Comfortable SCBA Weights from Biomechanical Models for Firefighting Tasks

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Abstract. Firefighters are required to use a self-contained breathing apparatus (SCBA) for respiratory protection when engaged in a variety of firefighting duties. While the SCBA provides crucial respiratory support and protection, it is also cumbersome and heavy. Questions have arisen to address the current weight limitation listed in 42 CFR Part 84, which mandates the maximum weight of 16 kg (35.2 lbs) for an SCBA system. The objective of the overarching study is to inform a maximum comfortable SCBA weight by developing static and dynamic biomechanical models and collecting physiological burden and postural stability data to evaluate stressors for firefighting tasks. This paper presents data from the static models. Eight representative firefighting tasks (stair climb, hose carry, weighted carry, rope pull, dummy drag, hammer slam, overhaul, and hose advance) were used in the biomechanical models. Maximum comfortable SCBA weights were calculated based on three biomechanical models (abdominal extension/tension, lateral extension/tension, and abdominal rotation). This study found that the maximum comfortable weight for an SCBA was 39 lbs for the static postures of interest. Further studies with human subjects to investigate the SCBA weight limit by using physiological burden and dynamic models are underway and will provide crucial data to inform updates to the current weight limits for SCBAs allowing more features and extended durations of these devices without compromising user safety, performance, or comfort.

Keywords: Biomechanical modelling · Shoulder force · Lumbar lift force · SCBA load carriage · Firefighting hazard evaluation

1 Introduction

Firefighting is one of the most dangerous occupations that require intensive physical work in hazardous environment [1]. Firefighters work in varied and complex environments that potentially expose them to a number of hazards. To combat this, firefighters wear a turnout ensemble (i.e., protective coat and pants) and other personal protective equipment (PPE) such as a helmet, gloves, boots, and a self-contained breathing apparatus (SCBA) approved by NIOSH's Respirator Approval Program as meeting the requirements of 42 CFR Part 84 and certified by NFPA (National Fire Protection Association). Firefighters' PPE have been designed to provide protection against multiple hazards such as thermal

J. L. Wright et al. (Eds.): AHFE 2021, LNNS 264, pp. 231–238, 2021.
https://doi.org/10.1007/978-3-030-79763-8_28

threats (e.g. exposure to flame and excessive heat), toxic gas inhalation, and physical injuries (e.g. cuts, collisions, punctures, slips, falls, etc.). While the SCBA is instrumental in reducing the risk of exposure to toxic gases, it increases the load that a firefighter must carry and shifts the center of mass (COM) away from the firefighter's core, limiting the range of motion and decreasing overall gait performance [2]. The SCBA has also been attributed to increased physiological burden [3]. Firefighters were more likely to be injured during fireground operations than during any other duties. In 2019, 23,825 injuries, or 39% of all reported firefighter injuries, occurred at the fireground. The leading cause of fireground injuries was overexertion or strain (29%) [4].

The firefighting industry has seen an increase in the usage of larger (and consequently heavier) extended duration SCBA cylinders (45-min or 60-min). The addition of new safety technologies including the Personal Alert Safety System, Heads Up Display systems, and buddy lights into the SCBA has also been a factor in the overall increase in weight. While the SCBA provides crucial respiratory support and protection, it is also cumbersome and heavy. Questions have arisen to address the current weight limitation listed in 42 CFR Part 84 [5], which mandates a maximum weight of 16 kg (35.25 lb) for an SCBA. The question at hand, however, is by what means this additional weight will contribute to biomechanical variables. Research is needed to inform decisions regarding any updates to the current SCBA weight limit. The objective of the overarching study is to inform a maximum comfortable SCBA weight by (1) developing static and dynamic biomechanical models and (2) collecting physiological burden and postural stability data to evaluate stressors for firefighting tasks. The goal of the study is to utilize static biomechanical modelling of common firefighting tasks to estimate the comfortable SCBA weight limit. The static biomechanical modeling is a commonly used, low cost and quick approach for obtaining preliminary results for the research questions.

2 Methods

The methodology used in this study includes two parts: selection of firefighting tasks and development of three static biomechanical models based on the firefighting tasks of interest.

