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Effects of different block designs on low back and shoulders biomechanical loads and postural stability during crab pot handling

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ABSTRACT

In commercial Dungeness crab fishing vessels, the block pulls crab pots for harvesting and typically positions them to the side of vessels, rather than the sorting tables on board. Consequently, fishermen must reach outside the vessel to grab the pots, posing increased risk of musculoskeletal and fall-related injuries. To investigate the effects of block design on these risks, 25 participants in a repeated-measures laboratory study handled a pot under two block conditions: away-from-table (conventional setting) and above-table (intervention). Low back and shoulder muscle activities, angles, moments, perceived exertion, and postural stability were measured. The results showed reduced L5/S1 and shoulder moments and angles; decreased muscle activities in the low back, shoulders, and upper extremities; and lower perceived exertion ratings and postural sway measures with the intervention. These findings indicate that positioning the pot closer to fishermen onboard could reduce the injury and fall risk associated with crab pot handling.

1. Introduction

Commercial Dungeness crab fishing is considered one of the most dangerous professions in the U.S. due to its high rate of fatal and non-fatal injuries (Bovbjerg et al., 2019; Kincl et al., 2019; Lin et al., 2008; Lincoln and Lucas, 2010). From 2002 to 2014, the fatality rate among Dungeness crab fishermen on the U.S. West Coast was 209 per 100,000 full-time equivalent (FTE) workers, significantly higher than the national rate for all commercial fishermen (128 per 100,000 FTE) and all U.S. workers (4 per 100,000 FTE) (Case et al., 2015). Following vessel disasters, falls overboard are the second leading contributor to worker fatalities in this industry. Regarding non-fatal injuries among Dungeness crab fishermen, surveys conducted as part of the Fishermen Led Injury Prevention Program (FLIPP) found that 21.5% of fishermen reported some form of non-fatal injury, with 22.5% of these being related to musculoskeletal injuries (i.e., sprains and strains) (Bovbjerg et al., 2019). The survey results also revealed that the majority (88%) of nonfatal injuries occurred among deckhands (FLIPP, 2017), who were also the primary victims of fatal falls (58.8% of total fatal falls) (Case et al., 2018).

The majority of these injuries have been reported to occur during operations involving fishing gear, such as setting, hauling, and handling crab pots, which are the main duties of deckhands (Case et al., 2015, 2018). In particular, 16.0% of nonfatal injuries and 7.9% of fatal falls overboard in this sector are associated with the handling of crab pots. The handling process typically involves guiding the pots lifted from the ocean using a mechanized winch crane, known as a block, and emptying them onto a sorting table (also referred to as a “dump box”), which is a recessed surface for temporarily holding catches of crab for sorting. With a typical commercial Dungeness crab vessel, blocks extend out to the ocean from the vessel to pull up the string of crab pots, requiring deckhands to adopt awkward shoulder and trunk postures to reach out and grab the pots. These awkward postures, coupled with the repetitive nature of the task and the substantial weight of the pots (up to 100 kg), may pose a substantial risk of musculoskeletal disorders among fishermen (Bernard et al., 1997; Hoozemans et al., 1998; Keyserling et al., 1992). Moreover, the postural stability of fishermen may be impacted as muscular fatigue and awkward trunk postures can negatively affect postural stability (Davidson et al., 2004, 2009; Granata and Wilson, 2001; Larson and Brown, 2018). Impaired postural stability may then lead to an increased risk of falls (Davidson et al., 2004; Pline et al., 2006) and potentially falls overboard. Therefore, although the blocks help with lifting the heavy pots from the ocean, the current block design can be a source of musculoskeletal and fall-related injuries for deckhands.

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Feedback from fishermen and local equipment fabricators in our previous field-based investigation (Kim et al., 2022) on vessel improvements revealed a lack of evidence-based recommendations for the design or positioning of blocks. However, they also noted that blocks can be designed to swing toward the vessel after lifting the pot from the ocean, which would position the crab pots closer to the deckhands. This altered design could reduce awkward postures of the deckhands and decrease the moment-arm distance between the center of mass of the pots and the low back and shoulder joints, thereby lowering biomechanical loads and the risk of musculoskeletal problems in the low back and shoulders (Bernard et al., 1997; Jorgensen et al., 2003). Similarly, reducing awkward postures and associated loads may decrease the risk of postural instability and, consequently, the risk of fall-related injuries (Davidson et al., 2004; Pline et al., 2006). However, despite the hazards associated with crab pot handling and the potential benefits of block design modifications, there has been a lack of studies to objectively quantify the physical injury risk associated with crab pot handling and how block designs may impact it. Therefore, to address this knowledge gap and need for evidence-based recommendations, the objectives of this laboratory study are twofold: First, to quantify the low back and shoulder biomechanical loads (joint angles, moments, and muscle activity), perceived exertion, and postural stability in the current block design (away-from-table) during crab pot handling tasks; and second, to evaluate the effects of block design (away-from-table versus above-table) on these measures. By achieving these objectives, we aim to enhance the health and safety of fishermen in the commercial Dungeness crab industry by objectively delineating biomechanical loads and postural stability during crab pot handling to develop recommendations for block design.

2. Methods

2.1. Participants

Twenty-five healthy adults (over 21 years old) were recruited for this laboratory-based study via email solicitation and printed flyers throughout the Oregon State University community in Corvallis, OR. The mean (standard deviation) age, weight, and height of the participants were 34.2 (13.3) years, 88.6 (10.1) kg, and 181.6 (3.0) cm. We only recruited male participants based on findings from our FLIPP research project, which surveyed over 400 Dungeness crab fishermen and found that this group was predominantly male (FLIPP, 2017). To avoid potential risk of injury during the experimental tasks, participants were screened to ensure that they: 1) had no restriction in physical activity; 2) had no musculoskeletal pain in the low back, shoulder, and upper extremity regions in the past 7 days; 3) were not under any medication for musculoskeletal disorders; and 4) had no visual or vestibular deficits that may influence normal balance control.

2.2. Experimental setup

Our laboratory setup consisted of a sorting table, a banger bar, a crab pot, and a block to simulate crab pot handling (Fig. 1). To ensure a realistic setup, we incorporated dimensions from crab sorting tables (height, width, and length), banger bars (height and length), crab pots (diameter, height, and weight), and the block (horizontal distance relative to the sorting table) from 13 commercial Dungeness fishing vessels in Oregon and Washington (Kim et al., 2022). Using these field data, a coastal vessel equipment fabricator, who collaborates with regional commercial fishermen, manufactured the crab sorting table and banger bar for our study. The fabricated table measured 86 cm in height, 92 cm in width, and 153 cm in length. The banger bar, a fishermen-developed control that can reduce biomechanical loads when

