Evaluating Firefighters' Joint Mobility and Muscular Activity during Load Carriage

Shi-Tan Wang [a,b,c,*]

[a] *Shanghai Yangzhi Rehabilitation Hospital (Shanghai Sunshine Rehabilitation Center), School of Medicine, Tongji University, Shanghai 201619, China*

[b] *The Clinical Research Center of Intelligent Rehabilitation, Tongji University, Shanghai 201619, China*

[c] *College of Fashion and Design, Donghua University, Shanghai 200051, China*

Abstract

This study aimed to quantify the firefighters' joint mobility and muscular activity during self-contained breathing apparatus (SCBA) carriage and evaluate the effectiveness of shoulder strap length variation. Three varying-strapped SCBAs and a control condition with no SCBA equipped were evaluated. Joint range of motion (ROM) and surface electromyography (sEMG) signals were synchronously collected when twelve male subjects walked in four test samples. Results showed that carrying SCBA had more pronounced impacts on the joint ROM and sEMG around the proximal torso, suggesting that the training of firefighters focuses on the coordinated movement of muscles and joints in the trunk. The length of the SCBA strap was suggested to be set at 98–105 cm for firefighters who are 172-178 cm.

Keywords: Firefighters; Biomechanical Evaluation; Personal Protective Equipment; Muscular Activity

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1 Introduction

Self-contained breathing apparatus (SCBA) provides an external air supply that is essential for the safety of firefighters at a fireground. However, as the heaviest item of personal protective equipment (PPE), frequent use of SCBA can cause an excursion of the centre of mass (COM) [1, 2]. As a result, the lower limb range of motion (ROM) is altered, and the metabolic cost and spine muscle activities are increased [3, 4]. It has been reported that heavy SCBA resulted in discomfort, fatigue, and even injury, for example, rucksack palsy and low back problems (LBP) [5-7]. Especially, the prevalence of LBP in firefighters is at 19.3% and is highest in the emergency service (31.8%) sector.

The SCBA is a single-piece, cylinder-shaped equipment made of carbon fibre and aluminium. It has a frame with a shoulder strap, hip-belt, and chest-belt. The weight of SCBA is acknowledged

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[*] Corresponding author.

Email address: `wangshitan@tongji.edu.cn` (Shi-Tan Wang).

as having the greatest impact on a firefighter's movement. To alleviate the biomechanical strain of SCBA, several strategies were developed, such as reducing the size and mass of the SCBA cylinder or redesigning the cylinder shape [7, 8]. However, a lighter SCBA cylinder only offers a little amount of breathing air capacity, and a low-profile SCBA is expensive and impractical. For firefighters using a traditional cylindrical SCBA with a certain weight and shape, the adjustment of shoulder strap length has been reported in a survey that could influence firefighters' perceived fatigue and comfort by shifting loads from one body region to another [9]. Our previous survey indicated that the adjustment of strap length by firefighters was primarily based on their convenience or habit, and 32.5% of firefighters preferred to adjust the shoulder strap in tight-fitting condition [10]. However, no quantitative data has been recorded about the biomechanical impacts of the strap length of SCBA systems, and an "optimal" arrangement for strap length has not yet been reached.

According to backpack studies, the strap design was a feasible solution to modify the soldiers' joint kinematics and interface pressure by moving the backpack's centre of gravity and changing the load transfer patterns [11, 12]. Both the backpack and the SCBA are built on back weight-bearing patterns, with the shoulder strap, hip belt, and chest belt supporting the carried load. The load distribution and transfer pattern of the SCBA is, in principle, compatible with the backpack. As an alternative, adjusting the weight distribution on the body and the SCBA's carrying techniques, such as strap lengths, may be chosen to enhance firefighters' joint and muscular reactions.

Nevertheless, some controversial statements and findings were observed regarding the "optimal" strap length of the backpack. According to the [12], a loose strap produced 40% less total shoulder pressure and 37% less strap tension forces than a tight strap, indicating that shoulder strap in backpacks should be looseness. On the contrary, several studies discovered that walking with a looser shoulder strap resulted in a bigger postural forward and more restricted joint mobility [13, 14]. These contradictory findings may attribute to a single test variable. While it was easier to examine either variable in exclusivity, those studies ignored the fact that the variables interact and were not mutually exclusive. From a biomechanical perspective, muscle contraction and joint movement is an integrated complex that is operating in a coordinated manner [15]. Examining the kinematic or kinetic variable alone just provided an isolated point that may restrict the comparability of the study to others. Therefore, a thorough assessment of joint mobility and muscle activity is required.