2.1 Firefighting Tasks

Eight common firefighting tasks were considered. For each task, one static posture was used in each of the models. The selected tasks included stair climb, hose carry, weighted carry, rope pull, hose advance, overhaul, hammer slam, and dummy drag and are shown in Fig. 1. Stair climb was defined as the subject climbing up the stairs. The static posture is where the left foot is at ground level and the right foot is on the first step. Both feet support the body. Hose carry was defined as the subject carrying a hose. The static posture is where the left foot is on the ground supporting the body and the right foot is just coming off the ground. A 50 ft. empty hose was modelled as weighing 30 lbs, with only a 70 in long section of the hose being lifted by the firefighter. This results in a 3.5 lbs load on the right hand at 45° from the horizontal. Weighted carry was defined as the subject holding weights with both arms. The static position is where the legs are mid stride and both arms are fully extended while carrying 45 lbs loaded on each hand, with only the right foot supporting the body. Rope pull was defined as the subject pulling a rope. The static posture is where the left leg is flexed and planted on the ground, while the right leg is planted on the ground and extended. The right and left arm are both holding the rope at chest level with 25 lbs loaded on the other end of the rope. The chest is perpendicular to the frontal plane and both feet are supporting the body. Dummy drag was defined as the subject dragging a dummy. The static posture is where both feet are planted on the ground and the arms are holding the dummy with the elbows bent at a 90°. The Dummy exerts 150 lbs of load on the subject's wrists and both feet are supporting the body. Hammer slam was defined as the subject slamming a hammer on a rubber tire. The static posture is where the feet are both planted on the ground, with the body facing perpendicular to the tire while both arms are holding the hammer. The hammer weights 20 lbs and both feet are supporting the body. Overhaul was defined as the subject pulling a load downwards. The static posture is where both feet are planted on the ground supporting the body and the right arm is holding the load at a higher position than the left. A 20 lbs load is applied to the hands at 45° from both horizontal and vertical. Hose advance was defined as the subject pulling a hose forward. The static posture is where both feet are planted on the ground supporting the body while the subject is crouched down. The arms are both holding the hose with 20 lbs resistance applied horizontally on the hands from performing the task. The torso is rotated 45°.

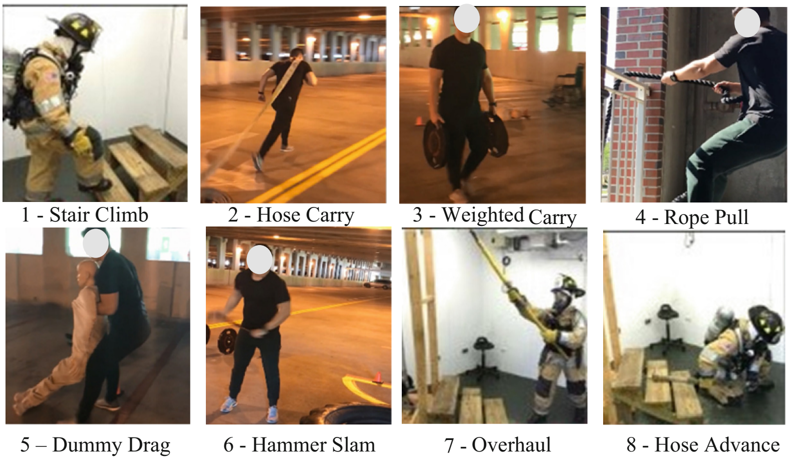

Fig. 1. Selected firefighting tasks (Photo credit: Illinois Fire Service Institute (IFSI) and Florida State University (FSU)).

2.2 Biomechanical Models

Maximum comfortable SCBA weights were calculated based on three biomechanical models. Two of the models in this study were developed to determine lateral extension/tension and abdominal rotation. The third model was abdominal extension/tension

[6]. From each model, final equilibrium equations were developed. According to a previous study [7], a comfortable SCBA weight results in a shoulder force and lumbar lift force less than 280 N and 135 N, respectively. Therefore, the maximum comfortable SCBA weights were determined using this threshold for each of eight representative static postures, which were shown in Fig. 1. Of the eight postures, stair climb, hose carry, weighted carry, rope pull, and dummy drag, had abdominal extension/tension. Hammer slam and overhaul had abdominal rotation. Hose advance had a complex posture that consisted of abdominal rotation, abdominal and lateral extension/tension. The weight of the SCBA was varied for each posture within the models, and the forces exerted on the shoulder and the lumbar lift forces were determined and compared to the comfortable limit.

Abdominal Extension/Tension Model

A biomechanical model previously developed by Kajaks [6] can calculate SCBA exerted forces that accounted for abdominal extension/tension. For a full description of this model please see Kajaks [6] and Pelot [7]. This model was used in this study to determine the abdominal extension/tension forces.

