Kakar et al., *Cogent Engineering* (2018), 5: 1502231
https://doi.org/10.1080/23311916.2018.1502231

cogent engineering

BIOMECHANICS | RESEARCH ARTICLE

Biomechanical and physiological load carrying efficiency of two firefighter harness variations

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Received: 06 February 2018
Accepted: 16 July 2018
First Published: 23 July 2018

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Reviewing editor:
Zhongmin Jin, Xian Jiao Tong University (China) and Leeds University.(UK), China

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Abstract: Firefighters and military personnel employ multiple backpack designs for carrying air tanks along with other heavy gear for occupational purposes. As the load increases, the biomechanical and physiological demands on the carrier change as well. The xPk® harness, a new design, claims to improve the load carriage ability for firefighters by allowing the load to be carried closer to the individual's center of mass (COM) thus reducing the energy cost and increasing comfort level compared with the traditional design. The study compared biomechanical and physiological differences during walking at 1.79m/s (4 mph) at different grades, while carrying a firefighter air tank in traditional harness to xPk® double strap harnesses. There were significant differences in grade kinematics, but differences between old and new harnesses were minor. The minimal differences and subjective preference for xPk® could potentially be helpful in improving load carrying capacity without having to retrain carrying mechanics.

Subjects: Ergonomics & Human Factors; Work Design - Ergonomics; Biomechanics; Exercise Physiology

Keywords: firefighter; harness; SCBA; backpack; gait

Practitioner summary
A new harness design (xPk®) was tested against the tradition design used to carry heavy self-containing breathing apparatus by firefighters. Gait mechanics and physiological responses were compared when participants walked on an inclined treadmill. New harness helped carry load closer to body's COM and decrease vertical displacement of the load. Participants reported subjective preference to use the xPk® harness system but minimal other biomechanical and physiological differences were observed.

ABOUT THE AUTHORS

The authors are interested in sport injuries, ergonomics, and injury risk factors. Research areas of the authors are varied with topics ranging from biomechanics of movement skills related to spine and lower extremity injury, impact forces, and loading of the lower extremity in ergonomics sport and physical activities. The research work in this paper addresses human factors and injury risks for firefighters while carrying heavy SCBA. Specifically, we are interested in how the carrying mechanics and physiology of the individuals change with a new harness system designed to carry the SCBA air tanks for firefighters.

PUBLIC INTEREST STATEMENT

Firefighters regularly carry heavy air tanks and other protective equipment in their work environment. These heavy loads can have detrimental effects in work demands, mobility and can lead to injuries. Redesigning the harness system that can potentially increase carrying comfort of the tanks and equipment can be an effective measure to help reduce injury risk in the firefighter population.

1. Introduction

Firefighters and other professionals encounter harsh environments requiring personal protective clothing (PPC) and self-contained breathing apparatus (SCBA) to protect themselves while completing physically demanding tasks. PPC and SCBA reduce mobility and increase physiological burden (Barr, Gregson, & Reilly, 2010; Coca et al., 2008; Coca, Williams, Roberge, & Powell, 2010; Dorman & Havenith, 2009; Havenith & Heus, 2004; Holmér & Gavhed, 2007; Huck, 1991). Modifications in the traditional PPC and SCBA designs may provide effective solutions in balancing the need for protection, comfort, and function. In particular, the weight of the PPC and SCBA and load location of the SCBA have detrimental effects in work demands, mobility, and comfort (Bakri et al., 2012; Coca, Kim, Duffy, & Williams, 2011; Dreger, Jones, & Petersen, 2006; Duggan, 1988; Griefahn, Künemund, & Bröde, 2003; Hooper, Crawford, & Thomas, 2001). Lighter and redesigned SCBAs improve mobility, comfort, and function (Bakri et al., 2012; Coca et al., 2011; Griefahn et al., 2003; Hooper et al., 2001).

