Biomechanical Modeling and 3D Simulation of Firefighting Tasks

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Abstract. Firefighting is an injury prone occupation. The self-contained breathing apparatus (SCBA) included as part of a firefighter ensemble contributes to these injuries by affecting a firefighter's balance. The objective of this study was to establish a method to determine the maximum allowable weight that would prevent firefighter injury by using a 3-Dimensional Static Strength Prediction Program (3DSSPP). Four representative firefighting tasks (stair climb, hose carry, weighted carry, and rope pull) were used to perform the simulation. A representation of a 50th percentile male firefighter was used in 100 simulated trials. 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. for the tasks examined. Policymakers may use this study's methods and findings to inform evaluation methods and performance requirements that will drive SCBA design improvements, ultimately reducing the risk of injury among firefighters.

Keywords: Biomechanical modeling · Simulation · Firefighter · 3DSSPP · Firefighter activities

1 Introduction

Firefighting and rescue operations involve work conditions that are unpredictable and rapidly changing. Firefighters wear personal protective equipment (PPE) to minimize the risk of injury or death. Specifically, the use of a self-contained breathing apparatus (SCBA) is a key component in reducing the risk of asphyxiation and the inhalation of dangerous or overheated gases. While the SCBA is instrumental in reducing the risk of exposure, 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 [1]. This results in an increased risk of slips, trips, and falls (STFs) among the firefighters and may also lead to musculoskeletal disorders and low back pain. [2] The Bureau of Labor Statistics (BLS) data indicated fire fighters reported musculoskeletal disorders (MSD) rate of 179 per 10,000 full-time workers (also more than five times the national average), total 5,760 MSD and median days away from work was 15 days [3]. Firefighters, an occupational group, are also at high risk for the back injury due to their requirement to lift and carry victims, wear heavy protective

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equipment such as SCBAs and perform rigorous activities [4]. Back pain has been reported as a contributing to early retirement among active firefighters [5].

The weight of the SCBA likely contributes to the development of low back pain among firefighters and 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. A review of literature has identified the negative effect of PPE on firefighter's locomotion and more specifically the SCBA was shown to be the most influential piece of firefighting gear effecting balance and contribute to the firefighter's injury [6]. Questions have arisen to address the current weight limitation listed in 42 CFR Part 84 [7], which mandates a maximum weight of 16 kg (35.25 lb) for an SCBA. So, the objective of this study was to establish a method to determine the maximum allowable weight that would not excessively challenge firefighter low-back injury during firefighting tasks by using a 3-Dimensional Static Strength Prediction Program (3DSSPP).

2 Methods

The methodology used in this study includes three parts: software, selection of firefighting tasks, and biomechanical modeling and simulation.

2.1 Biomechanical Modeling Software

3DSSPP which was developed by the Center for Ergonomics at the University of Michigan College of Engineering was used to simulate firefighting tasks with static strength analysis. This program allows for users to input anthropometric data and obtain the forces and moments computed by the program, rather than by manual calculation. Figure 1 shows the output of 3DSSPP. In addition, the program also combines the National Institute for Occupational Safety and Health (NIOSH) lifting data and other additional reports to identify risks associated with a particular task. This study used 3DSSPP to model the effects of heavier SCBA units on the firefighter's body, specifically the loading at the L4/L5 joint, when select firefighting tasks were simulated.

2.2 Selection of Firefighting Tasks

Four, separate common firefighter tasks were considered. For each task, one static posture was used in the model. The selected tasks, stair climb, hose carry, weighted carry, and rope pull, are shown in Fig. 2.