Lateral Extension/Tension Models

When a person laterally bends, the reaction force from the SCBA weight exerted on the shoulders are no longer equal and require additional calculations to determine the exact reaction force on each shoulder. Figure 2 shows a simplified view of the SCBA unit in the frontal plane. The straps are modelled as string tensions T_1 and T_2, and the SCBA belt is simplified to a point support at the bottom of the SCBA unit, we assumed that the location of this point support is unaffected with lateral bending. The support from the belt and back are represented by forces F_{Ly} and F_{Lz}. The weight of the SCBA unit is modeled as Fg, and angles θ_1 and θ_2 model the angles at which the strap extends from the SCBA unit, and θ_3 represents the angle at which the whole system is tilted at, compared to the horizontal. The length of the SCBA unit is d_1, and the vertical distance between the center of mass of the SCBA and the lumbar attachment point is d_2.

From Fig. 2, the following three static equilibrium equations were created:

$$\sum F_y = -T_1 cos\theta_1 + T_2 cos\theta_2 + F_g cos\theta_3 + F_{Ly} sin\theta_3 - F_{Lz} cos\theta_3 = 0 \quad (1)$$

$$\sum F_z = T_1 sin\theta_1 + T_2 sin\theta_2 - F_g sin\theta_3 + F_{Ly} cos\theta_3 + F_{Lz} sin\theta_3 = 0 \quad (2)$$

$$\sum M = F_g cos\theta_3 + T_2 cos\theta_2 (d_1) - T_1 cos\theta_1 (d_1) = 0 \quad (3)$$

After studying pictures of the connecting area between the straps and the SCBA unit, θ_1 and θ_2 were observed to be similar enough to be assumed to be the same and unified into θ, then T_1 and T_2 are solvable given F_{Ly}, F_{Lz}, F_g, θ_3, and θ. θ_3 was determined by the posture from the static image, and θ was determined from image analysis of a connecting point between the SCBA unit and the straps and was assumed constant throughout. F_{Ly} was assumed to be zero, and F_{Lz} was assumed to equal L_z from the abdominal extension/tension model where $\beta = 0°$, making this model an extension of the abdominal extension/tension model that assumes there is no postural bending in the coronal direction. As such, the first step of the lateral extension/tension model was to calculate shoulder force (S_Z) and lumbar lift force (L_Z) from the abdominal extension/tension model where $\beta = 0°$. Thus, the true inputs to this model were θ_3 and θ for the lateral model portion, and W and θ_1 from the abdominal model portion.

Since the only important effect of lateral extension/tension is the redistribution of weights on the shoulders, the output of this model should just be a force ratio between the forces applied to the shoulders by the SCBA straps (T_1 and T_2) that can be multiplied to or divided from S_Z values from the abdominal extension/tension model, allowing the S_Z's to account for lateral bending.

As a way to validate the model, T_1 and T_2 can be converted to S_{z1} and S_{z2} values via the following equation:

$$S_{z1,z2} = T_{1,2} sin\theta \tag{4}$$

One important note about this model is that it is very dependent on the unified strap angle (θ) value.

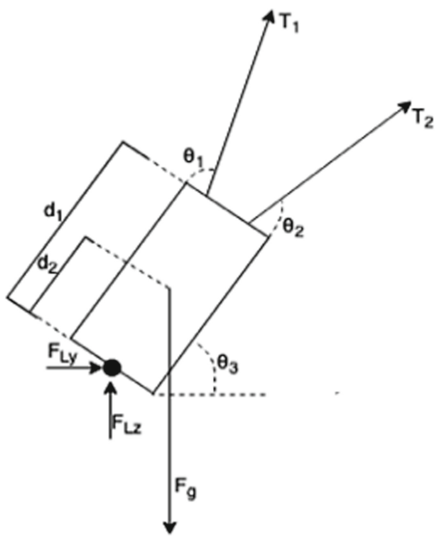

Fig. 2. Full-body diagram of the SCBA unit during lateral bending at angle θ3.

Abdominal Rotation Model

Once the static equilibrium models for both abdominal and lateral extensions/tensions were established, the static equilibrium model for abdominal rotation was created.

The abdominal and lateral extension/tension models have a sine and cosine relationship, with each model completely dominating the calculations at different degrees of rotation. Looking at the two abdominal and lateral extension models, SCBA weight is an input to both models and can be varied indpendent of the SCBA design, making it the ideal variable for which to apply the sine and cosine relationship. Thus, it was assumed the reaction forces exerted on the body by an SCBA unit in a posture with abdominal extension/ tension and rotation can be modeled by splitting the weight of the SCBA (Fg) into weight contributing to abdominal extensions/tensions (Fg_A) and weight contributing to lateral extensions/tensions (Fg_L), which are governed by the following equations:

$$Fg_A = Fgcos\theta_r \quad (5)$$

$$FgL = Fgsin\theta_r \quad (6)$$

Where θ_r is the rotation angle. Fg_A was then input into the abdominal extension/tension model with appropriate variables, and Fg_L is input into the lateral extension/tension model with appropriate variables. The forces calculated at each of the three contact points from both models are then summed together via the Pythagorean Theorem and then rotated based on the rotation angle, resulting in x-, y-, and z- components of the reaction forces applied to said posture with abdominal extension/tension and rotation.

