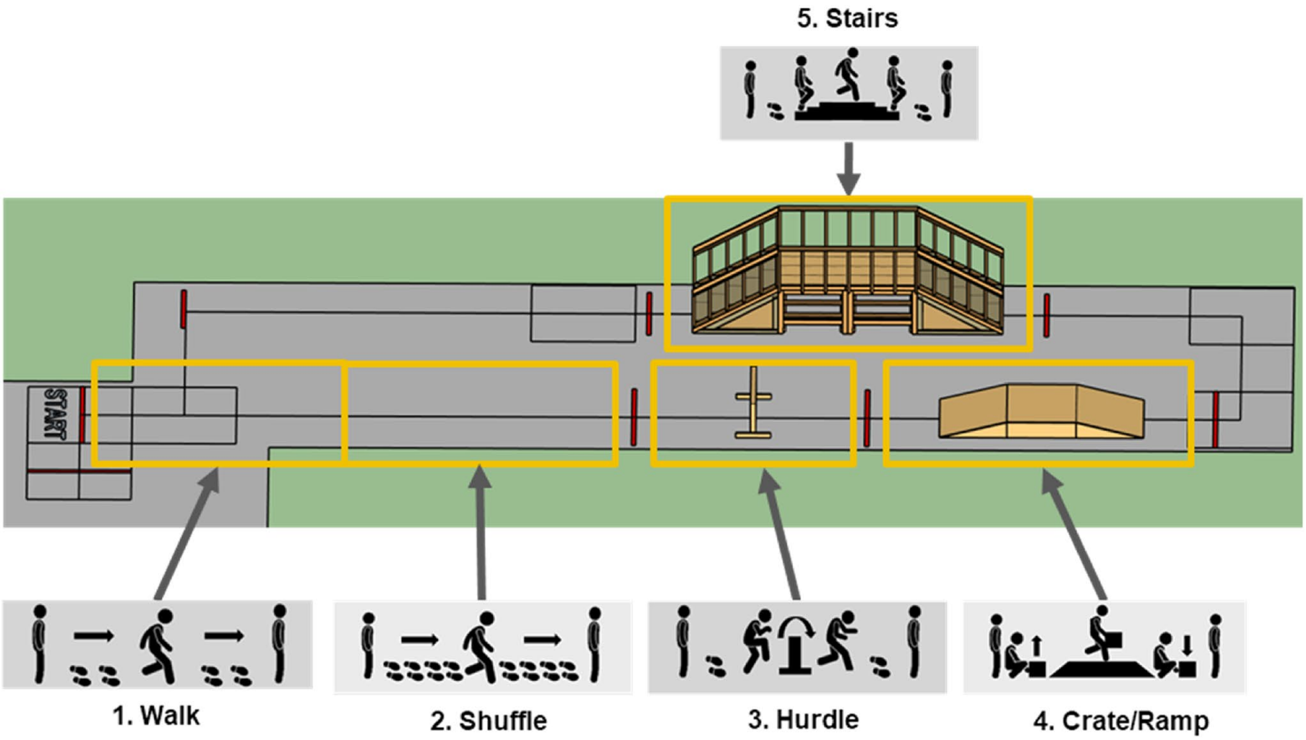


Fig. 3 Test course diagram with all 5 tasks labeled in order of completion

consisting of the subject standing still was inserted before and after each repetition of the test course. For the final repetition of the test course (Trial 5), the subject would stand still for 5 s between each task. For the remaining repetitions (Trial 1, 2, 3, and 4), the pauses were removed, so that there was no stopping between the five tasks. Trial 5 was then used as a reference to rapidly identify the 5 distinct tasks when the pressure was visually represented with respect to time. The subjects were asked between trials if they needed a break and to rank their perceived level of exertion on a scale of six to twenty (Borg 1990). The subject was free to stop and remove the EOD suit at any time, thus stopping and eliminating data collection for that trial. Finally, after the five repetitions of completing the test course the subjects would walk on a treadmill at a comfortable walking speed for 2 min only once, with and without the EOD suit being worn. An example of a subject using the treadmill is shown in Fig. 4. The treadmill data was collected for future use in a study that requires walking data as a training set for an artificial intelligence. The walking data from the test course was compared against the treadmill data and there was no significant difference between the data. Therefore, the walking data from the test course was deemed adequate to use without the need for the treadmill data.

The subject would then be asked to rank their perceived exertion using the Borg ranking criteria. The data from all five pressure sensors was collected at a recording frequency of 18 Hz and the data was transmitted via a fiber optic syncing cable. Total experiment time including preparation time was approx. 2.5–3 h. Subjects were given a guided walkthrough of the test course and were able to complete the test course once before testing began. On the treadmill, subjects were able to walk at a comfortable speed for about 2 min before data collection began. Subjects were instructed to walk at a comfortable pace on the treadmill. Subject walking speed was approximately 2.5 mph. This also allowed the EOD suit to settle on the subject to mitigate sensor drift associated with the pressure pads.

Upon completion of the test course and treadmill trials, participants were required to complete a questionnaire that asked them to generally describe the pain, discomfort, and exhaustion that was felt because of wearing the EOD 8. Due to the relatively low intensity of the experiment, there were no designated breaks, however subjects could briefly stop to sit or drink water at any time.

2.3 Data analysis

The pressure pad sensors were partitioned using masking to record specific regions of the body. The shoulder sensor pads were divided into three sections: chest, top shoulder, and upper back. The shoulder sensor pads were attached so that the cabling was aligned with the center of the biceps/triceps and spanned from the pectorals, past the trapezius muscles. The top shoulder region was then adjusted in the novel software package, so that the center portion of the sensor pad contained the scapula acromion and collar bone. The same methodology was applied to the leg sensor pads, where cabling would extend outward from the thigh region. The patella was then aligned so that the pressure detected was primarily in the center of the assigned knee section on the sensor pad. The remaining portion of the leg sensor pad was used to record pressure from the bottom of the knee to the groin (essentially the length of the femur). The lower back sensor was not segmented into the 5 different tasks, unlike the other pressure sensors. The lower back sensor recorded pressure from the lower portion of both the left and right latissimus dorsi muscles. This region is located just above the subject's waistline. The initial size of the sensor pad partitions was determined from preliminary analysis and was