Firefighters' joint mobility and muscle activity have frequently been evaluated using a range of motion (ROM) and surface electromyography (sEMG) techniques [16, 17]. Typically, a decrease in range of motion (ROM) indicates a loss of mobility, whereas an increased sEMG value indicates muscular fatigue [18]. ASTM F3031 (2017) specified the standard test protocol for measuring ROM and subjective perceptions while subjects wear protective garments. In the early stage, ROM was mainly measured using a variety of goniometers and flexometers [19]. However, these methods only measured the maximal ROM of a certain joint in standard static postures and did not assess the dynamic changes of body movement over time in real working situations. Researchers have recently employed a 3D motion capture system to investigate the impacts of firefighters' PPE on joint ROM at the hip, knee, and ankle joints [20, 21]; however, these were only focused on lower limb mobility. Because the SCBA is positioned on the firefighter's back; theoretically, the upper body mobility will be affected.

By addressing the literature gaps mentioned above, the purpose of this study was to calculate firefighters' joint ROM and sEMG while carrying SCBA by conducting the biomechanical experiment. The following three research questions will be answered: (1) how do the joint and muscle activity change in response to SCBA carriage? (2) whether the adjustment of shoulder strap lengths can be used as an alternate solution to alleviate the biomechanical strain of SCBA? (3) is the firefighters' habitual shoulder strap length consistent with the optimal shoulder strap length? The findings of this study are expected to provide guidelines on firefighters' SCBA carrying to secure firefighters' work efficiency and safety.

2 Methods

2.1 Test Samples

The PPE tested in this study, which consists of a turnout jacket, pants, gloves, helmet, and SCBA, complies with GA621 (2006). All recruited subjects were of an average build, and thus the same size (175 A) of turnout gear was offered to them. Each subject was given a choice between several sizes of brand-new running shoes and gloves in the same design. Each was provided with a pair of gloves and new running shoes in the appropriate size. The SCBA was a commercially accessible product that was an example of the kind that was frequently used in China. The backpack assembly consists of a backplate, shoulder strap, waist belt, a buckle, and a cylinder faster. Because the shoulder strap could be easily adjusted, we chose the length of the shoulder strap as the independent variable.

Currently, firefighters primarily modify the strap length based on their convenience or habit. A pilot test was done to determine the habitual strap length and base the test strap length on it to set the test strap length as appropriately as possible. Four sets of test samples were finally determined and examined in this study (Fig. 1), including three kinds of SCBA carriage with different strap lengths (loose-fitting, medium-fitting, and tight-fitting) and a control condition (CC) without SCBA equipped. The detailed information about the determination of SCBA shoulder strap lengths is described in [22].

Control condition (CC)

Loose-fitting straps (S1)
Length range: 106-112 cm
Test length: 109 cm

Medium-fitting straps (S2)
Length range: 98-105 cm
Test length: 101 cm

Tight-fitting straps (S3)
Length range: 90-97 cm
Test length: 93 cm

Fig. 1: Four types of test ensembles

2.2 Subjects and Inclusion Criteria

The sample size was determined by Power analysis using G*Power 3.1 software. Effect size set to be 0.6 (this value was calculated using the means and standard deviations within each group), alpha set to be 0.05, and power set to be 0.8. The corresponding sample size was calculated as eight. Twelve male firefighter candidates (age: 24.4±2 years, height: 174.6±2.4 cm, mass: 67±3.5 kg, BMI = 22±1, body fat percentage = 16.5±3.4%) were finally recruited for the experiment.

All subjects were healthy, non-smokers, and with no history of musculoskeletal or cardiopulmonary conditions. The research was approved by the Shanghai Yangzhi Rehabilitation Hospital Department of Ethics Committee (SBKT-2022-008). All the subjects provided written informed consent before participation. Prior to the formal experiment, each subject was asked to wear full PPE and perform movement tasks for one week to familiarize themselves with PPE.

2.3 Experimental Protocol

The whole test was conducted in a thermo-neutral environment with a temperature of 24±0.5 °C and humidity of 50±10%. Full-body 3D kinematic data were collected using the inertial motion capture systems (IMC)-Xsens MVN (Xsens Technologies B.V., Enschede, the Netherlands), sampling at 120 Hz, synchronously with sEMG using a Noraxon system (Noraxon, Scottsdale, Arizona, USA), sampling at 120 Hz.

The body dimensions for each subject were first extracted using a traditional tape in accordance with Xsens' instructions. Subsequently, subjects were instrumented with 17 motion sensors and secured on specific anatomical locations, including the head, sternum, pelvis, upper legs, lower legs, feet, shoulders, upper arms, forearms, and hands. Bipolar dual surface electrodes (Ag/AgCl, Noraxon, Arizona, USA) were placed over eight muscle bellies: cervical extensor (CE), trapezius (TR), latissimus dorsi (LD), erector spinae (ES), rectus femoris (RF), biceps femoris (BF), tibialis anterior (TA), and gastrocnemius (GM) (Fig. 2). Based on anatomical reference points, electrode placement locations were found, and they were then verified by palpating the muscles while the subjects engaged in isometric contractions.