Reducing weight of a traditional cylinder-shaped SCBA has been shown to have a significant effect on physiological response and comfort (Hooper et al., 2001). However, no differences in heart rates (HRs) in a firefighting exercise were reported by firefighters wearing, light, or heavy SCBAs as HRs plateaued 90 to 100% of maximum during the exercise regardless of SCBA weight (Manning & Griggs, 1983). SCBA design, however, can have a greater influence on physiological demand and comfort than reducing weight alone (Griefahn et al., 2003). A rucksack designed SCBA with weight positioned close to body center of mass (COM) resulted in lower HRs and more positively rated carrying features as compared with a standard and light cylinder (Griefahn et al., 2003). Similarly, a lightweight low profile SCBA designed with blow molded linings and a kevlar-coating increased range of motion, comfort, and delayed fatigue during firefighter field exercises (Coca et al., 2011)

These novel SCBA systems that improved mobility, function, and work capabilities required not just a new harness, but redesigned SCBA tanks (Coca et al., 2011; Griefahn et al., 2003). Utilizing re-designed shoulder and hip straps and a lightweight SCBA, metabolic rates were reduced over a standard weight and traditional harness SCBA (Bakri et al., 2012). Subjectively less muscle fatigue and lower thermal discomfort scores were also reported with the redesigned harness versus both a standard weight and lightweight tank in a traditional harness (Bakri et al., 2012). The harness used by Bakri (2012) did not change load position, but strap comfort and design. Harness design is important for function as well as comfort, mobility, and physiological work. Approximately, one quarter of surveyed firefighters reported problems with harness, material, strap tangling, and 15% with back plate design (Love et al., 1994). SCBA systems with weight positioned close to the body's COM had fewer problems (Love et al., 1994). Additionally, SCBA systems can be more detrimental to mobility than PPC (Huck, 1991). Thus, in addition to advantages to lightweight and redesigned SCBA, improvements in SCBA harness design and SCBA firefighter interface systems are clearly important in effecting physiological strain, mobility, function, and comfort in firefighters.

A new harness that can be used with a traditional SCBA cylindrical tank is the xPk® harness. The xPk® has a metal frame with shoulder straps and a waist belt. The xPk® harness is designed to improve the load carriage ability for firefighters as they carry heavy air tank and gear (Demskey, 2016). It has been proposed that xPk® pack design helps position the load closer to the body's COM thus reducing the energy cost of load-carriage (Demskey, 2016). The design also claims to assist in carrying heavier loads such that it does not pull on the shoulders and thus increasing the comfort level compared with the traditional SCBA harness commonly used by firefighters. The purpose of the study was to compare biomechanical and physiological differences as demonstrated by individuals while carrying a cylindrical SCBA air tank in traditional harness to when carried in xPk® double strap backpack harness design.

2. Materials and methods

In total, 12 healthy active adults *(age: 26.5 ± 5.8 years, height: 1.74 m ± 0.9 m: weight: 79.4 ± 15.9 Kg)* gave their written informed consent (IRB# 0316–08) and volunteered to participate in the study. A-priori power analysis was performed, and sample size of 12 was found to be adequate to detect a group difference (70% power) with an effect size of approximately 0.8 (alpha = 0.05) (Park et al., 2015). Age group was selected to represent young healthy potential firefighter recruits.

Test Task: Participants walked for 1-minute warm up at 0% grade for warm-up. Following warm-up, each participant completed two 10-minute 1.79 m/s (4 mph) walking trials on a PreCor treadmill (model C954, Woodinville, WA). Each 10-minute trial consisted of walking at three grades: 2 min at 5%, 4 min at 7.5%, and 4 min at 10%. During each trial, the participant wore one of the two harness systems (traditional: Mine Safety Appliances: 2.5 kg and xPk®: 3 kg) with the air tank (Mine Safety Appliances Stealth H30: 3.4 kg) (Figure 1). Harness order was counterbalanced. Participants wore Lycra spandex shorts, a sports bra or no shirt, and comfortable walking/running shoes.