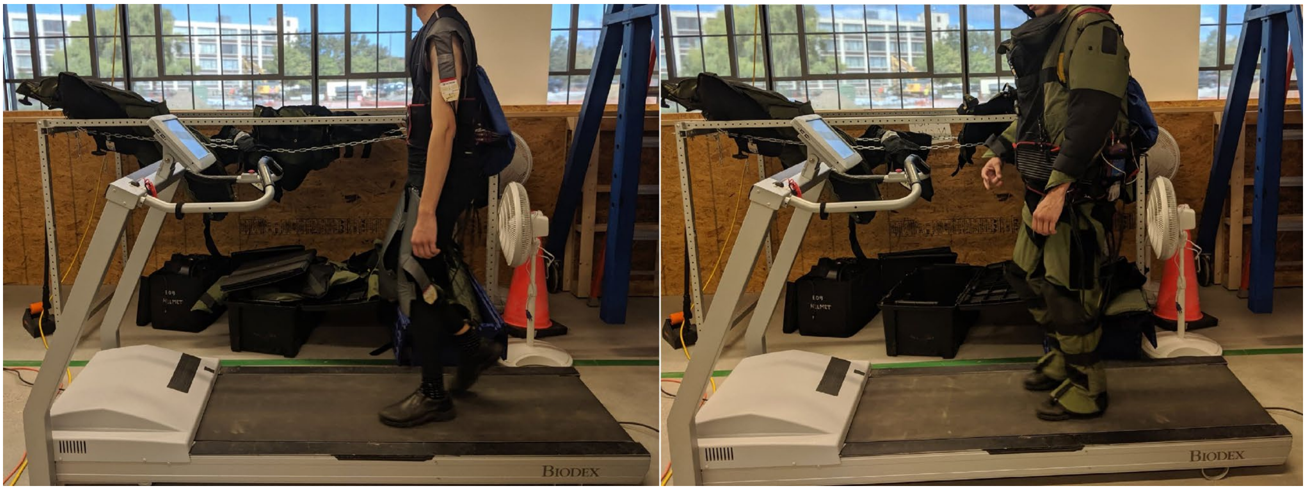


Fig. 4 Photo of a subject on treadmill not wearing EOD suit (left) and wearing EOD suit (right)

adjusted accordingly. See Fig. 5 for the shoulder/leg sensor placement and associated partitions for data collection.

The post-process data analysis was completed utilizing custom code developed in MATLAB R2020a's signal processing toolbox (MATLAB 2021). The raw data collected from the pad sensors included force (N), mean pressure (kPa), and max pressure (kPa). The mean pressure (the total force per unit area of activated sensors, with the exception of sensors recording zero pressure) and max pressure [highest pressure (kPa)] of a single sensor within the sensor matrix at the moment of collection) were manually segmented by task, using the subject test course data with pauses as a visual reference. From initial calibration studies conducted within the research group, it was determined that the pressure recorded at the knees provided the clearest data for determining the type of exercise or motion in question. The pressure data collected from the right knee was segmented by tasks for each subject. Since all the sensors were synchronized, the pressure data from the other sensors could be segmented as well. This was accomplished by using the timestamp where each of the 5 tasks begins and ends to partition the pressure data. The 'peak finder' function was utilized on each segment to further compress the data by collecting all the peaks greater than the standard deviation of the total signal to eliminate peaks due to noise, while retaining dynamic pressure peaks related to the actual motion. By averaging these segment peaks for each trial, the average dynamic pressure or peak-peak dynamic pressure can be obtained and analyzed. The flow chart depicted in Fig. 6 illustrates the entire data processing methodology utilized for this study.

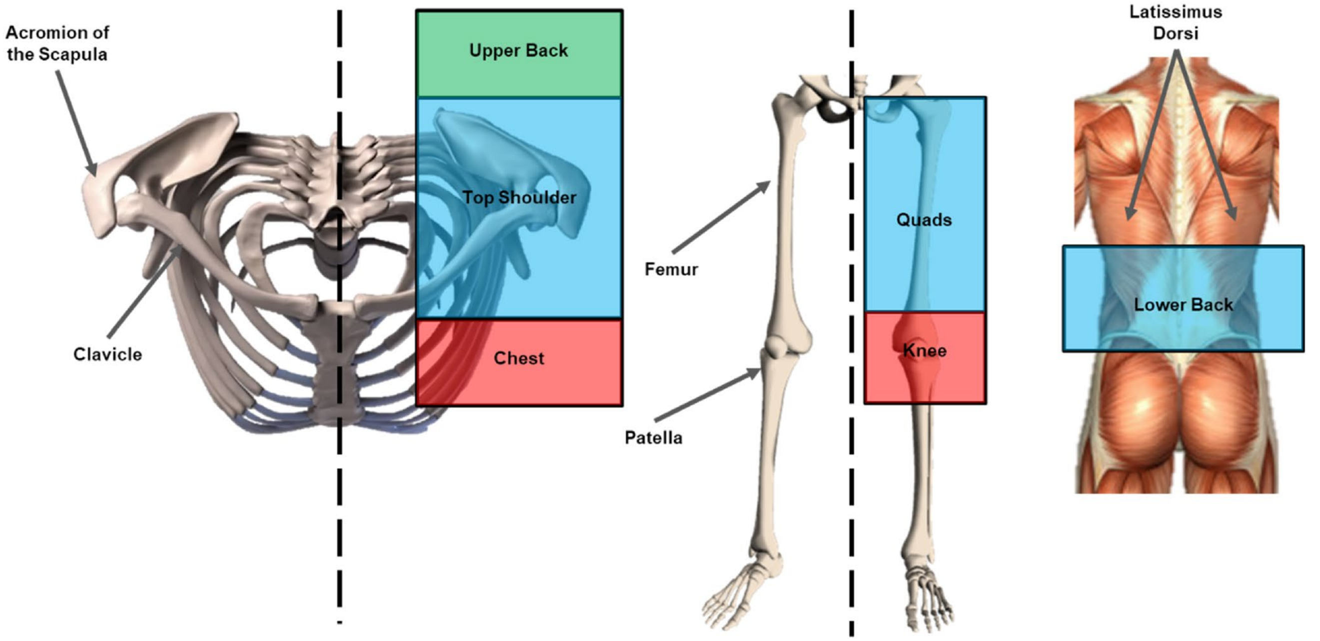


Fig. 5 Schematic showing the shoulder and leg sensor partitions (https://www.proko.com/wp-content/uploads/2015/06/14-shoulder-top-view-1-600x335.jpg, https://www.pngguru.com/free-transparent-background-png-clipart-jbjma, https://static8.depositphotos.com/1339288/830/i/450/depositphotos_8301311-stock-photo-male-muscles.jpg)