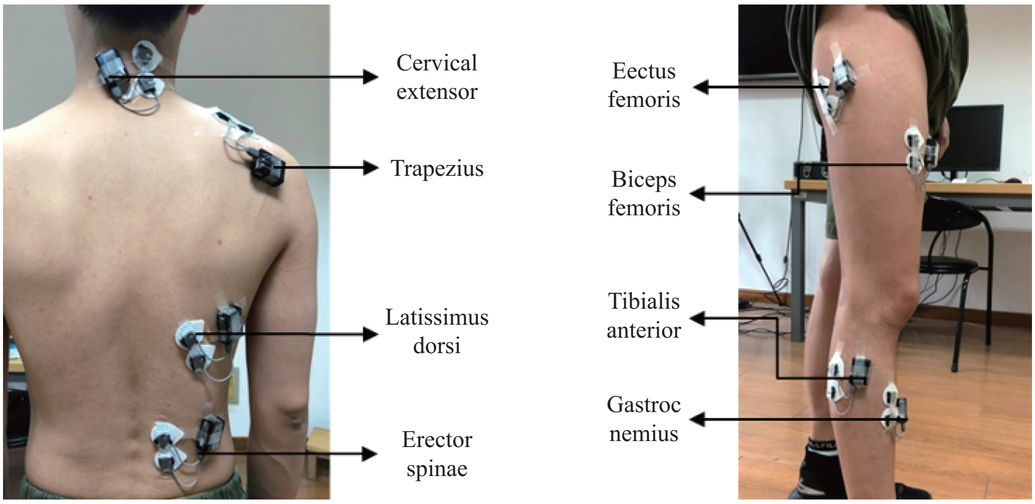


Fig. 2: Diagram of test muscles

After completing these test preparations, the subjects changed into the test sample assigned for the day and kept an upright standing neutral position (N-pose) to calibrate the Xsens system. Subsequently, subjects were asked to perform a 50 m walk at a speed of 1.5±0.25 m/s. Walking was chosen as the test motion in this study because it is both a typical motion in real-life settings and a component of firefighters' physical training programs. To reduce the potential influence caused by the Xsens system on subjects' body motion, all subjects were asked to begin walking with their left foot. After completing the walking routine test, subjects were asked to finish a questionnaire regarding their restriction perception. Restriction perception targeted the ease of movement at the whole body, shoulders, trunk, thighs, knees and calves, which was assessed using a 7-point scale, ranging from 1 (very difficult to move) to 7 (very easy to move). Each test sample underwent three iterations in a randomized order, for a total of twelve trials for every subject. Only one subject was scheduled to be tested in a given period, and the trial for each subject was separated by at least 1 h to minimize the impact of muscle fatigue on gait.

2.4 Data Processing

Python (version 3.9.4) was used to process the motion capture data in order to identify the gait cycle and determine the range of motion (ROM) of the joints in the frontal, transverse, and sagittal planes. To prevent any changes in gait patterns at the beginning and end of the walking routine in this study, the subjects' first and last steps were not included in the analysis. The peak position of the right hip motion curve was used to calculate the gait cycles, which had the right heel initial strike with the ground as their start point and the right heel striking the ground once more as their terminus (next peak point of the curve).

The peak-to-peak change of the Euler angles for each gait cycle served as the basis for computing the ranges of motion (ROM) for the lumbosacral joint (L5/S1), hip joint, knee joint, and ankle joint. Using the linear envelope detection method, sEMG data was processed. To create linear envelopes, raw sEMG data was first full-wave filtered with an eighth-order zero-phase-shift Butterworth low pass filter ($f_c = 20$ Hz). The linear envelopes were then full-wave rectified to convert any negative values arising from the filtering process to absolute values. To assess muscular contraction, the filtered and corrected sEMG signals were averaged and integrated to get the averaged sEMG value (AEMG). The sEMG data were then processed using Fourier transformation and the mean power frequency (MPF) was calculated to evaluate muscle fatigue.