2.1. Biomechanical testing

Kinematic and stride data were recorded with a six camera (200 Hz, Mx3+) Vicon® 3D motion capture system and Vicon® Nexus 2.6 (Vicon, Centennial, CO) using reflective markers. Totally, 53 markers (Figure 2) were placed on specific anatomical landmarks for a standing calibration with two additional markers on the air tank. Nine markers, both PSIS's and six medial lower leg markers, were removed for the walking trials. 3D motion data were recorded at the end of each grade condition for 10 s to capture 10–15 strides for both left and right.

The 3D data were analyzed in Visual3D (C-Motion, Germantown, MD). Marker positional data were low-pass filtered using a fourth-order Butterworth filter with a 6Hz cut-off frequency and used to create a seven segment plus tank model. Heel strike and Toe-off were determined using automatic gait events (Visual 3D). From the model, stride length width and stride rate were

Figure 1. 1a (top: left and right). Traditional harness with padded shoulder straps and plastic frame attaching to tank clamp, and 1b (bottom: left and right). xPk® harness with aluminum frame with shoulder straps and padded back supports.

Figure 2. Marker set comprising of 53 reflective markers used for the biomechanical analysis.

calculated along with ankle dorsiflexion/plantar flexion range of motion (ROM), knee flexion ROM, hip flexion ROM, pelvic tilt, pelvic obliquity ROM, anterior trunk tilt, and trunk lateral tilt ROM. The position and movement of the COM of the tank plus harness system were calculated relative to the mid-iliac crests along the anterior and longitudinal axes. Kinematic and stride variables were averaged across stride and leg for each participant prior to statistical analysis.

2.2. Physiological testing

Metabolic data were collected through a metabolic measurement system (ParvoMedics TrueOne 2400, Sandy, UT). Prior to each testing session, ParvoMedics Metabolic Measuring System was calibrated. A HR monitor (Polar Electro Inc., Lake Success, NY) was also secured around the participant's chest. Participants breathed through a mouthpiece connected to a two-way non-rebreathing valve and a nose clip was placed on the participant's nose. Physiological data were measured during the entire trial. Expired gases were measured breath-by-breath (Hans Rudolph Inc., series 5530 3-L, Kansas City, MO), and values were averaged every 15 s. HR and Rate of Perceived Exertions (RPE: Borg 6–20 scale) were recorded every 30 s for the three grades. Average HR, RPE, VO_2, and respiratory exchange ratio (RER) measurements were calculated for each grade. Following each condition, participants were asked to report their subjective preference for harness via a seven-point scale where 1 is minimal discomfort and 7 is extremely discomfort for walking while carrying the air tank. (Bakri et al., 2012)

2.3. Statistical analysis

Two-way repeated measures ANOVAs (Alpha = 0.05) were calculated to determine statistically significant difference for grade and backpack for all biomechanical and physiological variables. When interactions were significant, post-hoc *t*-tests were performed. Sphericity was assessed using Mauchly's test of sphericity, and Greenhouse–Geisser corrections were used for if data were in violations of sphericity using IBM SPSS 25. Bonferroni corrections were performed to take into account for family-wise errors. Effect sizes were also calculated for the comparisons (Cohen, 1988).

3. Results

3.1. Tank COM position

Tank harness COM position was 2 cm more posterior (p = .042) and 4 cm lower (p < .001) in the xPk® harness, and moved 5 cm less (p = .016) along the long axis as measured relative to the iliac crests during the walking trials (Figure 3). The corresponding effect sizes for these variables were large (ES = 0.72, 1.25, and 0.91, respectively). Tank COM anterior position was 2 cm farther back,