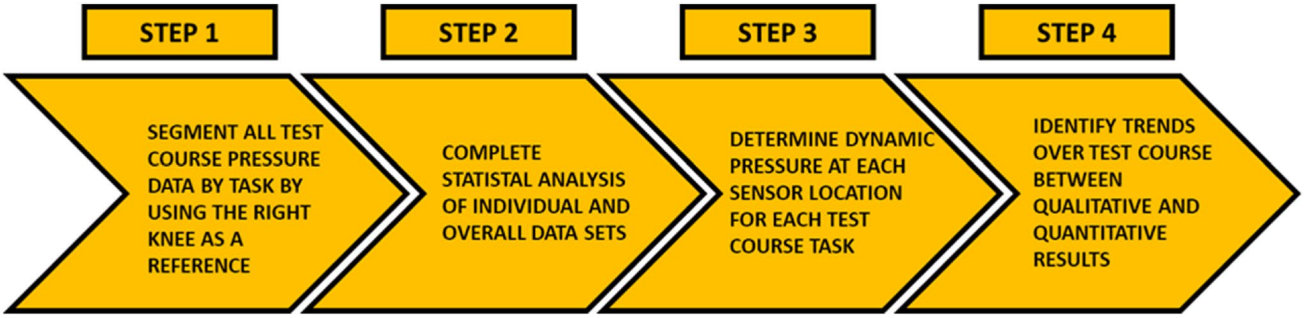


Fig. 6 Flowchart illustrating the data processing procedure

When comparing sensors on the right side of the body to the left side there was no significant difference, apart from the shoulders while the subject surmounted the hurdle. The left leg sensor pad displayed a bias at the patella (sensors in the left knee region were detecting pressure even when completely unloaded) that was removed to relate the pressure data more closely to the pressure data of the right patella.

Upon completion of the pre-processing of the raw mean pressure data, the dynamic peaks for each sensor partition was averaged for all 34 subjects and all five repetitions of the test course. The resulting averaged mean pressure values for each bodily location and task is shown in Table 2 below. It should be noted that the left leg sensor was consistently reporting a bias that was 2 kPa higher than the right knee. The left leg sensor was noticeably more sensitive than the right leg sensor with regards to pressure at the knee. An attempt was made to re-calibrate the sensor using a proprietary compressed air device, but the device broke and was rendered unusable. It is unknown why the left leg sensor specifically displayed a greater sensitivity and could be due to a variety of factors. One such common factor could have been a compression set in the elastomer material that envelopes the capacitive sensor matrix. Another is moisture absorption over time from test subject perspiration as these sensors had been used previously in military body armor studies.

For the statistical analyses, paired t-tests were used to compare the differences between the loaded (EOD worn) and unloaded (No EOD worn) conditions. We set the significance level at 0.05. The pressure data was then correlated with the body mass index (BMI) data using the Pearson correlation and other qualitative data using MATLAB. The RPE was compared against the pressure data using the Spearman's rank correlation. All statistical analyses were performed in MATLAB.

2.4 Results and discussion

The subjects were instructed to complete the course at their own pace, this was after completing the course twice without being recorded for practice. In general, the test subjects were able to complete the test course without the EOD in roughly 1 min. While wearing the EOD, completing the course took approximately 10 s longer. The 2 obstacles that would contribute the most to differences in completion time were the hurdle and the stairs. When surmounting the hurdle, subjects with longer legs were able to walk over the 2.5 ft obstacle with relative ease. With the stairs some subjects cautiously climbed down the stairs while holding the guard rail, while other subjects quickly descended the stairs at a jogging pace. These inconsistencies would appear in the pressure data as an increase or decrease in frequency between peaks.

Analysis of perceived exertion revealed a significant increase ($p < 0.05$) from the unloaded condition (6.82 ± 0.29) to the loaded (while wearing the EOD suit) condition (10.95 ± 0.67) and is depicted as bar chart in Fig. 7. However, this increase was from 'very, very light' to 'fairly light' activity due to the short amount of time spent wearing the suit and the relative ease of completing the tasks. Over a longer period, heat exhaustion would have further increased the exertion ranking (Stewart et al. 2011). On average, test subjects took 10.08 s longer to complete the test course while wearing the EOD suit. This time delay occurred when the subjects surmounted the hurdle (1.12-s increase),

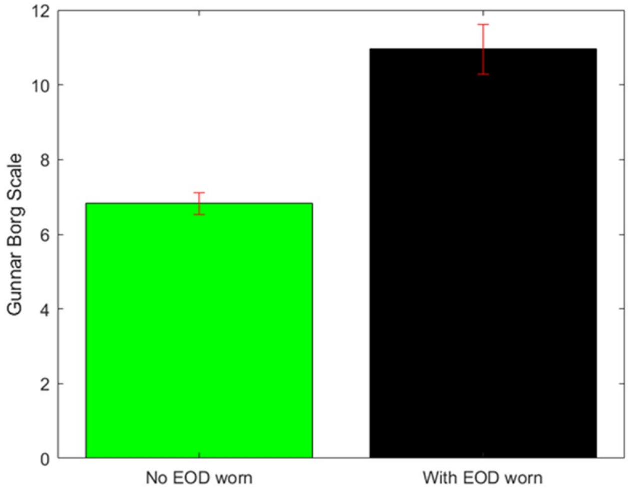


Fig. 7 Comparison of the average EOD fatigue versus the non-EOD fatigue. For each participant, the Borg rankings for all 5 trials were averaged

Table 2 Mean peak values of mean pressure (mean ± a 95% of confidence interval, CI 95) separated by task and sensor location

Task	Sensor region						
	R. knee	R. quad	R. shoulder	L. knee[a]	L. quad	L. shoulder	Lower back
Walking	2.81 ± 0.22	0.32 ± 0.04	3.06 ± 0.24	3.86 ± 0.29	1.20 ± 0.08	3.60 ± 0.31	0.11 ± 0.006
Shuffling	1.90 ± 0.17	0.18 ± 0.03	2.79 ± 0.24	3.02 ± 0.25	1.09 ± 0.08	3.28 ± 0.31	0.09 ± 0.004
Hurdle	4.30 ± 0.39	1.16 ± 0.16	2.58 ± 0.25	4.95 ± 0.53	1.88 ± 0.27	3.02 ± 0.25	0.26 ± 0.010
Crate/ramp	4.96 ± 0.40	9.91 ± 0.41	3.35 ± 0.22	6.26 ± 0.40	11.28 ± 0.75	3.90 ± 0.27	0.35 ± 0.008
Stairs	3.79 ± 0.27	1.56 ± 0.11	3.21 ± 0.22	5.29 ± 0.37	1.95 ± 0.10	3.74 ± 0.28	0.13 ± 0.004

[a] Left knee has a bias of approximately 2 kPa for all subjects

squatted to secure the 20-lb crate (4.53-s increase), and when the subjects ascended/descended the stairs (2.31-s increase). The remaining 2 s of delay was due to a decreased walking speed while wearing the EOD 8 when the subjects were walking from where the crate was placed on the ground to the stairs.