2.5 Statistical Analysis

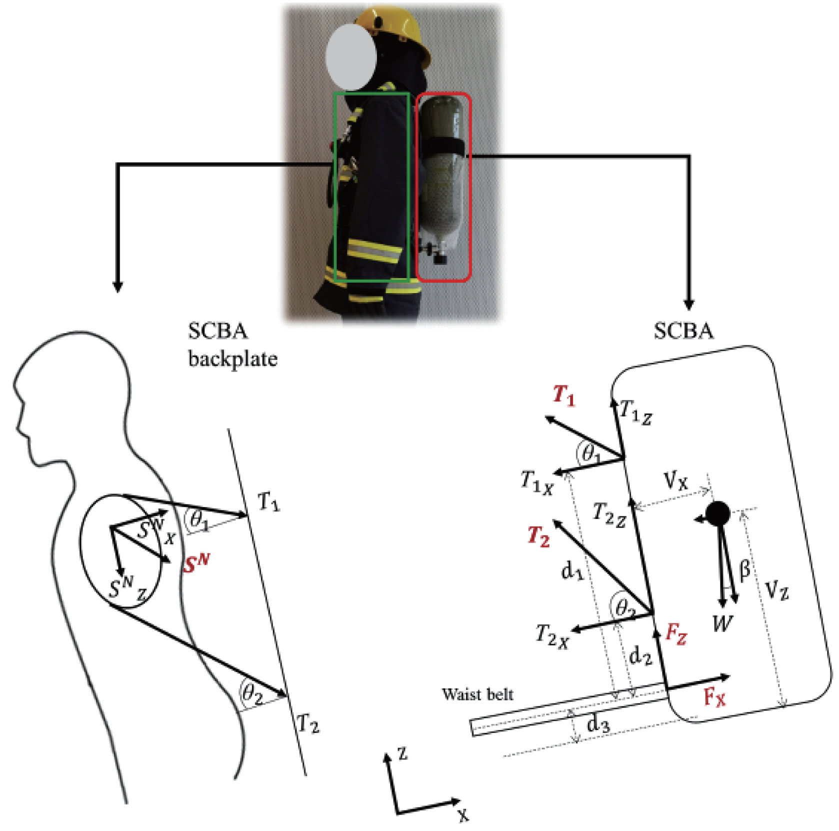
Statistical tests were performed using the SPSS software (version 22, SPSS Inc., IBM, Armonk, NY, USA) with a significance set at $p < 0.05$. All data were first tested for normality of distribution and homogeneity of variance using the Shapiro-Wilk test and the Levene test, respectively.

Joint ROMs, AEMG, and MPF data from 12 subjects were averaged, and standard deviations (SD) of the mean values were computed for each test sample. The kinematics and sEMG data of the four test samples were compared using a three-way repeated measures analysis of variance (ANOVA) on each measure, followed by the Bonferroni post hoc comparisons. The Kruskal-Wallis test was selected to assess the overall restriction perception between four test samples. Pearson correlation coefficients (r) between shoulder straps length and subjects' body height were also calculated and classified as "weak" ($r \leq 0.350$), "moderate" ($0.350 < r \leq 0.670$), "strong" ($0.670 < r \leq 0.900$), and "excellent" ($r > 0.900$) according to [23].

3 Results

3.1 Theoretical Force Analysis

The force on the shoulders and the force on the low back contact are the two main response forces operating on the upper body of firefighters while they are carrying an SCBA. To study the shoulder response force (S^N) and the low back contact force (F_X and F_Z) that result from different SCBA strap lengths, a theoretical force analysis was initially carried out using the biomechanical model [24] (Fig. 3).



T_1 and T_2 are tension in upper and lower shoulder straps, respectively;
F_X is the reaction force of lower back on SCBA in X-direction;
F_Z is the total lift force at lumbar contact point of SCBA;
W is the mass of SCBA;
V_X and V_Z are position of COM from body and bottom of SCBA, respectively;
d_1 is the distance from lumbar pad contact center to attachment point of upper shoulder strap;
d_2 is the distance from lumbar pad contact center to attachment point of lower shoulder strap;
θ_1 is upper shoulder strap angle from plane perpendicular to backplate;
θ_2 is lower shoulder strap angle from plane perpendicular to backplate;
S^N is the net force acting normal to the shoulder.

Fig. 3: Force analysis of load-bearing body and SCBA

From the static equilibrium equations, F_X and F_Z can be calculated from Eq. (1).

$$\begin{cases} F_X = W\sin\beta + S_X^N = W\sin\beta + T_1\cos\theta_1 + T_2\cos\theta_2 \\ F_Z = W\cos\beta - S_Z^N = W\cos\beta - T_1\sin\theta_1 - T_2\sin\theta_2 \end{cases} \tag{1}$$

S^N can be calculated from Eq. (2).

$$S^N = \sqrt{{S_Z^N}^2 + {S_X^N}^2} \tag{2}$$

S_Z^N and S_X^N are determined by the T_1, T_2, θ_1, and θ_2 using Eq. (3).

$$\begin{cases} S_Z^N = T_1\sin\theta_1 + T_2\sin\theta_2 \\ S_X^N = T_1\cos\theta_1 + T_2\cos\theta_2 \end{cases} \tag{3}$$

The moment equation of the COM of SCBA is shown in Eq. (4).

$$F_X(V_Z - d_3) - F_Z V_X - T_2 \cos\theta_2 (V_Z - d_2 - d_3) - T_2 \sin\theta_2 V_X + \\ T_1 \cos\theta_1 (d_1 + d_3 - V_Z) - T_1 \sin\theta_1 V_X = 0 \tag{4}$$