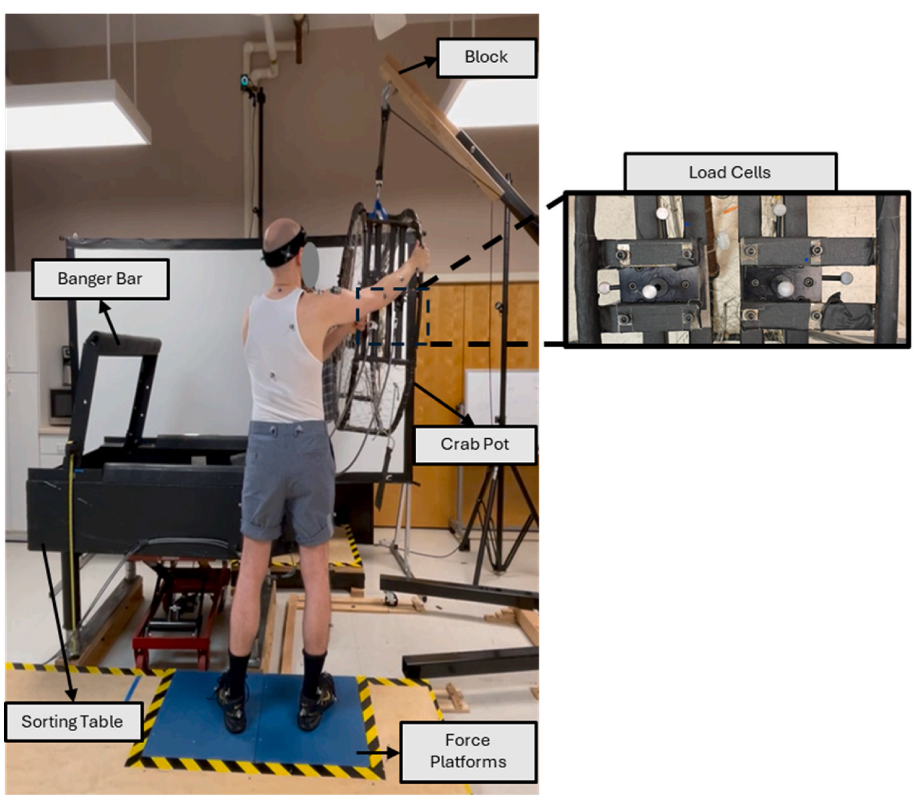

Fig. 1. Experimental setup with a crab sorting table, banger bar, crab pot, and block for simulating crab pot handling task; two force loads for collecting hand forces; and two force platforms for collecting ground reaction forces and moments.

emptying the crab pot (Kia et al., 2023), was set at a height of 60 cm from the top of the sorting table. Despite variations in the height of bang bars from field measurements (Kim et al., 2022), this height level was selected as it was shown to be optimal for reducing biomechanical loads (Kia et al., 2023).

The crab pot used in this study, previously employed in commercial crab fishing, had a diameter of 107 cm and a mass of 40 kg. To minimize potential interference with other experimental equipment, the pot was empty of crabs, bait, weights, or other gear required for fishing. Two load cells were embedded into the crab pot with custom-built brackets welded to its rims to measure three-dimensional (3-D) hand forces. This attachment allowed participants to handle the crab pot as commercial fishermen normally would during data collection. To simulate the block and evaluate the impact of each condition, a commercially available crane (Engine Crane 2T, COSTWAY, Fontana, CA) was used to hold the crab pot in place. The block was on wheels and moved based on the experimental condition, allowing the crab pot to be positioned hanging away from the sorting table outside the “vessel” or above it (Fig. 2). Additionally, two force platforms were positioned next to the sorting table where commercial fishermen typically stand to simulate realistic crab pot handling activities accurately in the laboratory setting.

2.3. Experimental protocol

The experimental protocol was approved by the University’s Institutional Review Board (IRB) (Protocol number: IRB-2019-0318). Before the experiment, all participants were informed about the study objectives, procedures, equipment, tasks, potential risks, and expected benefits. After providing written consent, reflective markers and electromyography (EMG) sensors were placed on the participants (Fig. 3). Subsequently, the maximum voluntary contractions (MVC) of the muscles were collected. Each participant was then given practice time to become familiar with the task and experimental setup, and this continued until they were able to perform the task correctly and confirmed their ability and familiarity with the task and setup. The practice sessions lasted approximately 5–10 min.

The experimental task involved grabbing the crab pot hanging from the block with both hands, placing it on the sorting table, tilting the pot (counterclockwise) from its vertical position to bang against the banger bar, and then tilting it back (clockwise) to its original vertical position on the sorting table (Fig. 2). Since this task is typically performed by two deckhands in the field, a member of the study team played the role of the second deckhand on the opposite side of the pot. The participants performed the experimental task in the task pace determined based on commercial fisher’s feedback throughout the experiments. The participants were instructed to stand on two force platforms, with their right foot on the right platform and their left foot on the left platform, maintaining this foot placement throughout the task. The experimental task was performed under two block conditions: away-from- and above-table. In the away-from-table condition (conventional setting), the crab pot was suspended 60 cm away from the vessel side rail end of the sorting table, simulating a block raising the pot directly upward (Fig. 2-a). In this condition, the participants had to reach and pull the crab pot to place it onto the crab sorting table. In the above-table condition (intervention), the pot was suspended directly over the sorting table, simulating an articulating block bringing the pot over once raised and enabling the participant to set the pot onto the table without having to reach out for the pot (Fig. 2-b). The task took an average (standard deviation) of 6.0 (1.1) seconds under the away-from-table condition and 4.8 (0.7) seconds under the above-table condition to complete. This task was repeated three times for each block condition.

The order of the experimental conditions was randomized and counterbalanced to minimize potential confounding effects from the experimental order. To minimize the residual fatigue effects of the previous condition, 5-min breaks were provided between each condition. During the task, angle, moment, and muscle activity (in the low back, shoulders, and upper extremities) and postural stability were measured. After each experimental condition, the perceived whole-body (Borg RPE) and localized exertion (Borg CR-10) ratings were collected via questionnaires.

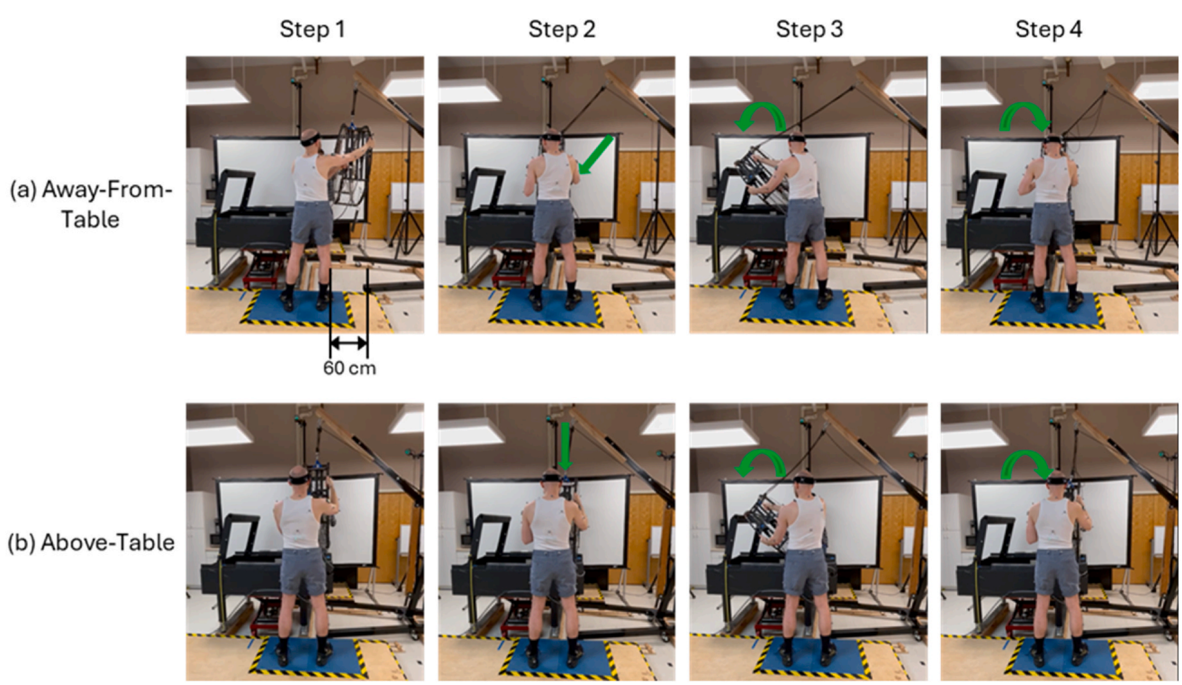

Fig. 2. A participant performing the experimental task consisted of grabbing the crab pot suspended by the block (step 1), placing it on the sorting table (step 2), tilting the pot counterclockwise to empty it (step 3), and tilting it back (clockwise) to its original position (step 4). The experimental task was performed in two block conditions: (a) away-from-table and (b) above-table. In the away-from-table condition (conventional setting), a crab pot was suspended 60 cm away from the sorting table. In the above-table condition (intervention), the pot was suspended directly over the sorting table.