Noticeable areas of mobility restriction and pressure concentrations for both the loaded and unloaded conditions were observed. One of the first important observations to note was the Pearson correlation between BMI and maximum recorded pressure (kPa). The Pearson correlation measures the strength of the linear association between two variables by attempting to draw a line of best fit through the data of both variables. A correlation coefficient close to the value of 1 indicates a strong correlation and whether the sign of the coefficient is positive or negative describes the relationship trend. While there was a correlation present ($r = -0.51$) when the influence of BMI on maximum pressure was analyzed, it was neither a strong nor a weak correlation (see plot in Fig. 8). This was indicative of how the broader the shoulder build of the subjects the lower the maximum recorded pressure. The possible explanation for the correlation of BMI vs. both shoulders (the right shoulder data was provided as an example) would be the size of the subjects' chest and shoulder region. Theoretically, a subject with a more pronounced chest and broader shoulders would experience a more even pressure distribution. Subjects with more slender body types would experience pressure concentrated on the scapula acromion. Subjects with broader shoulders would have a more evenly distributed pressure that would be noticeable on the top of the clavicle as well. For subjects with narrower shoulders, it appeared that the pressure was more concentrated on the scapula acromion, meaning that the vertical weight of the jacket portion of the EOD 8 was primarily resting on the outside of the shoulders. In previous studies on backpacks, it was shown that 70% of pressure rests vertically on the shoulders and the remaining 30% should rest on the lower back (Lafiandra and Harman 2004). If this logic is applied to EOD suits, then it is possible for more narrow body types to carry the majority of the jacket weight on the outermost part of the shoulders rather than the weight being more evenly distributed across the shoulders and neck. Most subjects reported discomfort and pain in the shoulders (59%).

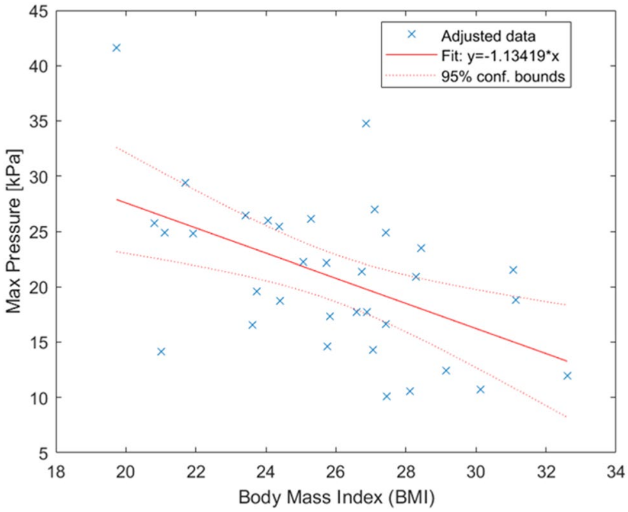


Fig. 8 Average maximum pressure for the right shoulder during the walking portion of the test course for each subject versus body mass index

It is important to note the response of the shoulders and knees when the subject cleared the hurdle. Some of the subjects were able to walk over the hurdle by rotating their entire body. First, the subject would place their dominant leg over the hurdle. Second, the subject would raise their non-dominant leg and rotate their body, so that the non-dominant leg passes over the hurdle heel first. This was done in a smooth, spinning motion. Subjects that took longer would pause before swinging their trailing leg with their toes first. This also caused the shoulder pressure to be higher on the right shoulder than the left. See Fig. 9 for the time domain plot of both quads clearing the hurdle for two different subjects.

Another observation worth noting was the groin protector as a site of restriction, especially with respect to when subjects had to squat down to pick up the crate. Without the EOD suit worn, the detected pressure was negligible for both the left and right side of the groin region. With the EOD suit worn there was a 30-times increase in mean pressure within the same groin region and subjects were forced to widen their stance to complete lifting the crate. When subjects were climbing the stairs mean pressure increased by 25-times at the groin. An example of this trend is shown in Fig. 10.

From the post-experiment questionnaire, the quads/groin was the second most reported location of discomfort (11%). In Fig. 11, the max pressure was compared against the mean pressure for the right quad. Upon inspection, the variability and degree of separation of the crate data from the other tasks is very distinguishable. The stairs data also has increased variability and is significantly different ($p < 0.05$) than the shuffling and walking data. The crate and stairs data were isolated into scatter plots in Fig. 12 to show the large increase in pressure from the loaded condition to the unloaded condition.

In Fig. 13, a heuristic overview of pressure increase is shown with the utilization of a visual aid to show the largest increases in pressure from the unloaded condition. From this diagram it is clear that, while the shoulders maintained a relatively constant change in pressure from the unloaded condition for most tasks, there were also larger spikes in pressure in other regions for certain tasks. As a result, the