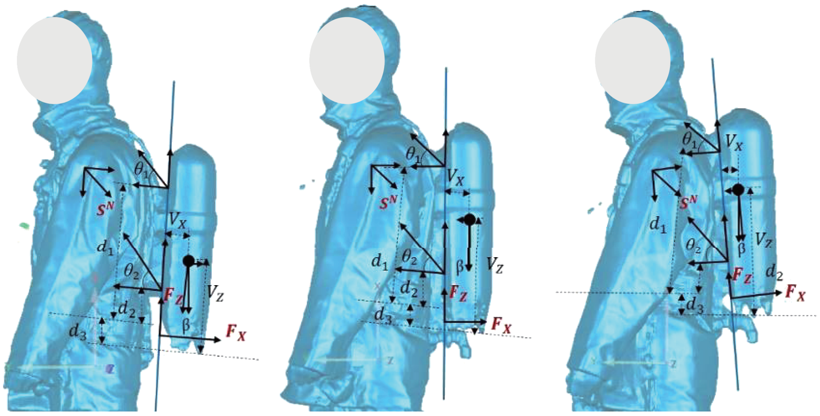
Pulley equation for shoulder wrap is shown in Eq. (5).

$$T_1/T_2 = \mathrm{e}^{\mu_S \alpha} \tag{5}$$

Using substitution and elimination, the T2 in the above expression can be isolated (Eq.(6)).

$$T_2 = \frac{W[V_X \cos\beta - (V_Z - d_3)\sin\beta]}{\mathrm{e}^{\mu_S \alpha} d_1 \cos\theta_1 + d_2 \cos\theta_2} \tag{6}$$

The force analysis while a subject is wearing various SCBA strap lengths is shown in Fig. 4. The S^N, F_X, and F_Z that result from the three SCBA strap lengths are depicted in Fig. 5. It was observed that the variations in S^N and F_X were not proportional to the increase or decrease in the SCBA strap lengths. Among the three SCBA strap lengths, the maximum S^N, F_X, and F_Z were all reported for S1, which was 24.13% higher than S2 in F_X ($p = 0.04$), and 41.35% higher than S3 in F_Z ($p = 0.00$). The findings showed that when the weight of the SCBA is inevitable, strap changes dramatically change the force distribution over the firefighters' lower back and shoulder.



(a) S1 (b) S2 (c) S3

Fig. 4: Force analysis in three SCBA strap lengths

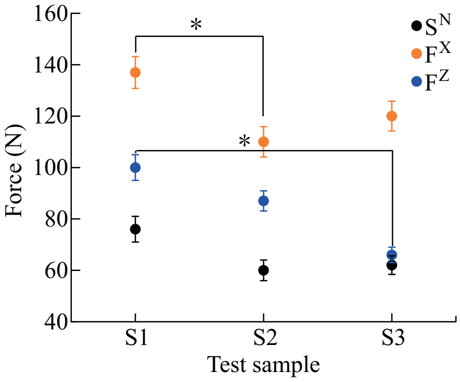


Fig. 5: Force at the shoulder and lower back

3.2 Joint Range of Motion

The joint ROMs while walking with various test samples are shown in Fig. 6. L5/S1, hip, and knee ROMs significantly changed when walking with the SCBA carriage ($p < 0.05$).