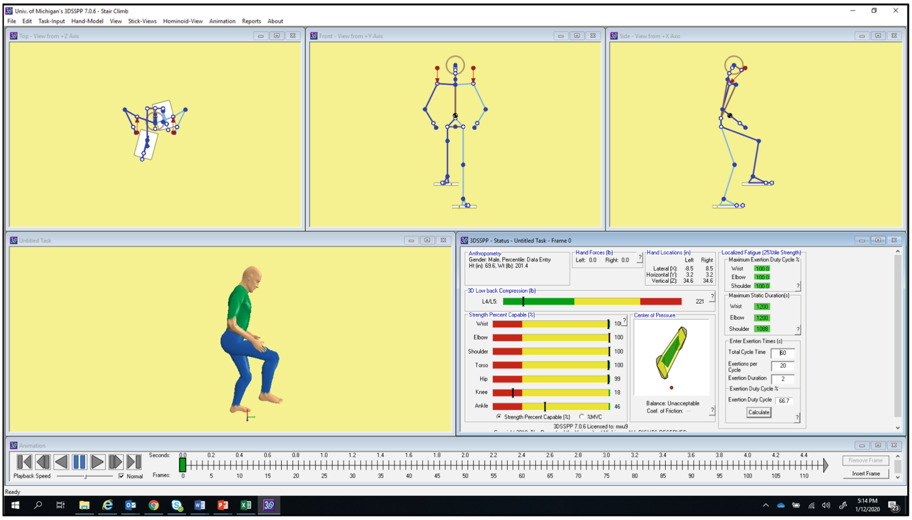

Fig. 1. The sample of 3DSSPP output.

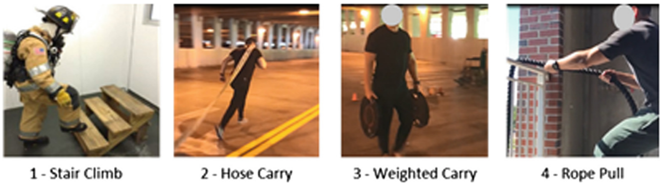

Fig. 2. Selected firefighting tasks. (Photo credit: Illinois Fire Service Institute (IFSI) and Florida State University (FSU)) (1) A stair climb in which the subject is climbing up the stairs. The static posture is where the left foot is at ground level and the right foot is on the first step. Both feet support the body. (2) Hose carry: only the left foot is supporting the body; the 50 ft. empty hose weighs 30 lbs., with only a 70 in. long section of the hose being lifted by the firefighter, 3.5 lbs. load on the right hand at 45° from the horizontal. (3) A simulated weighted carry: 45 lbs. loaded on each hand, with only the right foot supporting the body. (4) Rope pull: 25 lbs. loaded on the other end of the rope, with the chest perpendicular to the frontal plane. Both feet are supporting the body.

2.3 Biomechanical Modeling and Simulation

Biomechanical Modeling Assumption of External Loads. The external forces that were considered in this study were limited to the load of the SCBA and a realistic load due to the gear, including pants, jacket, and gloves which was approximately 12 lbs., based on measurements taken from a donated firefighter's set. The weight of the helmet and boots were not included.

3DSSPP Modeling Procedure. The procedure using the 3DSSPP software to simulate a firefighter static posture associated with the tasks is presented. First, the firefighters' anthropometric data was input using the 50^{th} percentiles of male firefighters' heights and weights [8] with 12 lbs. gear weight. Second, foot support was selected for standing postures as both feet support, left foot support, or right foot support according to the firefighter's posture. Third, a background image was inserted. Once the tasks were identified and the postures selected for simulation, then the photo for the selected task posture (as shown in Fig. 2) was inserted as the background image. The joint center locations were manually manipulated in the three fields-of-view accordingly to attain a similar pose and balance for all SCBA weights (See Fig. 1). Forth, the trunk flexion angle was determined from the posture report from 3DSSPP and input into the SCBA biomechanical model. The SCBA biomechanical model will be explained in the Sect. 2.3.3. Fifth, the horizontal and vertical components of the low back and shoulder joint reaction forces in the global coordinate system were determined. The model outputs these forces in the local coordinate system assigned to the SCBA. Thus, the force components must be rotated by the trunk angle in order to be presented in the global coordinate system prior to being included in the 3DSSPP software. The equal and opposite of these low back and shoulder joint reaction forces were then utilized as the external loads, which were calculated by the biomechanical model, acting on the low back and shoulder joints, respectively. Lastly the estimated hand loads based on static analysis and simulated weight were input.

3DSSPP software calculated low back compression forces and compared the result to NIOSH guidelines. And repeating Step 5 with SCBA weight increased by 1, 2 or 5 lbs. according to the previous calculation until the calculated data do not meet the NIOSH guidelines, which is no more than 770 lbs of force on the L4/L5 compression disc [9].