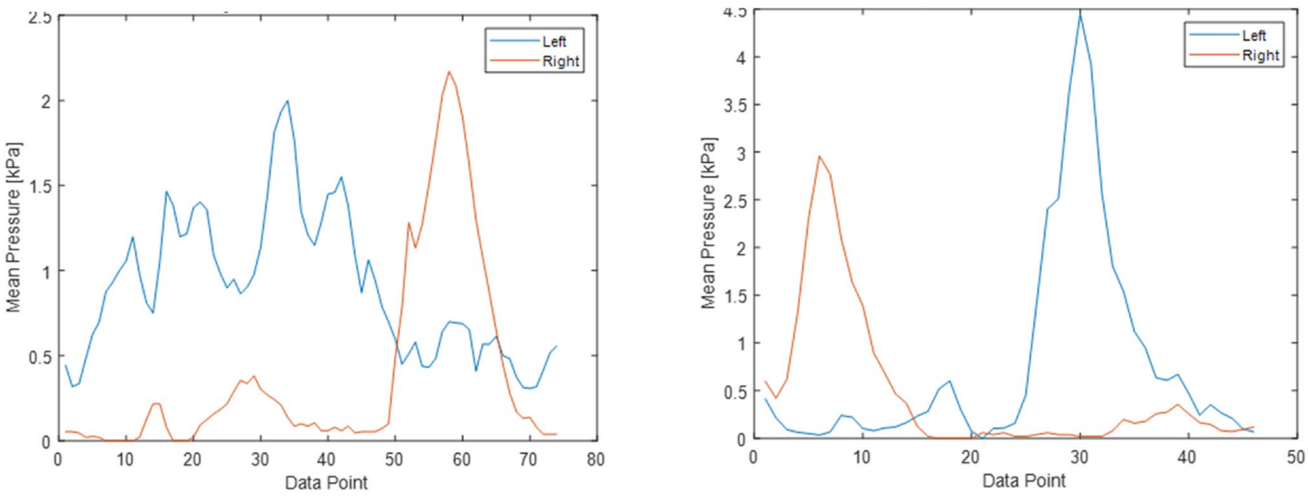


Fig. 9 Subject 14 left quad clears hurdle first (**a**) versus subject 16 right quad clears hurdle first (**b**)

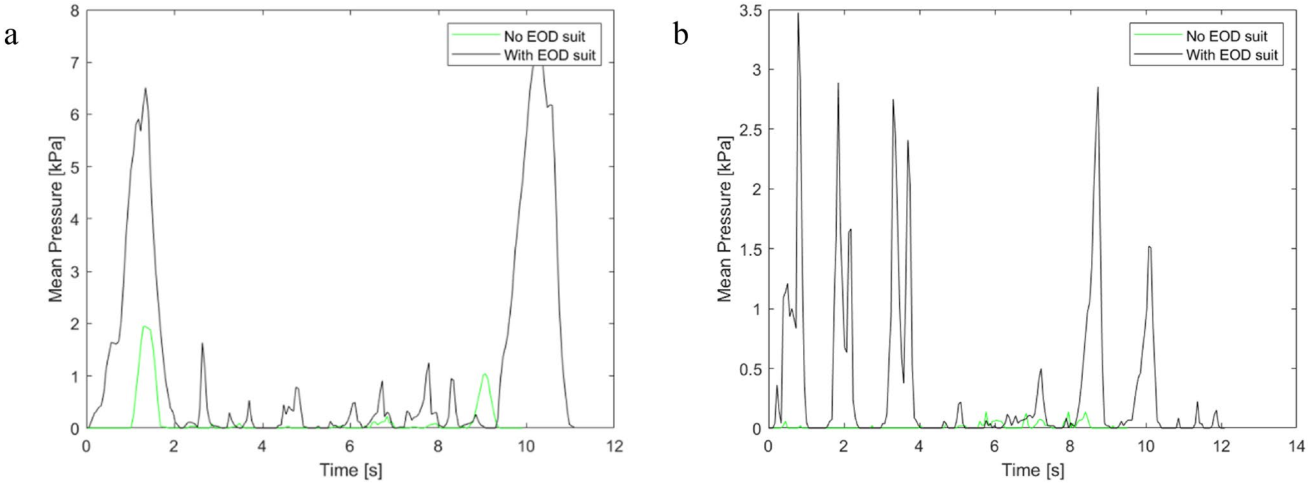


Fig. 10 Mean pressure over time of the right quad for crate (**a**) and stairs (**b**) tasks for loaded and unloaded conditions

shoulders were the source of most discomfort due to the pain associated with constant force being applied on the ends of the shoulders away from the neck. Simultaneously, in brief instances a portion of the EOD 8 can become cumbersome dependent on the task being accomplished. Typically, any task requiring a participant to change elevation results in noticeable restrictions at the interface of the legs.

3 Conclusions and future work

This was the first study conducted for the purpose of observing discomfort in EOD suits using strategically located pressure pad sensors combined with a relatively large number of diverse participants. A total of 34 subjects completed an obstacle course consisting of five different tasks and walked for 2 min on a treadmill. The obstacle course was completed five times and the treadmill was used once for both the loaded and unloaded conditions. Our results demonstrate that the EOD 8 consistently exerted a large amount of pressure in the acromion region of the shoulder, while also restricting motion in the groin.

This study demonstrates the feasibility that pressure could be used as a metric to help evaluate the ROM of EOD suits. This conclusion was supported by the recorded quantitative pressure data and qualitative discomfort anecdotes reported by participants in regions that showed a significant increase in pressure for certain tasks while wearing the EOD 8. Even the newer model EOD 9 bomb suit only added minor changes as compared to the EOD 8 to improve basic user quality and functionality. These changes included the addition of an improved helmet ventilation system to the back of