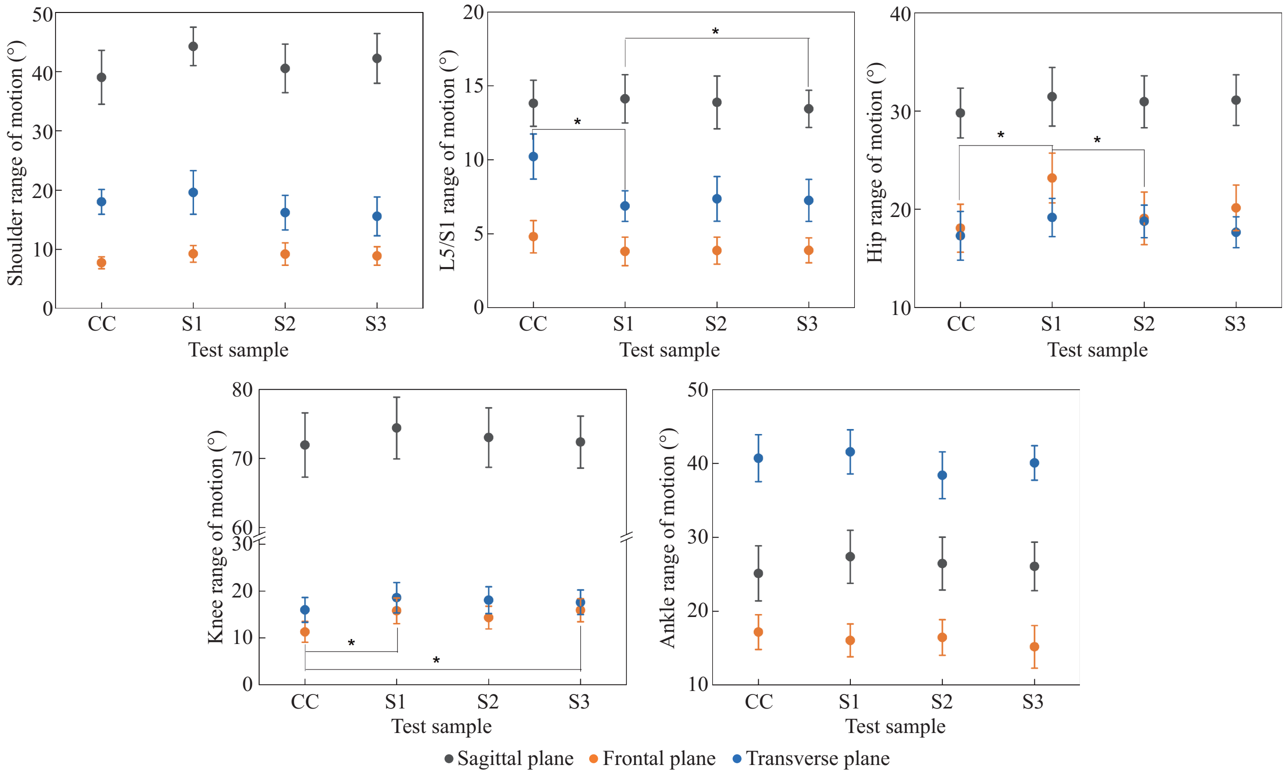


Fig. 6: Joint ROMs in three SCBA strap lengths

When compared to CC, carrying SCBA dramatically reduced rotation ROM at the L5/S1 joint from 10.22° to 6.87°. S2 had the highest decrease rate (32.78%). In contrast, L5/S1 tilt ROM increased by 10.92% and 6.78%, respectively in S1 and S2, but decreased by 8.24% in S3 compared with CC. L5/S1 tilt ROM in S1 was also considerably higher than in S3 ($p = 0.04$). When walking with the SCBA carriage, there was a rising trend in hip ROM at all three planes compared with CC. S1 significantly increased hip abduction-adduction ROM by about 28.29% and 23.56%, respectively, compared to CC and S2 ($p = 0.01$, $p = 0.00$). Furthermore, S1 had the highest ROM in the sagittal and transverse planes, but there was no significant difference ($p > 0.05$). The knee ROM increased in concordance with the hip in the frontal, transverse, and sagittal planes. Knee adduction-abduction ROM increased by 26.88-40.94% with the addition of SCBA, with S1 and S3 showing a significant increase ($p = 0.00$, $p = 0.00$). However, there was no significant influence of strap length on the knee in any of the three planes ($p > 0.05$).

Between of four test samples, there were no significant changes in the way the shoulders and ankles moved ($p > 0.05$). In the sagittal and frontal planes, carrying an SCBA increased shoulder ROM, but it decreased ROM in the transverse plane, with S3 exhibiting the highest reduction (13.62%) compared with CC. When SCBA was added, ankle movements in all three planes showed multiple trends. ROM showed a trend toward growth in the sagittal plane but a trend toward declines in the frontal plane. Wearing S1 enhanced ankle ROM in the transverse plane compared to CC, however, S2 and S3 exhibited a decreased ROM.

3.2 Muscle Electromyography

Table 1 displays the AEMG value at eight muscle groups when wearing four test samples and the MPF change rate while wearing an SCBA in comparison to a CC.

Table 1: AEMG values and change rate of MPF in four test samples

Index	Test muscles	CC	S1	S1	S1
AEMG (uV)	CE	19.11±1.79	18.76±1.81	22.89±2.44	14.44±2.34
	TR	42.10±1.32	36.53±3.17	55.42±2.73	42.57±5.24
	LD	16.10±1.42	18.38±2.56	28.01±1.56	32.29±2.89
	ES	34.46±2.85	39.89±5.46	39.47±3.61	39.16±2.65
	RF	45.09±2.76	37.53±3.67	41.90±2.97	40.69±2.11
	BF	41.95±3.12	28.84±4.71	42.27±2.74	32.62±1.75
	TA	64.11±4.33	66.80±5.94	76.20±6.71	64.73±5.38
	GM	65.76±4.37	57.11±4.79	65.20±6.41	65.79±6.47
MPF change rate (%)	CE	/	2.28±0.50	3.76±0.41	0.68±0.03
	TR	/	8.20±0.63	1.49±0.04	10.16±0.38
	LD	/	−12.78±1.57	−12.34±1.52	−6.51±1.04
	ES	/	−0.37±0.05	0.13±0.01	6.76±0.89
	RF	/	1.92±0.28	3.15±0.83	2.65±0.67
	BF	/	4.79±0.79	11.37±1.82	4.59±0.76
	TA	/	−3.52±0.72	−0.74±0.09	0.89±0.05
	GM	/	−5.54±0.97	1.02±0.18	0.07±0.03

The AEMG value acquired from TR and TA, as well as the MPF value obtained from LD, were significantly affected by the addition of SCBA ($p < 0.05$). The addition of SCBA increased the AEMG value for the TR, RF, BF, and TA in comparison to CC. S3 had a significantly larger AEMG value than S1 at the TR ($p = 0.023$). Nevertheless, it was noted a decreasing trend in MPF value for the LD, ES, TA, and GM when adding SCBA. When compared to CC, wearing S1 significantly reduced the MPF of LD by 12.86% ($p = 0.03$).