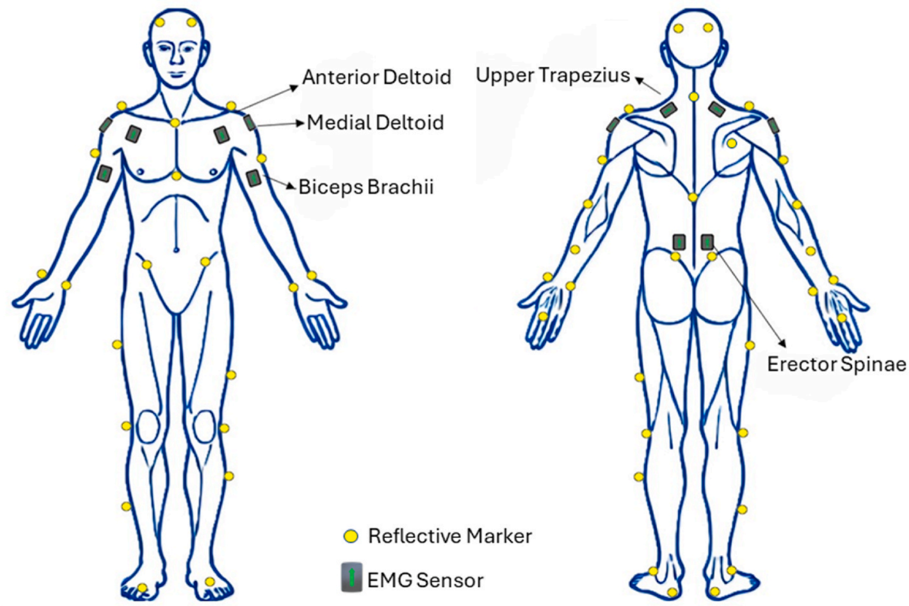

Fig. 3. Reflective markers and electromyography (EMG) sensors placements. Reflective markers were placed on 39 anatomical landmarks (shown as yellow circles) on the lower and upper body. Ten electromyography (EMG) sensors were bilaterally placed on five muscle groups: 1) erector spinae, 2) trapezius, 3) anterior deltoid, 4) medial deltoid, and 5) biceps brachii. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2.4. Outcome measures

2.4.1. Angle and moment

Thirty-nine reflective markers were placed on participants following a full-body biomechanics marker set (Fig. 3) from an optical motion capture system (Motive 3.1; Optitrack; NaturalPoint, Inc.; Corvallis, OR), developed based on previously established protocols (Leardini et al., 2007, 2011). Additionally, three noncolinear markers were placed on each of the two load cells (PY6; Bertec; Columbus, OH) to track the 3-D force vectors (Fig. 1). Marker positions were recorded at 200 Hz using an 8-camera optical motion capture system (Prime^{x} 13, Optitrack; NaturalPoint, Inc.; Corvallis, OR) and 3-D forces from both hands were measured bilaterally with two load cells at 1000 Hz. The raw kinematic and kinetic data were filtered using a digital zero-phase 4th order Butterworth filter with cutoff frequencies of 6 Hz (Motive 3.1; Optitrack; Natural Point, OR) and 10 Hz (Visual3D; C-Motion Inc.; Germantown, MD), respectively.

The filtered kinematic data were used to create a 3-D multi-segment model using a biomechanics analysis software (Visual3D, C-Motion Inc., Germantown, MD). In this model, joint centers, center of mass locations, and inertial parameters were estimated using a regression model that incorporated each participant's body measurements (de Leva, 1996a, 1996b). Then, trunk flexion/extension and lateral bending angles along with shoulder flexion/extension and abduction/adduction angles were calculated. Trunk angles were defined as the rotation of the thorax relative to the pelvis local coordinate system, while shoulder angles were defined as the rotation of the upper arms relative to the thorax. Additionally, flexion and lateral bending moments at the lumbosacral joint (L5/S1) and shoulder flexion and abduction moments at the shoulder joints were calculated using a top-down inverse dynamic approach (Faber et al., 2020; Iino and Kojima, 2012). This approach incorporated 3-D external hand forces, estimated body segment inertial parameters, and their respective moment arms. Finally, the calculated angles and moments were summarized as 5th, 50th, and 95th percentiles.

2.4.2. Muscle activity

Ten EMG sensors (Trigno Avanti; Delsys; Natick, MA) were placed bilaterally on five muscle groups in the low back, shoulders, and upper extremities of the participants: 1) erector spinae, 2) trapezius, 3) anterior deltoid, 4) medial deltoid, and 5) biceps brachii as shown in Fig. 3. Skin preparation, muscle identification, and electrode placement were conducted per the European Recommendation for Surface EMG (Hermens et al., 2000). A 16-channel wireless data logger was used to collect Raw EMG data at a sampling rate of 1000 Hz (Trigno Avanti; Delsys; Natick, MA). The raw EMG data were filtered (band-pass filter of 20–400 Hz), rectified, and averaged [root mean square (RMS)] using a 125-ms moving window (Visual3D; C-Motion Inc.; Germantown, MD). To normalize the EMG data, participants performed a series of MVCs following procedures detailed in previous studies (Boettcher et al., 2008; Roman-Liu and Bartuzi, 2018; Szpala et al., 2011). For erector spinae MVCs, participants assumed a prone position on a bench and attempted to lift their trunk against manual resistance applied around the scapula, while their feet were stabilized by holding the ankles by an experimenter (Szpala et al., 2011). MVCs for upper trapezius, anterior deltoid, and middle deltoid were obtained during 90° shoulder abduction in the scapula plane with internal humeral rotation and extended elbow against manual resistance (Boettcher et al., 2008). Biceps brachii MVCs were obtained during elbow flexion starting from 90° elbow flexion against manual resistance (Roman-Liu and Bartuzi, 2018). Each MVC contraction lasted 3 s and was repeated three times with 2-min breaks between contractions to minimize the risk of muscular fatigue (Soderberg and Knutson, 2000). The highest RMS signal over a 1-s period of the MVC contractions was used for normalizing the data as a percentage of the MVCs (%MVC). The normalized data were summarized based on the amplitude probability density function (APDF): the 10th (static muscle activity), 50th (median), and 90th (peak muscle activity) percentile (Jonsson, 1978).

2.4.3. Perceived exertion

To quantify whole-body exertion, the Borg Rating of Perceived Exertion (RPE) scale, ranging from 6 (no exertion) to 20 (maximal exertion), was utilized (G. Borg, 1970). Localized perceived exertion in the low back and shoulders was measured using the Borg category ratio (CR-10) scale, which ranges from 0 (no exertion) to 10 (maximal exertion) (G. A. Borg, 1982). The associated verbal anchors were provided for the participants.

2.4.4. Postural stability

3-D ground reaction forces and moments were recorded at a sampling rate of 1000 Hz using the two force platforms (AMTI BMS464508-2K-SYS; Watertown, MA) located under the participants' feet. The recorded data were then low-pass filtered (4th order, zero-phase-lag, Butterworth, 10 Hz cut-off frequency) and used to estimate the center of pressure (COP) positions. Postural stability measures were calculated based on the COP time series and displacement trajectories (Lin et al., 2008; Park et al., 2021). These postural stability measures were COP mean velocity and RMS distance (in mediolateral and anteroposterior direction), and elliptical sway area.

2.5. Statistical analysis

The R programming language (R 4.3.1, R Core Team; Vienna, Austria) was used for the statistical analysis. Generalized linear mixed models (GLMM) were used to determine whether there were differences across the two block conditions (away-from-table and above-table) with respect to the dependent variables [low back and shoulder biomechanical loads (joint angles, moments, and muscle activity), postural stability, and perceived exertion associated with crab pot handling]. All the dependent variables followed normal distributions except for muscle activity, which was highly skewed and consequently log-transformed. The block condition was set as the fixed factor, and participants were included as random intercepts to account for the within-subject correlations. An alpha (Type I) error of 0.05 was used as a statistical significance threshold. Data summaries, p-values, and 95% confidence interval limits for differences in mean values between the two block conditions are presented in the Appendices.