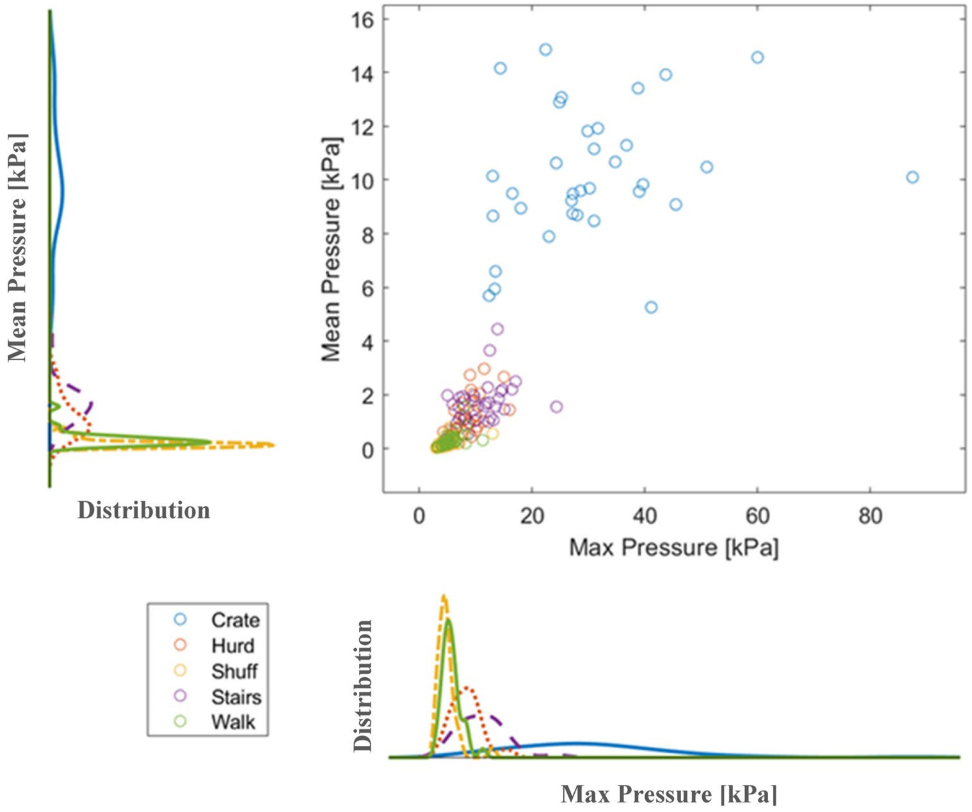


Fig. 11 Right quad pressure scatter plot shows that the crate and the stairs have a significantly higher pressure than the other tasks and increased variability

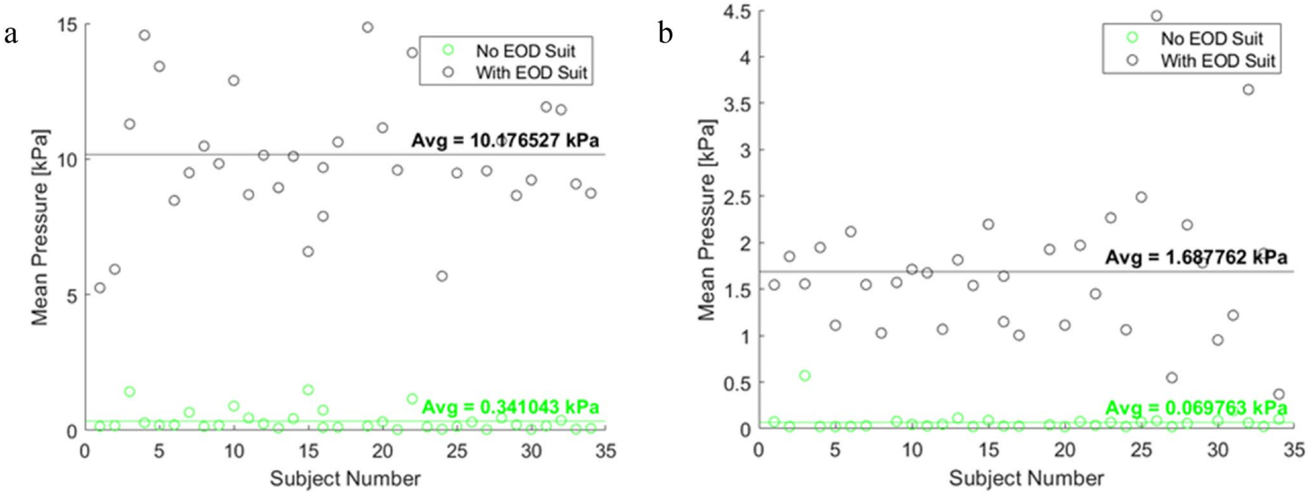


Fig. 12 Mean pressure on the right quad picking up the crate (**a**) and mean pressure at the right quad ascending/descending the stairs (**b**)

the helmet and a cabled control panel on the sleeve to actuate the helmet ventilation system and lights built into the helmet (Kemp et al. 2008). While these additions provided modest improvements in comfort and convenience to the user, it is only recently that there have been substantial changes to the suit with the release of the EOD 10. The biggest change being the elimination of the separate groin protector that was a source of movement restriction identified in this current study. With these insights, our study has provided a methodology to assist with the quantification of task performance, mobility, restriction, and discomfort while wearing EOD suits.

Based on the findings of this study, we would like to propose three recommendations to reduce EOD suit restriction and discomfort. Our first recommendation is to avoid unnecessary material bulk that may hinder hip joint rotation,