Biomechanical Modeling. The external forces exerted on the firefighter's body by the SCBA unit weight needed to be calculated separately. The selected tasks involved abdominal extension/tension. Fortunately, Kajaks [10] developed a biomechanical model which was able to calculate SCBA exerted forces that accounted for abdominal extension/tension. This model was used in this analysis. For a full description of this model please see Kajaks [10] and Pelot [11].

3 Biomechanical Analysis Results

The acceptable maximum SCBA weights calculated were for each posture. For stair climb, weighted carry, and rope pull, the maximum SCBA weights are 43, 35, and 49 lbs, respectively. For the hose carry posture, it can support 75 lbs. of SCBA weight without exceeding the NIOSH recommendations. The weighted carry, with its 35 lbs extra load, resulted in the lowest acceptable SCBA weight, while the hose carry, even with its 75 lbs extra load, allowed the highest SCBA weight. This study also found that low back (L4/L5) compression forces are strong and positively linearly correlated with SCBA weights for each posture. So, we can use SCBA weight to predict low back compression force for each posture. The linear regression models are showed in Fig. 3.

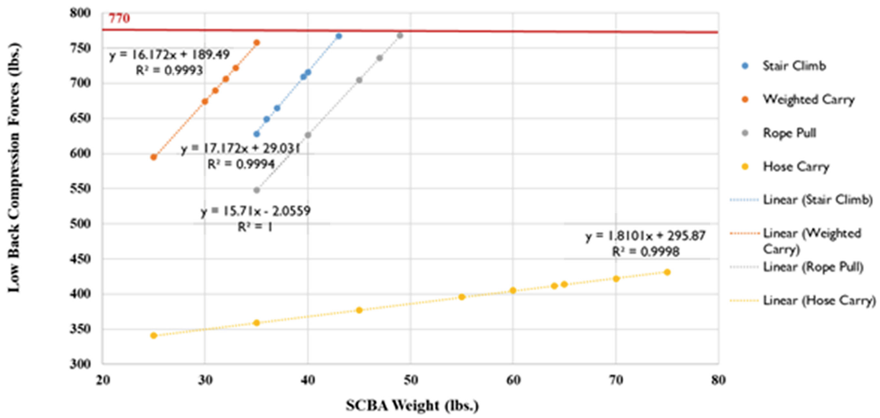

Fig. 3. Low back (L4/L5) compression forces vs SCBA weights. The red line indicates the NIOSH-recommended maximal L4/L5 compression force of 770 lbs.

4 Discussion

This study was the first step to try to understand and establish the maximum allowable weight that would prevent firefighter injury. Only four, separate common firefighter tasks were included in this study. However, some firefighter postures place the knees or even the hands to the ground for extra support, and 3DSSPP was unable to accurately model those postures. As such, 3DSSPP could only model a limited number of the given firefighter postures. This study utilized the male firefighter's anthropometric data and did not consider female firefighters. Additionally, the external loads due to the helmet and boots weren't considered in the biomechanical model, posing limitations to this research.

Significant differences of maximum SCBA weights were found among tasks. The simulated task of weighted carry of 45 lbs. loaded on each hand, with only the right foot supporting the body was the most stressful task that resulted in the smallest allowable weight of 35 lbs. More tasks need to be modeled to have better understanding of the biomechanical loadings associated with firefighting activities and weight limits. The use of static strength models also has its limitations and next steps may include studies using motion capture systems and dynamic biomechanical models. During task performance, trunk kinematics, kinetics, and muscle activities should be collected using non-invasive measures and instrumentation.

A laboratory study involving human subject tests is under development to measure physical and psychophysical variables to support the evaluation of SCBA design and weight on firefighter stamina, comfort, and postural stability. The subjects will perform firefighting activities while wearing a standard firefighting ensemble and SCBA (three different weights) in hot conditions.

5 Conclusions

This study found that different tasks had different maximum weight limits for the SCBA based on the calculations from 3DSSPP. This study found low back (L4/L5) compression forces are strong and positively linearly correlated with SCBA weights for each posture of interest. The maximum safe weight of an SCBA ranged from 35 to 75 lbs. Future studies are needed to establish the SCBA weight limit based on dynamic activities while accounting for all external loads and environmental stressors.

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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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