3.3 Perceived restriction rating

Perceived restriction ratings did not show a significant difference among the four test samples ($p > 0.05$). Subjects rated S1 as the most restrictive (3.56±1.16), followed by S3 (4.27±1.06), whereas S2 showed better comfort perception (4.27±0.88). Local restriction perception at the knees, lower back and shoulders were also stronger when wearing S1 compared to S3 and S2.

4 Discussion

In this study, joint ROM and sEMG were examined to explore the effects of SCBA carriage and shoulder strap length on firefighters' joint mobility and muscular activity. It was hypothesized that the adjustment of shoulder strap length would alter firefighters' biomechanical performance, which in turn influences the potential risk of load-related MSDs.

4.1 Effect of SCBA Carriage on Joint Mobility

Carrying SCBA dramatically changed firefighters' joint ROM in the proximal torso when performing common functional tasks, such as walking, when compared to the no-SCBA condition. The greatest variation occurred at the L5/S1 joint, followed by the hip joint and knee joint.

A decrease in ROM (the average percentage of all three planes in one particular joint) was observed in the L5/S1 (15.52%) when compared to the CC. Reduced ROM at the L5/S1 indicated a limitation in pelvis mobility, which may be due to the SCBA weight being concentrated on the pelvis, and the load deviating from the body's centre of gravity. The pelvis was the middle segment of the lumbar-pelvis-hip complex. Limited pelvis mobility may disturb the trunk balance and influence the smooth transfer of system weight along the lower limb, causing potential low-back pain and lower limb injuries. Contrary to the results observed in L5/S1 ROM, an increase in ROM was observed in the hip (8.53%) and knee (5.11%) when wearing SCBA. During loaded walking, the hip, knees and ankles joints perform the main function to propel gait movement and complete the smooth transfer of system weight in the forward direction [21, 25]. In addition, our study found that the medial-lateral ROM of the hip and knee increased observably. This adaptation could be seen as an attempt at locomotion to broaden the base of support during heavy walking, which provides individuals with increased stability. A larger knee flexion combined with ankles dorsiflexion could also be considered as a protective mechanism to absorb impact forces when foot contact with the surface and reduce injury risk during load carriage [26]. However, the increased joint ROM needs greater muscle efforts and energy costs to counter [27], especially when performing repetitive motions like walking and ladder climbing, placing firefighters at an elevated risk for overuse musculoskeletal injuries.

Regarding the effects of SCBA strap length, the loose-fitting strap showed a more pronounced adverse influence on the pelvis, hip, and knee mobility than the medium-fitting strap and the tight-fitting strap. This is evidenced by the significantly increased hip adduction-abduction ROM, decreased L5/S1 rotation ROM, as well as significantly increased shoulder response force and low back contact force. As shown in Fig. 4, when the shoulder strap was loosened, the trunk would be set at a forward inclination condition. Thus, more of the load borne by the back support force and hip-belt tension, especially the lateral force of load may act directly on the rear part of the trunk. Concentrated load pressure at the trunk and pelvis may constrain the legs swinging forward, and thus require greater moments at the lower limb to provide forward driving forces [28]. These findings showed that loose-fitting strap had the highest risk of trunk musculoskeletal injuries and were more likely to modify typical lumbar spine mechanics [29]. On the other hand, a tight-fitting shoulder strap obviously reduced ROM for the shoulders rotation by 13.62% as compared to the no-SCBA condition, demonstrating a restriction of shoulder mobility. As shown in Fig. 4, most of the load is borne by the strap tension when the shoulder strap is tighter, which will be attached to the anterior and superior surfaces of the shoulders. Increased load pressure on the shoulders inevitably caused a restriction on joint movement, which was consistent with the results of [30]. Several subjects also reported that tight-fitting shoulder strap caused evident restriction and pressure on the shoulders, chest, and upper trunk. When wearing a medium-fitting shoulder strap, joint ROM in the shoulders, L5/S1, knee, and ankle joints were most similar to that when not wearing an SCBA, indicating that overall joint movements were similar to the “economical condition.” Subjects also showed a preference for medium-fitting shoulder strap and ranked loose-fitting shoulder strap as the most restricted condition.

4.2 Effect of SCBA Carriage on Muscular Activity

Muscular activity tends to be altered to coordinate the result of force analysis and joint movement, especially for the TR, RF, and TA. Similar to the results of joint ROMs, the AEMG of the TR and TA increased the greatest with SCBA carrying, indicating stronger muscle activations across the trunk. Additionally, it was discovered that the AEMG of RF had strong correlations with shoulder adduction-abduction ROM (correlation coefficients = 0.94), L5/S1 tilt, and rotation ROM ($r =$ 0.99 and 0.98, respectively). Hip flexion-extension ROM and knee adduction-abduction ROM both showed strong correlations with AEMG of RF ($r = 0.99$ and 0.96, respectively). Therefore, it was determined that the majority of the positive mechanical effort during loaded locomotion was performed by thigh muscle activation.