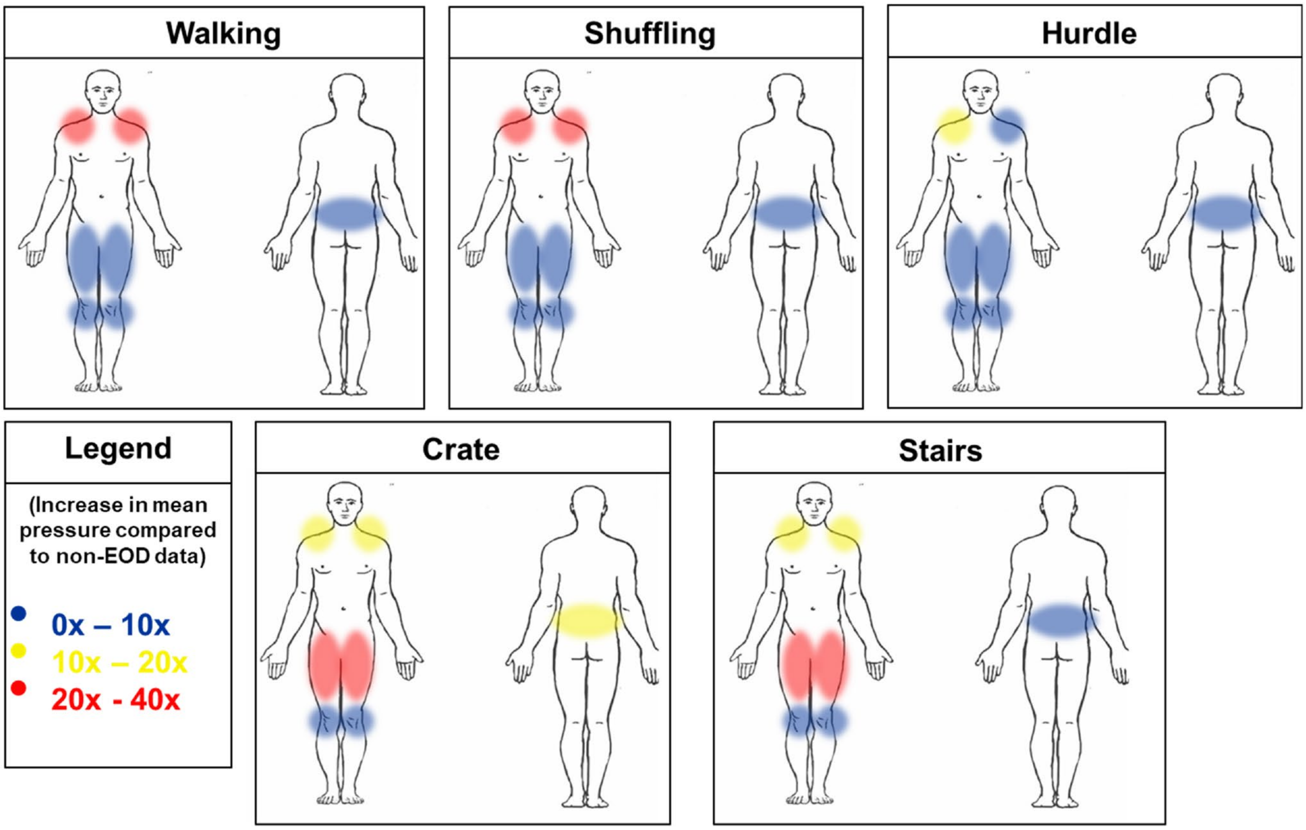


Fig. 13 EOD 8 mean pressure normalized by the unloaded condition for each task and bodily region

shoulder joint rotation, elbow, and/or knee rotation. If material bulk is necessary at a bodily joint to protect vitals, there should be some form of strain relief to allow joint rotation in that region. The second suggestion would be to design EOD jackets that rest closer to the midline of the shoulder while reducing weight. This suggestion would be critical to avoid soft tissue damage under the clavicle with future iterations of any EOD suit (Hadid et al. 2015). Finally, EOD suits should be redesigned to better fit the contours of the human torso, so that the suit is resting proximal to the shoulder. Better shoulder pressure distribution and a tighter fit on the pectoral region would increase the surface area to distribute the vertical forces on the shoulder while the compression of the suit on the chest would help partially redistribute the load. This would reduce the physiological strain on the EOD technician and increase the effectiveness of their performance (Holewijn 1990; Vacheron et al. 1999). These measures would help improve task performance and mobility while also reducing the risk for spinal and soft tissue damage from continuously carrying a heavy load (Roy et al. 1976; Park 2013).

Future research should utilize smaller sensors, especially on joints like the knees and shoulders to produce a more precise pressure reading. It is also crucial to protect the sensors from humidity and moisture since it could affect the material properties of the elastomer containing the sensor matrix (Wettenschwiler et al. 2015b; Jansson et al. 2012). Multiple EOD suits such as the Med-Eng EOD 9 and EOD 10, as well as a Next Generation Advanced Bomb Suit prototype developed by Combat Capabilities Development Command Soldier Center in Natick, Massachusetts, could be tested against each other in conjunction with the inclusion of a load distribution system (LDS) and exoskeleton. Load redistribution systems can be used to alleviate discomfort at the shoulders by redistributing some of the pressure to the hips using a passive mechanical system. Exoskeletons can assist the muscles in the body by redistributing or reducing their loads. As an example, motorized or hydraulic actuators that are strategically placed parallel to the quads could reduce muscle fatigue during a squatting motion (Hite 2014; Mooney et al. 2014; Zhang et al. 2017; Ding et al. 2018; Xia et al. 2020; Patil et al. 2018; Xu et al. 2020). An example of a passive exoskeleton system would be elastic bands spanning the length of the quads, acting as an artificial muscle (Herr and Langman 1997; Briner and Linn. 2011; Hite 2014). The results in this paper have provided a baseline to conduct these evaluations and could inform better EOD suit designs, while also examining the effects of passive and active assistive devices using distributed pressure sensing or other sensing approaches. This methodology could also be used to improve the fit a functionality of exoskeleton systems.

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References

Barker, A.D.: Improvised explosive devices in Southern Afghanistan and Western Pakistan, 2002–2009. Stud. Confl. Terror. **34**(8), 600–620 (2011). https://doi.org/10.1080/1057610X.2011.582630

Bass, C., et al.: A methodology for assessing blast protection in explosive ordnance disposal bomb suits. Int. J. Occup. Saf. Ergon. **11**(4), 347–361 (2005). https://doi.org/10.1080/10803548.2005.11076655

Borg, G.: Psychophysical scaling with applications in physical work and the perception of exertion. Scand. J. Work. Environ. Health **16**(Suppl 1), 55–58 (1990). https://doi.org/10.5271/sjweh.1815

Briner, H.H.L.: Design, prototyping and preliminary testing of an elastic-powered climbing exoskeleton. Diss. Massachusetts Institute of Technology (2011)

Brusey, J., Rednic, R., Gaura, E.I., Kemp, J., Poole, N.: Postural activity monitoring for increasing safety in bomb disposal missions. Meas. Sci. Technol. (2009). https://doi.org/10.1088/0957-0233/20/7/075204

Coca, A., Williams, W.J., Roberge, R.J., Powell, J.B.: Effects of fire fighter protective ensembles on mobility and performance. Appl. Ergon. **41**(4), 636–641 (2010). https://doi.org/10.1016/j.apergo.2010.01.001

Ding, Y., Kim, M., Kuindersma, S., Walsh, C.J.: Human-in-the-loop optimization of hip assistance with a soft exosuit during walking. Sci. Robot. **3**(15), eaar5438 (2018)

Gmitrzuk, M., Starczewski, L., Szcześniak, K., Danielewicz, D., Nyc, R., Kosmala, L.: The influence of the explosive ordnance disposal suit on the bomb squad safety. Probl. Mechatron. Armament Aviat. Saf. Eng. **9**(2), 27–44 (2018). https://doi.org/10.5604/01.3001.0012.1099

Hadid, A., Belzer, N., Shabshin, N., Zeilig, G., Gefen, A., Epstein, Y.: The effect of mechanical strains in soft tissues of the shoulder during load carriage. J. Biomech. (2015). https://doi.org/10.1016/j.jbiomech.2015.10.020

Herr, H., Langman, N.: Optimization of human-powered elastic mechanisms for endurance amplification. Struct. Optim. **13**(1), 65–67 (1997)

Hite, N.: Augmentation of muscular endurance in lower-limb exercises via a passive elastic exoskeleton. Ph.D. dissertation, Harvard University (2014)