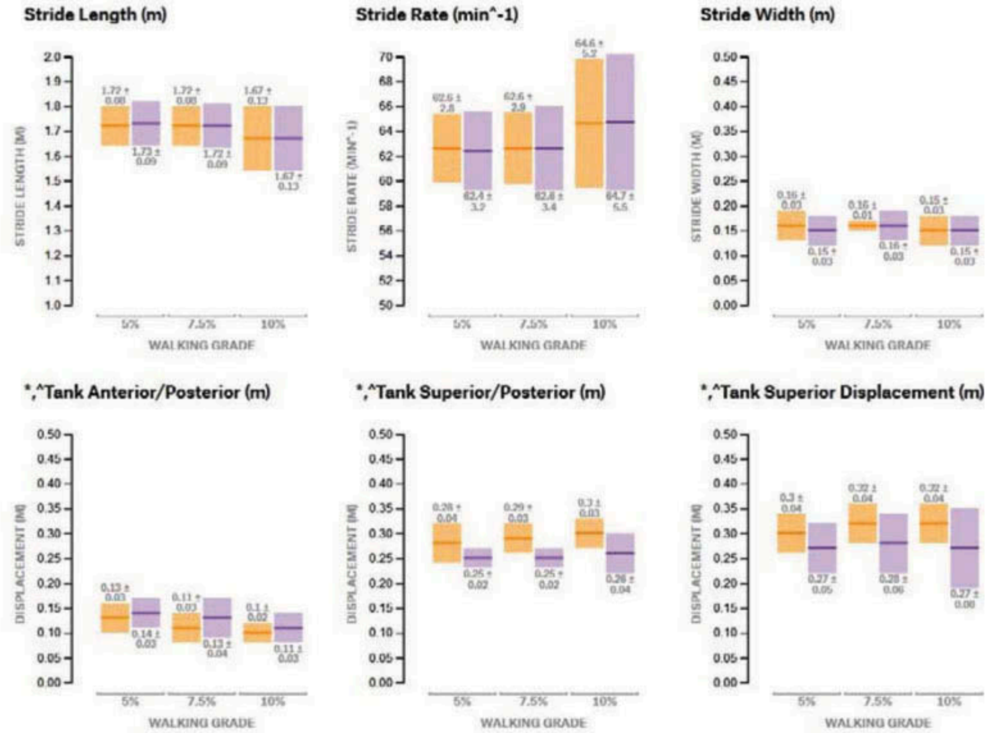


Figure 3. Gait spatial/temporal variables and Tank COM displacements across the three grades with the traditional and new xPk® Harness. Values are mean ± SD.

relative to the iliac crests, on the 5% grade as compared with the 7.5% grade (p = .004) and 1 cm farther back on the 7.5% grade as compared with the 10% grade (p = < .001) with moderate (ES = .54) and small (ES = .28) effect sizes (Figure 3).

3.2. Kinematics

Statistically significant differences in angular kinematic variables were mainly observed for grade effect and only some differences between the traditional and xPk® harnesses (Figure 4). Ankle dorsiflexion/plantar flexion ROM had a significant interaction (F(2,22) = 11.624, p < .001). *Post hoc* analysis revealed 1.2° greater ankle ROM with the xPk® harness as compared with the traditional harness at the 5% grade with a moderate effects size (ES = .34). Hip flexion ROM increased 3.5° from the 5% grade to 7.5% grade and 2.5 from 7.5% to 10% grade (p = .009) with large (ES = 1.29) and moderate (ES = 0.42) effect sizes, respectively. Anterior trunk tilt increased 3.3° from the 5% grade to 7.5% grade and 2.9° from 7.5% to 10% grade (p < .001) with large effect sizes (ES = .84 and .85, respectively). Pelvic anterior tilt increased 2° both from the 5% grade to 7.5% grade and from 7.5% to 10% grade (p = .003) with moderate effect sizes (ES = .49 and .48, respectively). No differences were observed in the spatial–temporal variables of gait (Figure 3).