3. Results

3.1. Trunk angle and L5/S1 moment

Trunk flexion angles (50th and 95th percentiles) were smaller (on average by up to ~2.4°) under the above-table condition than the away-from-table condition (Fig. 4). However, the 5th percentile values showed slightly lower trunk extension angles under the away-from-table condition instead (on average by up to ~|-1.5|°). Additionally, the lateral bending angles (5th and 95th percentiles) were smaller above-table than away-from-table (on average by up to ~3.8°). Similarly, the above-table condition posed lower L5/S1 flexion and lateral bending moments to the participant's right (95th percentile) than the away-from-table condition, decreasing on average by up to ~44.6 Nm and up to ~48.1 Nm respectively.

3.2. Shoulder angle and moment

Under the above-table condition, the crab pot handling tasks posed smaller shoulder flexion angles in both the left (on average by up to ~20.4°) and right (on average by up to ~24.1°) shoulders than the away-from-table condition (Fig. 5). A similar trend was observed with the shoulder abduction/adduction angles, with abduction angles being smaller under the above-table condition for the left (on average by up to ~|-4.6°|) and right (on average by up to ~|-13.2°|) shoulders. The exception was the 95th percentile abduction/adduction angle, where the left shoulder was abducted (|-17.2°|) under the above-table condition but slightly adducted (2.8°) under the away-from-table condition. Additionally, when comparing the shoulders to each other, right shoulder flexion and abduction angles were generally larger than their corresponding left shoulder angles (on average by up to ~46.7° flexion and up to ~26.2° abduction) under both conditions.

The shoulder flexion/extension moment data yielded similar results as flexion moments (50th and 95th percentiles) tended to be significantly smaller above-table than away-from-table in both left (on average by up to ~5.6 Nm) and right (on average by up to ~15.7 Nm) shoulders (Fig. 6). However, the data for the 5th percentile shoulder flexion/extension showed slightly higher shoulder extension moments in both shoulders (on average by up to ~2.1 Nm) under the above-table condition. The abduction moments of the right shoulder (5th and 50th percentiles) were also lower under the above-table condition compared to the away-from-table condition (on average by up to ~4.3 Nm). Similarly, the 95th percentile left shoulder adduction moment was smaller under the above-table condition (on average by up to ~20.9 Nm). However, for the other percentile shoulder abduction/adduction moments, the effect of the block condition was reversed (i.e., greater moments under the above-table condition than away-from-table). When comparing the left and right shoulders, the shoulder moments tended to be larger in the left shoulder than the right (on average by up to ~23.7 Nm).

3.3. Muscle activity

The erector spinae muscle activities were significantly lower on the left side (on average by up to ~16.4 %MVC) under the above-table condition than the away-from-table condition. A similar trend was observed on the right side, but only for the 10th and 50th percentile values (on average by up to ~1.2 %MVC) (Fig. 7). Both medial deltoids had lower muscle activities under the above-table condition than away-from-table (on average by up to ~13.2 %MVC), but the effect of the block condition was only marginally statistically significant for the 90th left medial deltoid. The other shoulder muscle activities were also

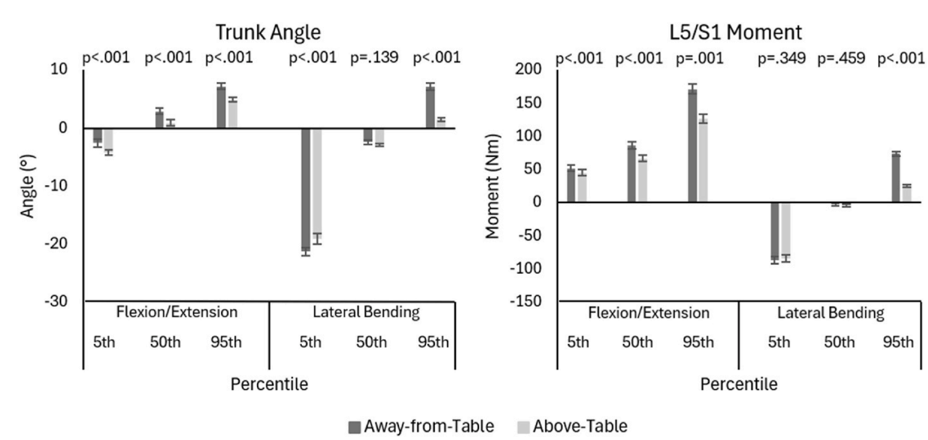

Fig. 4. Mean and standard error of the 5th, 50th, and 95th percentile trunk angles and L5/S1 moments [flexion (+)/extension (−) and lateral bending to the right (+)/left (−)] during crab pot handling under the two block conditions. P-values were calculated from mixed models with the block condition (fixed effect) and the participant (random effect).

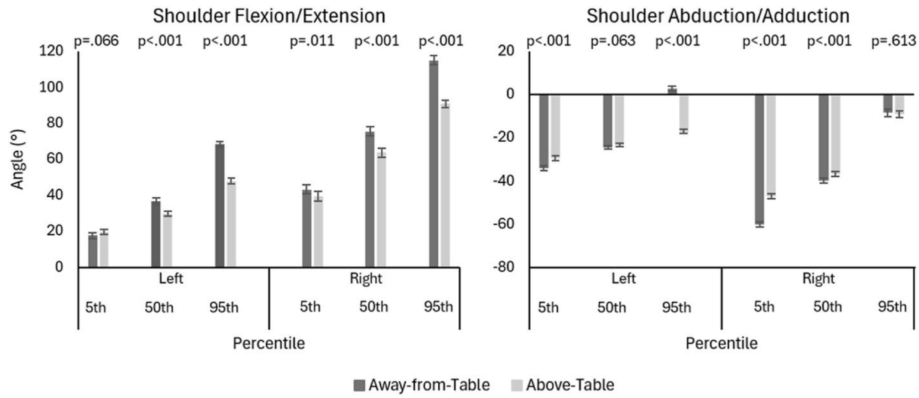

Fig. 5. Mean and standard error of the 5th, 50th, and 95th percentile left and right shoulder angles [flexion (+)/extension (−) and adduction (+)/abduction (−)] during crab pot handling under the two block conditions. P-values were calculated from mixed models with the block condition (fixed effect) and participant (random effect).

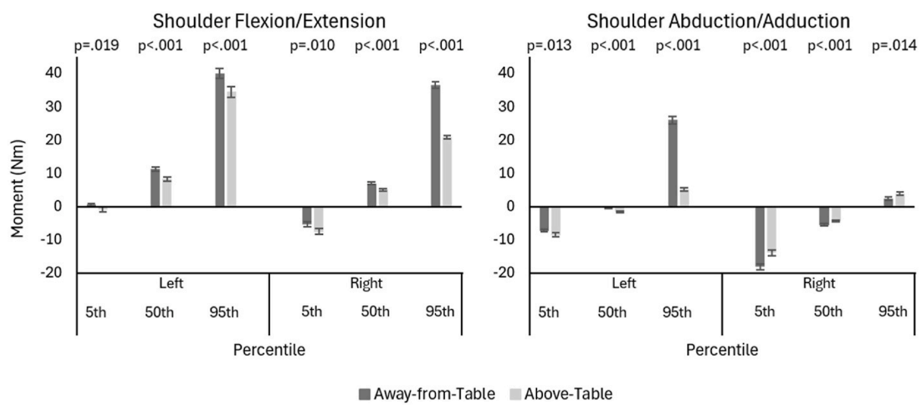

Fig. 6. Mean and standard errors of the 5th, 50th, and 95th percentile left and right shoulder moments [flexion (+)/extension (−) and abduction (+)/adduction (−)] during crab pot handling under the two block conditions. P-values were calculated from mixed models with the block condition (fixed effect) and participant (random effect).

affected by the block condition (Fig. 7), with lower activities in the left (9.2 %MVC) and right (17.4 %MVC) trapezius and left (16.6 %MVC) and right (12.6 %MVC) anterior deltoids under the above-table condition than away-from-table. Both biceps had significantly lower activities under the above-table condition as well, with a 17.4 %MVC difference for the left and an 18.7 %MVC difference for the right.