Regarding the effects of SCBA strap length, sEMG at the back showed notable major effects as a result of strap lengths. According to the findings of force analysis, joint ROM, and sEMG, changing the length of the SCBA strap was an effective way to change the joint mobility and muscle activity of firefighters, particularly in the area of the proximal torso during load-carrying activities. Specifically, the AEMG value at the TR in the tight-fitting strap was 26.67% greater than in the loose-fitting strap, which was consistent with the result of limited shoulder mobility in the tight-fitting strap. According to earlier research, tightening the shoulder strap increases interface pressure, which might cause shoulder pain and rucksack palsy [31]. It is possible to interpret this enhanced shoulder muscle contraction as a form of compensation for the limited shoulder rotation to increase the body’s inertia. In general, a decrease in shoulder rotation of 1° was equivalent to an increase in TR muscle contraction of 20.91%. However, increased muscle contraction could exacerbate local muscle fatigue and contribute to the development of repetitive strain injury [32]. Previous studies have reported shoulders discomfort and rucksack palsy due to greater interface pressure when the shoulder strap was tightened [12]. The present study further found that tight-fitting shoulder strap contributed to increased shoulder muscle contraction, which may increase the risk of shoulder muscle fatigue and repetitive strain injury. In the loose-fitting shoulder strap, a considerable drop in MPF value of 12.86% was discovered at the LD, which was a symptom of back muscular exhaustion [33]. It may be due to a more forward pelvis location when a loose-fitting shoulder strap was equipped, which increased the force and torque exerted around the lower back region. Moreover, 58.27% greater AEMG value at the TA and 6.49% lower MPF value at the GM were found in loose-fitting shoulder strap, which indicated higher muscle contraction force and muscle fatigue occurred at the calves. These results may be accompanied with greater lower limb movements, which probably cause overuse injuries at the lower body. The medium-fitting strap, on the other hand, did not cause overuse muscular fatigue or excessive muscle contraction. Combined with the results of joint mobility and muscular activity, a medium-fitting strap length of around 98-105 cm was recommended for firefighters.

4.3 Comparison between habitual shoulder strap length and optimal shoulder strap length

Our previous survey indicated that the adjustment of strap length by firefighters is primarily based on their convenience or habit. The present experiment further observed that body height was a contributing factor influencing firefighters' habit on the adjustment of strap length.

A negative correlation coefficient $r(r = -0.707$, $n = 12$, $p = 0.01)$ was found between the strap length and subjects' body height, indicating the strap length decreased with the increase of body height. For subjects with a height of 172-178 cm, biomechanical measurements suggested that the optimal strap length was around 18-21 cm. However, four subjects adjusted the shoulder strap at the looser condition (average strap length was 11.50±1.31 cm) and these subjects were generally taller than 176 cm. Therefore, the present study speculated that the adjustment of strap length by taller firefighters ($>$ 176 cm) did not conform to the optimal condition. This may due to the additional load placed high on the back elevated taller subjects' already high COM and destabilized their posture to a greater extent [34]. Accordingly, taller subjects tended to locate the load to a lower position by loosening their shoulder strap. Considering the comprehensive results of postural balance, joint mobility and muscular activity, firefighters taller than 176 cm were recommended to adjust the shoulder strap tighter.

5 Conclusion

The effects of SCBA use on firefighters' joint mobility and muscle activity were assessed in the current study. The ideal strap length was also recommended for firefighters. According to the findings of the experiment, the proximal torso's mobility and muscular activity were the ones that responded to SCBA carriage the most, indicating that firefighters should focus their training on the coordinated movement of their trunk muscles and joints. The variation of SCBA strap length was verified as a feasible and convenient strategy to adjust loading at the shoulder, pelvis anterior-posterior, and hip medial-lateral movement. A medium-fitting shoulder strap of approximately 98-105 cm was suggested for firefighters who measure between 172-178 cm in height. Furthermore, body height was identified as a significant factor influencing firefighters' habit on the adjustment of strap length. Firefighters taller than 176 cm were recommended to tighten their shoulder strap.

This study has several limitations that should be taken into account. The present study only measured walking, which may limit the practical use of the findings. Different tasks related to the jobs of firefighters require different physical capacities and levels of muscular strength. Testing more difficult firefighting simulation tasks, such as climbing, rescuing, and filling hoses, will require additional research. Additionally, the sample size was limited, and the subjects' physical attributes were similar. In order to offer more detailed instructions on firefighters' strap adjustment, it will be necessary to recruit additional subjects with a variety of physical features in the future.

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