In the case of the hose advance posture, the posture contains abdominal extension/tension, lateral extension/tension, and abdominal rotation. As such, it was assumed that once the reaction forces were adjusted for the combination of abdominal extension/tension and rotation, they only needed to be multiplied by a force ratio corresponding to the lateral bend angle to account for the lateral extension/tension.

3 Biomechanical Analysis Results

The maximum comfortable SCBA weights were calculated for each biomechanical model across postures. For the abdominal extension/tension model, the maximum comfortable SCBA weight was 39 lbs, for the abdominal rotation model, the maximum comfortable SCBA weight was 43 lbs, and for the three combination biomechanical models, the maximum comfortable SCBA weight was 40 lbs. See Fig. 3.

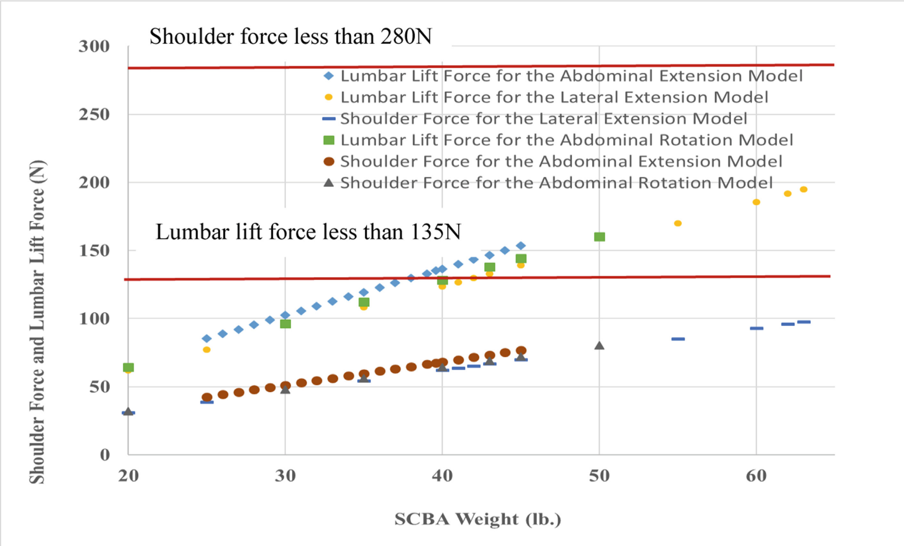

Fig. 3. Shoulder force and lumbar lift force vs SCBA weights at three models.

4 Discussion

This study was the second step of an overall research effort to understand and establish the maximum allowable weight that would prevent firefighter injury while maintaining comfort. The first step was to determine the maximum allowable weight by using a 3-Dimensional Static Strength Prediction Program (3DSSPP). Based on a biomechanical model, 3DSSPP calculated lower back (L4/L5) compression forces and the results were compared to the NIOSH guidelines. The maximum safe weight of an SCBA ranged from 35 to 75 lbs [8].

In this study, maximum comfortable SCBA weights were calculated based on three biomechanical models (abdominal extension/tension, lateral extension/tension, and abdominal rotation). Significant differences in maximum SCBA weights were found among tasks. The maximum comfortable weight for an SCBA was 39 lbs for the static postures of interest. This is heavier than the 35 lbs obtained from the 3DSSPP method.

Individual firefighter strength would impact postural stability and comfort as well as other physiological variables and was not accounted for in this study. This is a limitation of this study. Future studies are planned to investigate physical and psychophysical variables to support the evaluation of SCBA design and weight on firefighter stamina, comfort, and postural stability with human subjects. Subjects will perform firefighting activities while wearing a standard firefighting ensemble and SCBA (three different weights) in hot conditions. The human subject data will be used to compare with and validate the static and dynamic biomechanical models. These models will then be used to assess more scenarios to provide results to improve SCBA designs and develop guidance and recommendations on practical use during firefighting activities.

5 Conclusions

This study found that the maximum comfortable weight for an SCBA was 39 lbs for the static postures of interest. Further studies with human subjects to investigate the SCBA weight will provide crucial data to inform updates to the current weight limits for SCBAs allowing more features and extended durations of these devices without compromising user safety, performance, or comfort.

Acknowledgments. The authors thanks for Illinois Fire Service Institute (IFSI) and Florida State University (FSU) to support our study.

Disclaimer. The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention.

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