3.4. Perceived exertion

While the localized perceived exertion measures were not significantly impacted by the block condition for the low back, shoulders, and arms, the results indicated that the average whole-body exertion was lower with the above-table condition by ~1.8 points on the 15-point Borg RPE scale (Fig. 8).

3.5. Postural stability

Postural stability was significantly affected by the block condition for most measures (Table 1). The mean velocities were lower under the above-table condition in both the anterior-posterior (AP) (~24.0 mm/s) and medial-lateral (ML) (~82.7 mm/s) directions. The root-mean-squared (RMS) displacement in the ML direction was also significantly lower under that condition (~101.9 mm), but that was not the case in the AP direction as it appeared slightly higher under the above-table condition (~5.7 mm). Additionally, the total sway area was smaller under the above-table condition compared to the away-from-table condition (~22,382 mm^2).

4. Discussion

This study examined the effects of a conventional block design and an alternative one that brings the pot to the "work area" of the deck on biomechanical loads in the low back and shoulders, perceived exertion, and postural stability during crab pot handling tasks. Overall, the results show that when the block was articulated to position the crab pot above the sorting table on the vessel (alternative design), the biomechanical loads in both the low back and shoulders were reduced during crab pot handling compared to when the block was positioned away from the table (conventional design). Moreover, the perceived general exertion and postural stability measures were improved when the crab pot was positioned above the table.

4.1. Effects of block condition on biomechanical loads in low back

Crab pot handling with the block at its conventional setting posed a peak (95th percentile) flexion angle of ~7° and peak (95th percentile) lateral bending angle to the right of ~7° (toward where the block was placed), while the peak angle to the left (5th percentile) for lateral bending (toward the banger bar) was more extreme (~21.9°). These angles, particularly the lateral bending to the left, can be more extreme (up to 45°) in the field when the sorting table is not equipped with a banger bar (Kia et al., 2023). As such, performing the handling task under the conventional block setting can increase the risk of injuries in the low back as fishermen are likely to adopt extremely awkward trunk postures that exceed the limits of a neutral posture (20°) (Keyserling

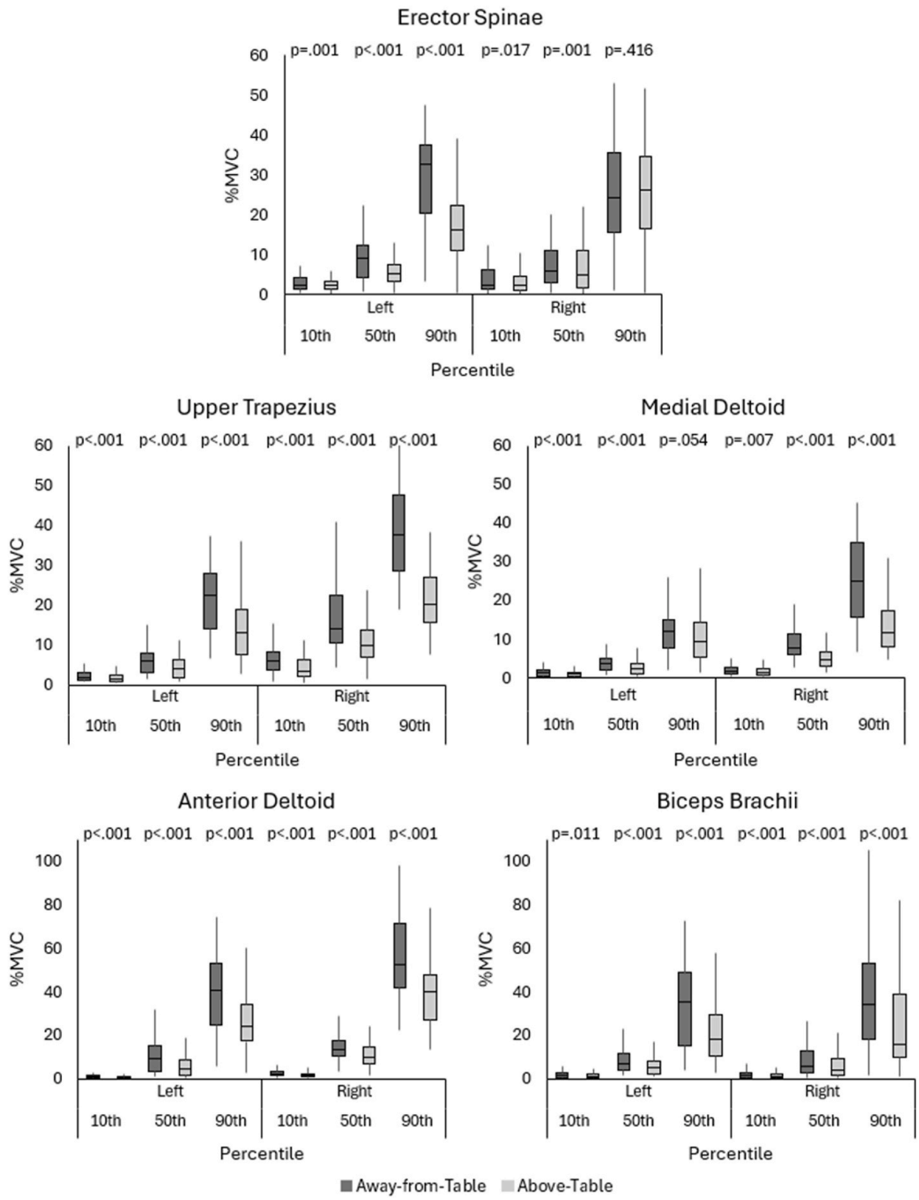

Fig. 7. Box plots of 10th, 50th, and 90th percentile muscle activities in the left and right erector spinae, upper trapezius, anterior deltoid, medial deltoid, and biceps brachii [Maximum voluntary contraction (%MVC)] during crab pot handling under the two block conditions. The minimum and maximum values are capped at ± 1.5*IQR. P-values were calculated from mixed models with the block condition (fixed effect) and the participant (random effect).

et al., 1992; Punnett et al., 1991).

Moreover, crab pot handling with the pot positioned away-from-table posed substantial L5/S1 flexion moments (peak, 95th percentile, moment of ~171.4 Nm) and lateral bending moments (peak, 95th percentile, moment of ~73.8 Nm to the right and the peak moment to the left (5th percentile) of ~86.2 Nm). This moment generation around the L5/S1 joint may be due to the large distance from the L5/S1 joint to the crab pot's center of mass, which was about 60 cm away from participants, and the distance from the joint to the banger bar, which was about 70 cm away from participants would cause the upper body's center of mass to shift when reaching for and banging the pot. Although these values were lower than the 200 Nm NIOSH action limit for compression force and maximum vertebral strength among 20–50-year-old males (Adams, 2004; Gallagher et al., 2002, 2009), the observed moments during crab pot handling were similar to those reported during other occupational tasks that are associated with increased low back injury risk, such as high-risk lifting and patient handling (Hwang et al., 2020; Kingma et al., 2006). Furthermore, it should be noted that the crab pot handling tasks performed in the laboratory setting were conducted with a pot devoid of bait, gear, and crabs, and so the pot (40 kg) was lighter than what would typically be encountered in the field (100 kg) (Kim et al., 2022). Consequently, the L5/S1 moments will likely be higher when handling the full crab pots on vessels, which may partially explain the musculoskeletal injuries experienced by Dungeness crab fishermen.