3.3. Physiological

All four physiological variables had statistically significant increases (p < 0.001) from the 5% to 7.5% to 10% grade (Figure 5). RPE had a significant interaction ($F_{2,18}$ = 14.646, p < .001) and harness main effect ($F_{1,9}$ = 11.287, p = .008). *Post hoc* analysis revealed that RPE was statistically higher (2.1) with the xPk® harness as compared with the traditional harness on the 10% grade only (P = .003). No other differences were observed between harnesses for the physiological variables. Sixty percent of the participants preferred walking with the xPk® design compared with the traditional harness design suggesting greater comfort.

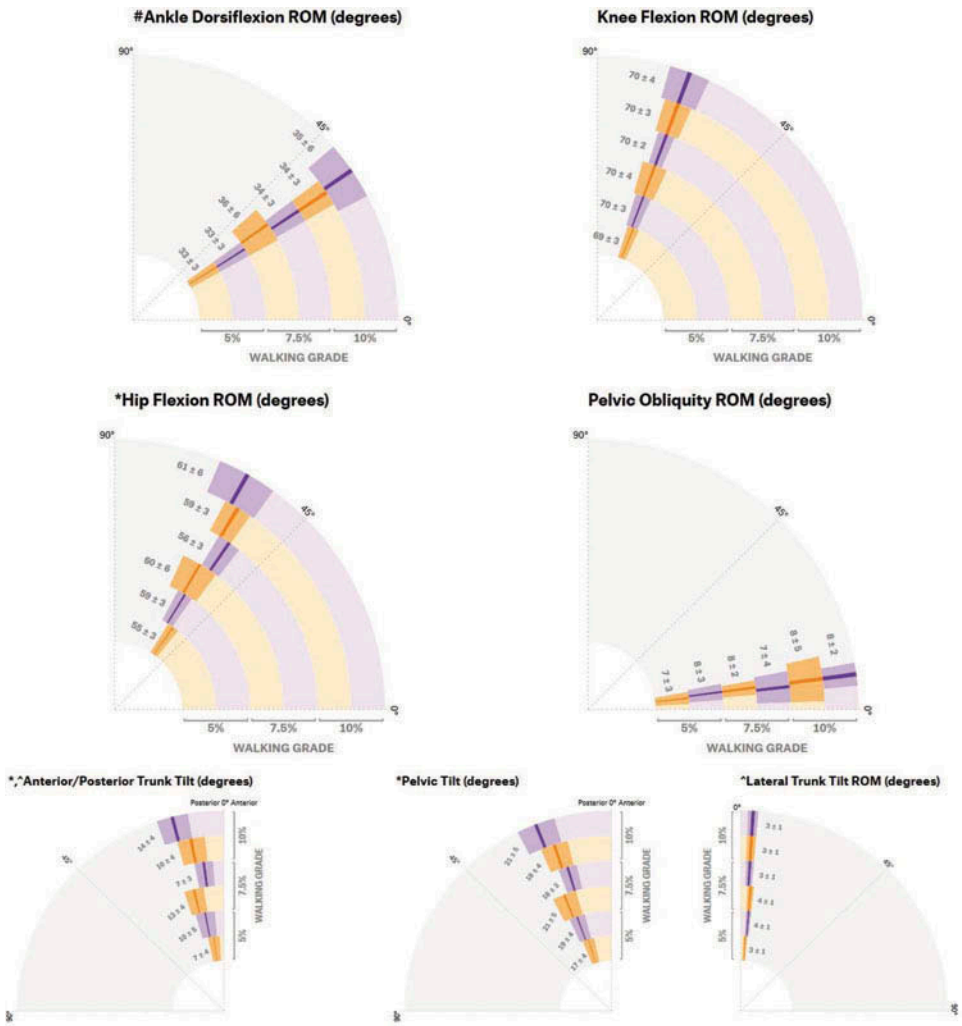


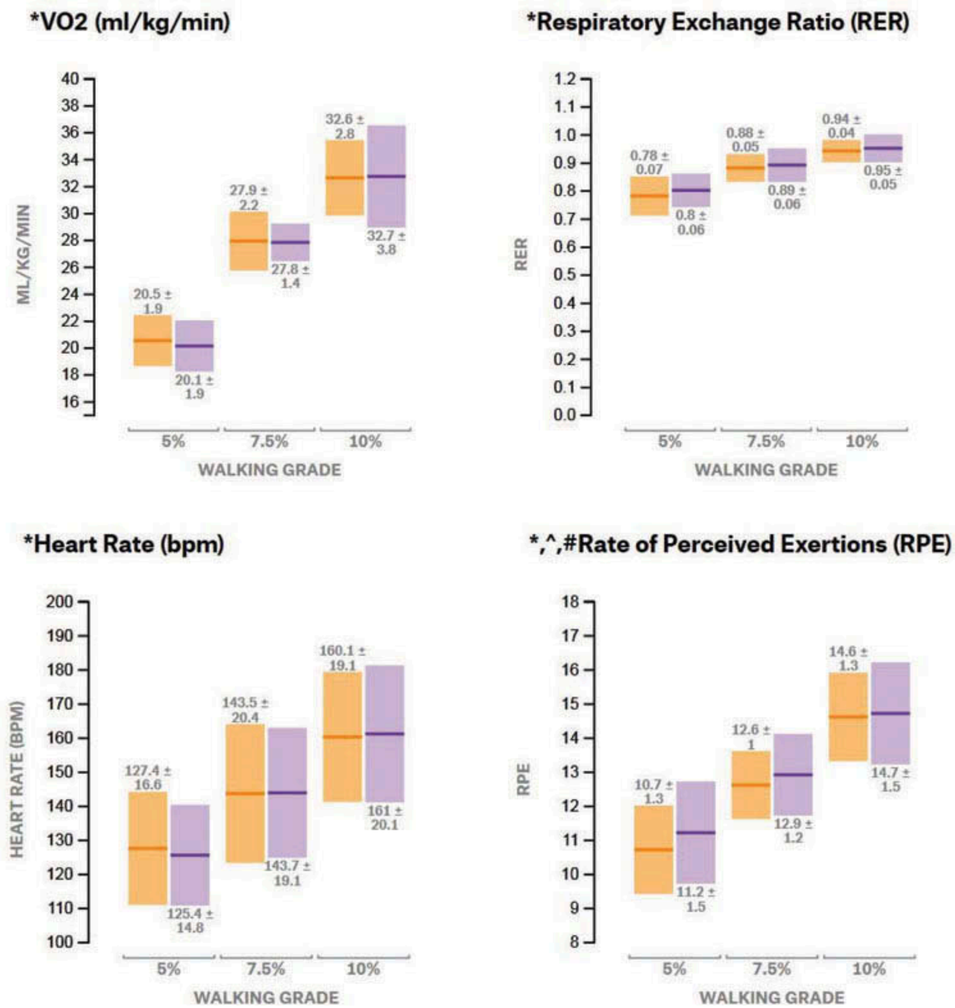
Figure 4. Kinematic variables across the three grades with the traditional and new xPk® Harness. Values are mean ± SD.

4. Discussion

The xPk® harness was designed to position the load closer to the body's COM reducing the cost of carriage while using the xPk® as compared to a traditional harness (Demskey, 2016). Results from this study suggest that when walking while carrying an air tank, the xPk® and tank COM are positioned lower, closer to the iliac crests of the user and slightly more posterior. Vertical displacement of the tank was also decreased in xPk® harness compared with the traditional design. The lower load position with the xPk® harness accompanied by less superior inferior displacement of the xPk® and tank system relative to the iliac crests may have attributed to more participants preferring to carry the SCBA tank in the xPk® harness system. Despite the preference for the xPk®, higher RPE's were reported with the xPk® on the steepest 10% grade. The increased perception in effort could have been related to the slightly more posterior positioning of the xPk® and tank COM relative to the iliac crests, which could create a larger extension torque on the back due to an increased moment arm to the load. Moreover, there were no differences in VO_2, HR, or RER between the harnesses on any of the grades.