Holewijn, M.: Physiological strain due to load carrying. Eur. J. Appl. Physiol. Occup. Physiol. **61**, 237–245 (1990). https://doi.org/10.1007/BF00357606

https://static8.depositphotos.com/1339288/830/i/450/depositphotos_8301311-stock-photo-male-muscles.jpg. Accessed 11 Mar 2020

https://www.pngguru.com/free-transparent-background-png-clipart-jbjma. Accessed 19 Jan 2020

https://www.proko.com/wp-content/uploads/2015/06/14-shoulder-top-view-1-600x335.jpg. Accessed 19 Jan 2020

Jansson, K., Michalski, M., Smith, S., LaPrade, R., Wijdicks, C.: Tekscan pressure sensor output changes in the presence of liquid exposure. J. Biomech. (2012). https://doi.org/10.1016/j.jbiomech.2012.09.033

Kemp, J., Gaura, E.I., Brusey, J., Thake, C.D.: Using body sensor networks for increased safety in bomb disposal missions. In: 2008 IEEE International Conference on Sensor Networks, Ubiquitous, and Trustworthy Computing (SUTC 2008), 2008, pp. 81–89. https://doi.org/10.1109/SUTC.2008.25

Krzystała, E., Kawlewski, K., Kciuk, S., Machoczek, T., Bienioszek, G.: Experimental research assessing threat of EOD technicians from explosive blast. In: Advances in Intelligent Systems and Computing, 2019, pp. 269–276

Lafiandra, M., Harman, E.: The distribution of forces between the upper and lower back during load carriage. Med. Sci. Sports Exerc. **36**, 460–467 (2004). https://doi.org/10.1249/01.MSS.0000117113.77904.46

Lenton, G.K., Doyle, T.L.A., Saxby, D.J., Billing, D., Higgs, J., Lloyd, D.G.: Integrating a hip belt with body armour reduces the magnitude and changes the location of shoulder pressure and perceived discomfort in soldiers*. Ergonomics **61**(4), 566–575 (2018). https://doi.org/10.1080/00140139.2017.1381278

MATLAB: The MathWorks, Inc., Natick, MA. https://www.mathworks.com/products/new_products/release2020a.html (2021).

Mooney, L.M., Rouse, E.J., Herr, H.M.: Autonomous exoskeleton reduces metabolic cost of human walking during load carriage. J. Neuroeng. Rehabil. **11**(1), 1–11 (2014)

N. Institute of Justice, O. of Justice Programs, D. of Justice: Public Safety Bomb Suit Standard NIJ Standard-0117.00. http://www.ojp.usdoj.gov (2012a)

N. Institute of Justice, O. of Justice Programs, D. of Justice: Public safety bomb suit standard NIJ Standard-0117.00. http://www.ojp.usdoj.gov (2012b). Accessed 24 May 2019

Nindl, B., Williams, T., Deuster, P., Butler, N., Jones, B.: Strategies for optimizing military physical readiness and preventing musculoskeletal injuries in the 21st century. US Army Med. Dep. J. **2013**, 5–23 (2013)

Park, H., et al.: Impact of ballistic body armour and load carriage on walking patterns and perceived comfort. Ergonomics (2013). https://doi.org/10.1080/00140139.2013.791377

Patil, G., Rigoli, L., Richardson, M.J., Kumar, M., Lorenz, T.: Momentum-based trajectory planning for lower-limb exoskeletons supporting sit-to-stand transitions. Int. J. Intell. Robot. Appl. **2**(2), 180–192 (2018)

Roy, T., Lopez, H., Piva, S.: Loads worn by soldiers predict episodes of low back pain during deployment to Afghanistan. Spine (Phila Pa 1976) (2013). https://doi.org/10.1097/BRS.0b013e31829265c4

Stewart, I.B., Rojek, A.M., Hunt, A.P.: Heat strain during explosive ordnance disposal. Mil. Med. **176**(8), 959–963 (2011). https://doi.org/10.7205/milmed-d-11-00052

Vacheron, J., Poumarat, G., Chandezon, R., Vanneuville, G.: The effect of loads carried on the shoulders. Mil. Med. **164**, 597–599 (1999). https://doi.org/10.1093/milmed/164.8.597

Wettenschwiler, P., Lorenzetti, S., Stämpfli, R., Rossi, R., Ferguson, S., Annaheim, S.: Mechanical predictors of discomfort during load carriage. PLoS ONE **10**, e0142004 (2015a). https://doi.org/10.1371/journal.pone.0142004

Wettenschwiler, P., Stämpfli, R., Lorenzetti, S., Ferguson, S., Rossi, R., Annaheim, S.: How reliable are pressure measurements with Tekscan sensors on the body surface of human subjects wearing load carriage systems? Int. J. Ind. Ergon. **49**, 60–67 (2015b). https://doi.org/10.1016/j.ergon.2015.06.003

Xia, J., Huang, D., Li, Y., Qin, N.: Iterative learning of human partner's desired trajectory for proactive human–robot collaboration. Int. J. Intell. Robot. Appl. **4**, 229–242 (2020). https://doi.org/10.1007/s41315-020-00132-5

Xu, F., Huang, R., Cheng, H., Qiu, J., Xiang, S., Shi, C., Ma, W.: Stair-ascent strategies and performance evaluation for a lower limb exoskeleton. Int. J. Intell. Robot. Appl. **4**(3), 278–293 (2020)

Zhang, J., Fiers, P., Witte, K.A., Jackson, R.W., Poggensee, K.L., Atkeson, C.G., Collins, S.H.: Human-in-the-loop optimization of exoskeleton assistance during walking. Science **356**(6344), 1280–1284 (2017)

Zhou, B., Sundholm, M., Cheng, J., Cruz, H., Lukowicz, P.: Never skip leg day: a novel wearable approach to monitoring gym leg exercises. In: 2016 IEEE International Conference on Pervasive Computing and Communications (PerCom), pp. 1–9. https://doi.org/10.1109/PERCOM.2016.7456520 (2016)

Zhou, B., Sundholm, M., Cheng, J., Cruz, H., Lukowicz, P.: Measuring muscle activities during gym exercises with textile pressure mapping sensors. Perv. Mob. Comput. **38**, 331–345 (2017). https://doi.org/10.1016/j.pmcj.2016.08.015

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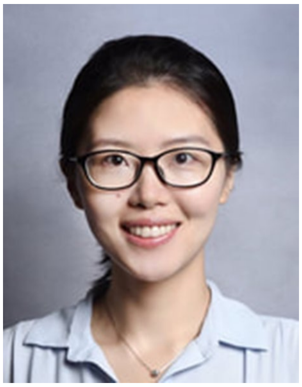

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