However, these observed biomechanical loads during the crab pot handling were reduced by having the block position the crab pot above the table. With the block above the table, we observed participants required less trunk bending to their right side (the direction of the block/ocean) to grab the crab pot. Moreover, the significant impact of moving the pot closer to the table manifested in the reduced peak (95th percentile) low back flexion moment (by 41.9 Nm; ~26% reduction) and lateral bending moments to the right (by 47.0 Nm; 3-fold reduction). This adjustment shows that moving the crab pot closer to the table reduced the moment arm between the upper-body center of mass and the center of mass of the crab pot relative to the L5/S1 joint center.

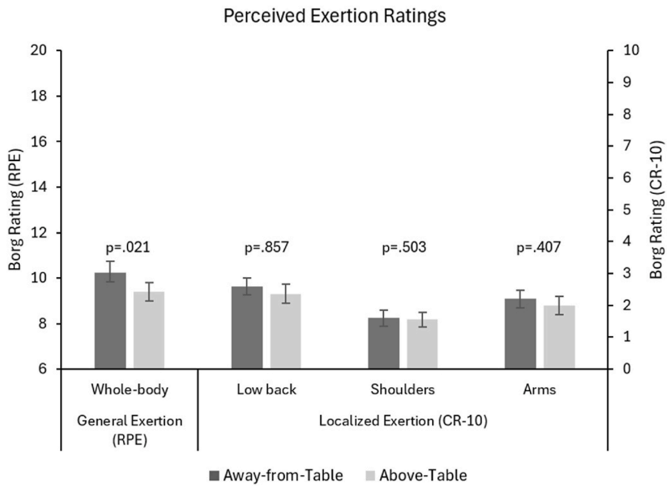

Fig. 8. Mean and standard error perceived whole-body and localized exertion ratings in the arms, low back, and shoulders during crab pot handling under the two block conditions. The Borg RPE scale ranges from 6 (no exertion) to 20 (maximal exertion) while the Borg CR-10 ranges from 0 (rest) to 10 (maximal). P-values were calculated from mixed models with the block condition (fixed effect) and the participant (random effect).

Table 1
Mean (Standard Error) of postural sway measures during crab pot handling under the two block conditions. ML and AP indicate medial-lateral and anterior-posterior directions, respectively. P-values were calculated from mixed models with block condition (fixed effect) and the participant (random effect).

Parameter	Direction	Block Condition		P-Value
		Away-from-Table	Above-Table	
Mean Velocity (mm/s)	ML	262.13 (9.92)	179.5 (9.16)	**0.011**
	AP	84.75 (2.41)	60.8 (2.72)	**<0.001**
RMS Displacement (mm)	ML	140.78 (16.38)	38.93 (2.62)	**0.010**
	AP	61.53 (11.89)	67.22 (2.28)	0.734
Sway Area (mm^2)		35125.4 (2049.2)	12743.3 (1147.8)	**<0.001**

Consequently, lower joint moments were posed during crab pot handling with the alternative block design.

Correspondingly, these reductions translated to lower muscle activity in the erector spinae as well, which is responsible for trunk extension and lateral bending. Specifically, the left erector spinae muscle, responsible for lateral bending to the right and counteracting lateral bending moments in that direction, showed significantly lower activity (a ~16.4 %MVC reduction in peak, 90th percentile, activity) when the block positioned the crab pot closer to the table. Previous studies have also shown lower erector spinae muscle activities with reduced trunk angles and low back moments, indicating that such changes may reduce the risk of musculoskeletal injuries in the low back (Gallagher et al., 2002; Granata et al., 1997; Jorgensen et al., 2003). Therefore, implementing a block design that positions the crab pot above the table may be helpful in reducing the risk of low back musculoskeletal injuries among Dungeness crab fishermen when handling gear.

4.2. Effects of block condition on biomechanical loads in shoulders and upper extremities

The handling task when the pot was positioned away from the table posed substantial biomechanical loads on the shoulders. Performing the task under this condition required extreme shoulder flexion (peak, 95th percentile, angle of ~115.1°) and abduction (peak abduction, 5th percentile, angle of ~60.2°). Shoulder angles greater than 60°, as observed in our study, have been shown to be associated with an increased risk of musculoskeletal injuries in the shoulder (Bernard et al., 1997; Silverstein et al., 2008). In addition, under this condition, handling the crab pot brought up ~60 cm away from the table resulted in moments of up to ~40.1 Nm around the shoulder joints. Although these moments did not exceed the males' shoulder strength capability limits (~36–61 Nm) (Chow and Dickerson, 2016), which is indicative of shoulder injury risk (Hoozemans et al., 1998), the crab pot used in the study was empty. Therefore, the shoulder moments are likely to underestimate the actual impact of the task in the field. These observed elevated biomechanical loads in shoulders suggest that crab pot handling with the current conventional setup for the pots carries a significant risk of shoulder pain and injuries (Antony and Keir, 2010; Bernard et al., 1997; Brookham et al., 2010). This may partially explain the high number of shoulder and upper extremity injuries in the crab fishing industry (Bovbjerg et al., 2019; Case et al., 2015; FLIPP, 2017; Kincl et al., 2019).

As with the low back, positioning the pot above the table overall lowered the biomechanical loads in the shoulders during crab pot handling. In particular, peak (95th percentile) left shoulder flexion angles decreased from 68.4° to 48.0°, which brought the shoulder flexion within the recommended threshold of 60° to minimize the risk of musculoskeletal injuries in shoulders (Bernard et al., 1997; Silverstein et al., 2008). However, despite significant reductions in the right shoulder angles (up to ~21%), the flexion angle in the right shoulder remained over 60° (peak, 95th percentile, angle of ~91.0°). This shows that there may still be a risk of injury in the shoulders even if the block articulates the pot closer to table. In line with the shoulder angles, positioning the crab pot above the table also resulted in decreased shoulder moments (by up to ~20.9 Nm) and muscle activities in the upper trapezius, medial and lateral deltoids (by up to ~17.4 %MVC). Muscle activities in the upper extremities (biceps brachii) were also lower under this block condition (by up to ~18.7 %MVC). The lower shoulder angles likely reduced the length of the moment arm between the shoulder joint center and the upper arm center of mass, decreasing moments and shoulder muscle activities to counteract the resultant moments. Additionally, positioning the center of mass of the crab pot closer to the shoulder joints likely contributed to the reductions in shoulder moments and muscle activities. These reductions in biomechanical loads, in turn, can lead to a decreased risk of musculoskeletal disorders in the shoulders (Brookham et al., 2010; Nordander et al., 2016). Therefore, having the block articulating the crab pot above the table is a promising design modification to reduce the risk of musculoskeletal injuries in shoulders but further design improvements should be considered to mitigate such risks.

4.3. Effects of block condition on perceived exertion

The reductions in biomechanical loads associated with the above-table block condition were also mirrored in the perceived exertion ratings. Participants rated their general exertion to be ~1.8 points higher when the block positioned the crab pot away from the table, which is a clinically important difference (Kelly, 1998; Ries, 2005). However, there was no significant difference in participants' ratings of localized exertion in the low back, shoulders, and arms. The lack of significant changes in localized exertion ratings could be due to the similarity between conditions and the short task duration (less than a minute for each crab pot condition). Overall, based on the lower angles, moments, and muscle activities in the low back and shoulders, as well as the reduced general perceived exertion ratings when the crab pot is closer to the table, it can be concluded that this change is effective in decreasing the risk of musculoskeletal problems associated with crab pot handling.