To the author's knowledge, only two previous studies have examined positioning the SCBA tank harness system closer to the body COM (Coca et al., 2011; Griefahn et al., 2003). Both of these studies used redesigned SCBA that do not rely on the traditional cylindrical tank. Neither study reported the change in tank COM location relative to the body COM; although, both tanks had positive results in

Figure 5. Physiological variables across the three grades with the traditional and new xPk® Harness. Values are mean ± SD.



physiological, comfort, mobility, or performance variables. In the current study, as measured along the resultant, the tank harness COM was on average 4.5 cm lower and posterior with the xPk® harness. Lower loads have smaller moments, reduce muscle activity, and are more stable (Bobet & Norman, 1984; Hellebrandt, Fries, Larsen, & Kelso, 1944). The physiological effect of lower COM loads is less clear with studies showing no effect, increases metabolic cost with lower loads (Abe, Muraki, & Yasukouchi, 2008), and decreased metabolic cost with lower loads (Johnson, Pelot, Doan, & Stevenson, 2001; Liu, 2007; Obusek, Harman, Frykman, Palmer, & Bills, 1997). The majority of research on vertical load positioning has moved the load from high on the back/shoulders to the mid or low back without providing measures of COM load position (Abe et al., 2008; Bobet & Norman, 1984; Devroey, Jonkers, De Becker, Lenaerts, & Spaepen, 2007; Gregorczyk et al., 2010; Johnson et al., 2001; Liu, 2007; Obusek et al., 1997; Singh & Koh, 2009). It is unlikely that the 4 cm difference in vertical load position between the two harnesses in this study would have a meaningful effect physiological or performance effect due to the similarity in gait kinematics and economy between the two harnesses. Marginal differences in load positioning, using a compartmentalized backpack versus standard backpack had no measurable effect on metabolic or biomechanical parameters in walking conditions; though the exact difference in load position in the two packs were not reported (Wood & Orloff, 2007). In the current study, the two harnesses were only compared in inclined walking. Investigating the harness systems during maneuvers that may better simulate firefighting such as crawling, stooping, duck walking, and climbing is needed to determine whether difference in load positioning would alter performance in these scenarios.

Numerous studies support redistributing the load around the trunk, using front backpack systems, circumferential systems, and side-to-side systems due to improved walking economy, fewer kinematic perturbations, or increased comfort (Birrell & Haslam, 2010; Dahl, Wang, Popp, & Dickin, 2016; Datta & Ramanathan, 1971; Fiolkowski, Horodyski, Bishop, Williams, & Stylianou, 2006; Harman et al., 2000; Lloyd & Cooke, 2011, 2000a, 2000b). However, redistributing the SCBA from a traditional back position to a position distributed around the trunk may not be practical or safe for firefighters. Firefighters must maneuver around obstacles, crawl through small places, and have good mobility for optimal task performance. SCBA systems designed to have minimal depth, such as the low profile SCBA (Coca et al., 2011) may offer advantages due to not only the tank and harness COM position but also mobility and maneuverability through tight spaces. For firefighters using traditional SCBA cylinders, though, harness design aimed at improving tank and harness position and movement as well as carrying comfort is likely the most feasible solution for optimizing performance and safety.

In addition to repositioning load COM, harness design can have a direct effect on comfort. Using a cylindrical SCBA tank, wider shoulder straps and a wide cushioned hip strap, firefighters reported less muscle fatigue and thermal discomfort compared with a traditional harness (Bakri et al., 2012). Harness designs, including backpacks with stiff frames, lateral stiffness rods, and waist belts to transfer load to the pelvis are more comfortable and reduce back muscle activity (Holewijn, 1990; Lafiandra & Harman, 2004; Reid, Stevenson, & Whiteside, 2004; Southard & Mirka, 2007; Stevenson, 1995; Stevenson et al., 2004). Backpack strap stiffness also affect comfort with stiffer straps reducing trunk flexion and improving comfort in the neck, shoulder and low back muscles (Mallakzadeh, Javidi, Azimi, & Monshizadeh, 2016). Strap length effects comfort when walking with a backpack with shorter straps reducing pain and neck angle (Abdelraouf, Hamada, Selim, Shendy, & Zakaria, 2016). The decrease in vertical displacement of the tank is likely related to greater harness stiffness also and has been shown to be related to lower peak pressures at shoulder region but greater forces at hip (Stevenson, 1995; Stevenson et al., 2004).