4.4. Effects of block condition on postural stability

Having the block position the crab pot above the table significantly reduced the COP-based postural sway measures, including the mean velocity (up to ~32% for both ML and AP directions), RMS displacement (up to ~73% also for both directions), and sway area (~64%). These reductions indicate an overall lower deterioration of postural control compared to the conventional block design (away-from-table condition) (Lin et al., 2008; Prieto et al., 1996). As expected, changes in block condition had more pronounced effects in the medial-lateral direction, reflecting the nature of the task which requires reaching out in that direction. The observed reductions in COP-based postural sway measures may also be linked to the observed decreases in trunk angles. Positioning the pot above the table resulted in lower trunk lateral bending to the right. Since the trunk is the most inertial segment of the body, this reduced trunk angle may have contributed to lower postural sway metrics under the above-table condition (Duchene et al., 2021). Overall, the observed reductions in COP-based postural stability sway measures show that having the block articulating the crab pot the sorting table reduces the risk of losing postural stability.

Additionally, it is worth mentioning that, although the short duration of our experimental task prevented us from measuring fatigue directly, the overall reduction in muscle activities and other biomechanical load measures under the above-table condition that we observed may indicate a lower risk of fatigue associated with the block condition (Ahmad and Kim, 2018; Nur et al., 2015). Previous research has shown that general and localized fatigue, as well as the associated loss of muscle strength, can negatively impact sensory input and motor outputs, which can then adversely affect postural control (Davidson et al., 2009; Ito et al., 2021; Paillard, 2012; Pline et al., 2006). Therefore, one could speculate that this intervention may help reduce the risk of falls by reducing fatigue. However, since fatigue was not measured directly in our study, further investigation is required.

4.5. Strengths and limitations

The experimental setup and crab harvesting tasks were recreated based on vessel configurations measured from the field and feedback from commercial fishermen, such that our findings should closely resemble the biomechanical loads that fishermen experience in the field. Additionally, our use of multiple objective biomechanical measures, along with subjective measures, with a relatively large sample of participants allows for reliable and robust results. Consequently, our findings could be used to inform and recommend block designs that position crab pots above sorting tables to reduce the risk of musculoskeletal and fall-related injuries among fishermen associated with crab pot handling tasks.

However, we acknowledge that our study results are from a simulation of crab pot handling in a controlled laboratory setting and may differ from actual field conditions. For example, as previously discussed, the crab pot used in this study was empty, so the biomechanical load and postural stability measures may be underestimated. Similarly, the task duration was short and did not reflect the 50–150 pots that fishermen would regularly handle on a fishing line. Consequently, we were unable to capture the effects of long-term fatigue. Regardless, future studies with heavier loads, longer task durations, and actual blocks are recommended to better assess the impacts of crab pot handling with the block. Furthermore, additional feedback from fishermen will be vital to ensure that design recommendations consider the engineering and operating constraints of blocks on fishing vessels to ensure that modifications will be feasible to install and are not cumbersome to use.

Another limitation is that the study sample consisted of participants who had no experience with commercial Dungeness crab fishing activities. As such, the effects of the block swing on muscle activity may differ from actual fishermen because motor unit recruitment strategy can be impacted by a person's skill in performing a task (Bernardi et al., 1996). However, the task was relatively straightforward and unlikely to require much skill to perform. Moreover, participants had time to practice the task before data collection and so they are likely to have been sufficiently familiarized with the task and study setup.

5. Conclusions

This study comparably evaluated the biomechanical loads in the low back, shoulders, and upper extremities for Dungeness crab fishermen, as well as their perceived whole-body exertion and postural stability during simulated crab pot handling under two block conditions: block positioning the pot away (conventional design) or above the sorting table (alternative design). We found that having the block position the crab pot above the table rather than away generally resulted in reductions in biomechanical loads and perceived exertion, as well as postural instability. Consequently, block designs that position the pot above the vessel could be an effective engineering control to address the high prevalence of musculoskeletal and fall-related injuries among commercial Dungeness crab fishermen. We do not have specific recommendations for how the block should be designed as that will depend on vessel-specific parameters, such as the distance from the vessel's side to the sorting table and how crews prefer to conduct their crab pot handling activities with the block. However, the general recommendation of having the pot brought to the table may be sufficient and appropriate for this worker population as the differences in vessel layouts and gear-handling methods would favor more flexible recommendations.

CRediT authorship contribution statement

Kiana Kia: Writing – review & editing, Writing – original draft, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Allen Chan:** Writing – review & editing, Writing – original draft, Visualization, Software, Investigation, Formal analysis, Data curation. **Mina Salehi:** Writing – review & editing, Investigation, Data curation. **Laurel Kincl:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Investigation, Funding acquisition, Conceptualization. **Jeong Ho Kim:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Mean (Standard Error) of the 5th, 50th, and 95th percentile angles and moments during crab pot handling under the two block conditions. P-values were calculated from mixed models with the block condition (fixed effect) and the participant (random effect). The 95% confidence interval limits for the differences in mean angles and moments between the two block conditions are presented

Parameter		Percentile	Block Condition		P-Value	95% Confidence Interval	
			Away-from-Table	Above-Table		Lower Limit	Upper Limit
Trunk Angles (°)	Flexion (+)/Extension(−)	5th	−2.65 (0.66)	−4.17 (0.50)	**<0.001**	−2.15	−0.95
		50th	2.86 (0.48)	0.90 (0.50)	**<0.001**	−2.46	−1.46
		95th	7.22 (0.49)	4.89 (0.44)	**<0.001**	−2.92	−1.66
	Lateral Bending to the Right (+)/Left (−)]	5th	−21.33 (0.70)	−19.11 (0.89)	**<0.001**	3.29	1.15
		50th	−2.40 (0.35)	−2.92 (0.33)	0.139	0.15	1.11
		95th	7.19 (0.58)	1.49 (0.31)	**<0.001**	−4.57	−6.68
L5/S1 Moments (Nm)	Flexion (+)/Extension(−)	5th	51.82 (4.60)	45.13 (4.48)	**<0.001**	−2.8	−10.12
		50th	86.88 (5.47)	66.82 (4.75)	**<0.001**	−16.88	−22.42
		95th	171.37 (7.18)	126.78 (6.57)	**<0.001**	−36.88	−51.60
	Lateral Bending to the Right (+)/Left (−)]	5th	−86.25 (5.31)	−84.25 (5.35)	0.349	−2.37	6.71
		50th	−2.69 (1.41)	−3.85 (1.74)	0.46	−3.39	1.53
		95th	73.82 (3.18)	25.73 (2.22)	**<0.001**	−53.82	−41.96
Shoulder Angles (°)	Left shoulder	5th	17.83 (1.56)	19.58 (1.40)	0.07	−0.11	3.59
	Flexion (+)/Extension (−)	50th	36.66 (1.79)	29.92 (1.35)	**<0.001**	−8.83	−4.78
		95th	68.39 (1.28)	48.00 (1.58)	**<0.001**	−22.06	−18.84
	Right shoulder	5th	43.41 (2.64)	39.59 (2.70)	**0.011**	−7.01	−0.93
	Flexion (+)/Extension (−)	50th	75.53 (2.62)	63.72 (2.59)	**<0.001**	−14.7	−9.22
		95th	115.09 (2.49)	91.01 (2.08)	**<0.001**	−26.92	−21.35
	Left Shoulder	5th	−34.00 (1.12)	−29.42 (1.06)	**<0.001**	3.37	5.99
	Adduction (+)/Abduction (−)	50th	−24.51 (0.93)	−23.30 (0.89)	0.063	−0.06	2.47
		95th	2.82 (1.32)	−17.04 (0.84)	**<0.001**	−21.87	−17.99
	Right Shoulder	5th	−60.17 (1.13)	−47.05 (1.15)	**<0.001**	11.53	14.85
	Adduction (+)/Abduction (−)	50th	−39.72 (1.19)	−36.74 (0.99)	**<0.001**	1.42	4.48
		95th	−8.50 (1.57)	−8.95 (1.55)	0.613	−2.45	1.45
Shoulder Moments (Nm)	Left shoulder	5th	0.58 (0.40)	−0.74 (0.66)	**0.019**	−2.44	−0.23
	Flexion (+)/Extension (−)	50th	11.33 (0.64)	8.44 (0.59)	**<0.001**	−3.85	−1.77
		95th	40.08 (1.53)	34.55 (1.67)	**<0.001**	−8.20	−2.77
	Right shoulder	5th	−5.33 (0.78)	−7.43 (0.87)	**0.010**	−3.59	−0.51
	Flexion (+)/Extension (−)	50th	6.96 (0.39)	5.10 (0.34)	**<0.001**	−2.51	−1.18
		95th	36.65 (0.89)	20.87 (0.64)	**<0.001**	−17.48	−14.02
	Left Shoulder	5th	−7.23 (0.45)	−8.40 (0.70)	**0.013**	−2.27	−0.28
	Adduction (+)/Abduction (−)	50th	−0.40 (0.25)	−1.53 (0.19)	**<0.001**	−1.59	−0.72
		95th	26.08 (1.07)	5.18 (0.43)	**<0.001**	−22.65	−19.03
	Right Shoulder	5th	−18.09 (0.92)	−13.84 (0.82)	**<0.001**	2.56	5.56
	Adduction (+)/Abduction (−)	50th	−5.43 (0.25)	−4.17 (0.22)	**<0.001**	0.86	1.48
		95th	2.41 (0.49)	3.86 (0.55)	**0.014**	0.28	2.36

Appendix B. Median [25th, 75th percentile] of the 10th, 50th, and 90th percentile muscle activities [Maximum voluntary contraction (%MVC)] during crab pot handling under the two block conditions. P-values were calculated from mixed models with the block condition (fixed effect) and the participant (random effect)

Muscle		Percentile	Block Condition		P-Value	95% Confidence Interval	
			Away-from-Table	Above-Table		Lower Limit	Upper Limit
Erector Spinae (%MVC)	Left	10th	2.5 [1.3,4.3]	2.3 [1.4,3.2]	**0.001**	−0.13	−0.03
		50th	9.0 [4.2,12.3]	5.3 [3.3,7.5]	**<0.001**	−0.41	−0.24
		90th	32.6 [20.4,37.6]	16.2 [10.9,22.2]	**<0.001**	−0.72	−0.59
	Right	10th	2.4 [1.4,6.2]	2.4 [1.0,4.7]	**0.017**	−0.11	−0.01
		50th	6.0 [3.2,11.1]	4.8 [1.9,11.2]	**0.001**	−0.17	−0.04
		90th	24.5 [15.7,35.7]	26.1 [16.6,34.5]	0.416	−0.05	0.11
Upper Trapezius (%MVC)	Left	10th	1.9 [1.2,3.2]	1.4 [0.8,2.6]	**<0.001**	−0.27	−0.11
		50th	6.0 [3.3,7.9]	4.2 [1.8,6.2]	**<0.001**	−0.37	−0.22
		90th	22.3 [14.2,28.0]	13.1 [7.6,18.9]	**<0.001**	−0.56	−0.35
	Right	10th	5.9 [3.7,8.3]	3.5 [2.1,6.4]	**<0.001**	−0.43	−0.21
		50th	14.2 [10.5,22.6]	9.8 [7.1,13.8]	**<0.001**	−0.51	−0.36
		90th	37.5 [28.7,47.7]	20.1 [15.8,27.0]	**<0.001**	−0.68	−0.52
Middle Deltoid (%MVC)	Left	10th	1.4 [0.4,2.1]	1.0 [0.4,1.4]	**<0.001**	−0.22	−0.11
		50th	3.8 [2.2,4.9]	2.4 [1.1,3.8]	**<0.001**	−0.34	−0.19
		90th	12.0a [7.6,15.0]	9.4 [5.4,14.5]	0.054	−0.20	−0.01
	Right	10th	1.7 [1.0,2.6]	1.3 [0.7,2.4]	**0.007**	−0.20	−0.03
		50th	7.8 [6.1,11.4]	4.7 [3.2,6.6]	**<0.001**	−0.51	−0.35
		90th	24.9 [15.7,34.9]	11.7 [8.0,17.2]	**<0.001**	−0.72	−0.55

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(*continued*)

Muscle		Percentile	Block Condition		P-Value	95% Confidence Interval	
			Away-from-Table	Above-Table		Lower Limit	Upper Limit
Anterior Deltoid (%MVC)	Left	10th	0.9 [0.5,1.4]	0.8 [0.5,1.1]	**<0.001**	−0.19	−0.06
		50th	9.0 [3.6,14.9]	4.3 [1.8,8.5]	**<0.001**	−0.64	−0.36
		90th	40.8 [24.4,53.1]	24.2 [17.2,34.3]	**<0.001**	−0.59	−0.34
	Right	10th	2.0 [1.3,3.4]	1.3 [0.8,2.5]	**<0.001**	−0.32	−0.14
		50th	13.7 [10.2,17.6]	9.6 [6.7,14.7]	**<0.001**	−0.45	−0.19
		90th	52.5 [41.7,71.3]	39.9 [27.1,47.8]	**<0.001**	−0.49	−0.28
Biceps Brachii (%MVC)	Left	10th	1.4 [0.7,2.7]	1.0 [0.5,2.0]	**<0.001**	−0.33	−0.10
		50th	6.7 [3.7,11.4]	5.1 [2.1,8.0]	**<0.001**	−0.42	−0.23
		90th	35.3 [15.1,48.6]	17.9 [10.7,29.4]	**<0.001**	−0.61	−0.37
	Right	10th	1.4 [0.5,3.0]	0.8 [0.4,2.2]	**0.011**	−0.24	−0.03
		50th	5.8 [2.8,13.0]	3.8 [1.8,9.5]	**<0.001**	−0.35	−0.17
		90th	34.2 [18.4,53.0]	15.5 [9.9,38.6]	**<0.001**	−0.63	−0.44

* **Note:** The 95% confidence interval limits for the differences in mean log-transformed muscle activities between the two block conditions are presented.

Appendix C. Mean (Standard Error) perceived whole-body and localized exertion ratings in the arms, low back, and shoulders during crab pot handling under the two block conditions. The Borg RPE scale ranges from 6 (no exertion) to 20 (maximal exertion) while the Borg CR-10 ranges from 0 (rest) to 10 (maximal). P-values were calculated from mixed models with the block condition (fixed effect) and the participant (random effect). The 95% confidence interval limits for the differences in mean exertion ratings between the two block conditions are presented

Parameter		Block Condition		P-Value	95% Confidence Interval	
		Away-from-Table	Above-Table		Lower Limit	Upper Limit
General Exertion (RPE)	Whole-body	10.24 (0.49)	9.40 (0.39)	**0.021**	−1.52	−0.16
Localized Exertion (CR-10)	Low Back	2.60 (0.26)	2.36 (0.30)	0.857	−0.81	0.33
	Shoulders	1.60 (0.26)	1.56 (0.23)	0.503	−0.48	0.40
	Arms	2.20 (0.28)	2.01 (0.29)	0.407	−0.79	0.39

Appendix D. Mean (Standard Error) of postural sway measures during crab pot handling under the two block conditions. ML and AP indicate medial-lateral and anterior-posterior directions, respectively. P-values were calculated from mixed models with block condition (fixed effect) and the participant (random effect). The 95% confidence interval limits for the differences in mean postural sway between the two block conditions are presented

Parameter	Direction	Block Condition		P-Value	95% Confidence Interval	
		Away-from-Table	Above-Table		Lower Limit	Upper Limit
Mean Velocity (mm/s)	ML	262.13 (9.92)	179.50 (9.16)	**0.011**	−96.5	−69.5
	AP	84.75 (2.41)	60.80 (2.72)	**<0.001**	−27.61	−20.39
RMS Displacement (mm)	ML	140.78 (16.38)	38.93 (2.62)	**0.01**	−118.12	−85.88
	AP	61.53 (11.89)	67.22 (2.28)	0.734	−5.18	17.18
Sway Area (mm^2)		35125.40 (2049.20)	12743.30 (1147.80)	**<0.001**	−24687.56	−20076.44

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