Both harnesses in the current study have two shoulder straps and a waist belt; however, the xPk® harness has a metal frame which may increase stiffness which could account for the increased preference for xPk® similar to using non-flexible straps (Mallakzadeh et al., 2016) or stiff rods (Reid et al., 2004). Further investigation would be needed to determine whether the straps themselves and/or metal tank carrying frame are more influential in both the positioning and movement of the air tank on the wearer and in the improvement in perceived comfort. However, advanced harness designs off-loading the shoulders, are less effective in non-neutral postures (Southard & Mirka, 2007). Considering that firefighter duties involve crawling, stooping, and maneuvering over obstacles, further research is warranted on harness and strap stiffness and length on energy expenditure as well as mobility, performance, and comfort in standard firefighter duties.

In the current study, participant height varied greatly, though all participants were fit and capable of completing 4 mph walk on an increasing incline. Harness preference was not related to height; however, it would be important to determine whether harness preference or performance is related to participant size and fitness. Longer straps have been related to upper trapezius pain and increased forward head position (Abdelraouf et al., 2016). Thus, a harness system with straps that adjust to position the load appropriately for each firefighter will be important for comfort as energy expenditure and performance. With preference for the xPk® by 7 out of 12 of the participants, gathering data on a larger more varied sample is required to confidently conclude that more people prefer walking up hill using the xPk® harness.

The authors acknowledge limitations of the current study. Study neither examined physiological demands during firefighter exercises nor evaluated performance. Moreover, the harness and SCBA tank were worn over shorts and *t*-shirts not PPC. It would be important to measure the two extremes heaviest with a full tank and lightest with an empty tank as the weight being carried could affect harness performance. This study measured the xPk® in its' lightest configuration.

However, due to positive results in repositioning the tank and harness load and greater preference reported by the majority of participants, further research on the xPk® in full turn out gear during simulated firefighter duties or actual firefighter drills with a full tank and extra weight from bulky turnout gear, hoses, bunker gear, and other tools is warranted.

5. Conclusions

In conclusion, the xPk® did position the load COM more toward the iliac crests and reduced vertical motion, while walking uphill. For young athletic adults, the xPk® performed equally to the traditional harness across grades, despite a slightly more posterior positioning and was preferred by 60% of participants. While there were some significant and meaningful differences in grade kinematics, changes in kinematic and physiological data between old and new harnesses were minor and unlikely to provide meaningful differences within a clinical setting. Young adults may prefer the xPk® due to comfort reasons without having to retrain carrying mechanics or impose any different physiological strains.

Acknowledgement
Authors would like to thank the undergraduate research assistants Beatrice Jin for data visualization, Alexa Chandler, Andrew Ward, Zachary Finer, Natalie Knight, Victoria Vorhees, Daniel Drill, Adam Fong, and Ravjot Singh for assistance with data collection, Joan Dempsey for the xPk® harness and Ithaca Firefighter department for supplying with the traditional harness and air tank used in the study.

Funding
This work was supported by the Cornell Center for Materials Research, Cornell University [Jumpstart Program 2016];

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Conflict of Interest
The study was supported by a grant from Cornell University, Cornell Center for Materials Research (CCMR), Jumpstart Program 2016. No other conflicts of interests exist for the authors.

Citation information
Cite this article as: Biomechanical and physiological load carrying efficiency of two firefighter harness variations, Rumit Singh Kakar, Joshua M Tome & Deborah L. King, *Cogent Engineering* (2018), 5: 1502231.

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