Future Design Challenges for the Firefighter Turnout Boots

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Background. In 2018, 22,975 firefighter injuries resulted from fire ground operations in United States, and 38% of fire ground injuries involved strain, sprain, or muscular pain injuries (Campbell et al., 2019). Wearing turnout boots has been reported as a primarily negative cause to impact firefighter's safety and health. Specifically, the poor design of the turnout boots would expose firefighters at the potential risk of fall (loss of body balance), muscular injuries, and lumbar injuries (Taylor et al., 2015; Vu et al., 2017).

The turnout boots or bunkers, as one of the common personal protective equipment (PPE) for the firefighters, is designed to afford protection to the foot and lower leg from heat, liquids, and falling objects, and is typically worn for urban firefighting (Smith et al., 2008; Sokolowski et al., 2018). Also, some of the functional requirements for firefighter protection include providing stability to the foot, making the wearer's feet feel fit and comfortable, and the material should be durable. Moreover, there are twelve properties that have been listed as important elements for boots' design as shown in Figure 1. The two materials normally used in turnout boots production are leather and rubber, which have different flex resistances, and most of the toe caps are made of steel or composite (Park & Hahn, 2014).

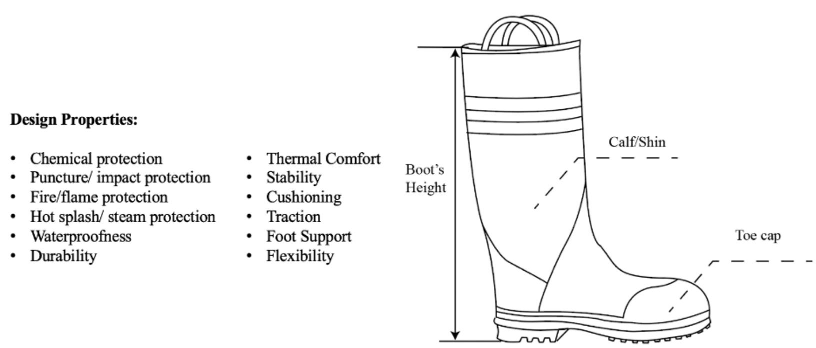

Figure 1. Firefighter boots' structure and design properties (adapted from Sokolowski et al., 2018; Park et al., 2014)

Given the rapid advances in material and manufacturing technologies, the functional design of firefighter boots will keep improving. The purpose of this systematic review of the literature was to highlight a design direction for future prototypes, by summarizing the findings of most current studies focused on the firefighter's turnout boots evaluation.

Method and Results. The literature review sampling was based on constrained snowball sampling method, using various journals across disciplines, and was initiated by Google scholar searches of key words "firefighter boots design" (Lecy & Beatty, 2012). The initial search resulted in 10 high-quality articles related to the evaluation of firefighter turnout boots. Seven out of the ten studies conducted human participant tests on healthy firefighters. Table 1 summarizes the different independent variables including material, weight, sole flexibility, height, and fit being tested in the settings of the experiments.

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Table 1. Characteristics of the included human participant testing studies.

Year	First Author	Subjects (firefighters)	Independent Variables (Related to boot design)	Dependent Variables
2009	Huang	12 males	Material (leather/ rubber)	Physiological effects
2009	Park	11 males & 3 females	Size, height	Range of motion
2010	Turner	25 males & 25 females	Material (leather/ rubber)	Physiological effects
2012	Chiou	14 males & 13 females	Boots weight, sole flexibility	Physiological effects
2015	Park	8 males & 4 females	Material (leather/ rubber)	Gait related characteristic
2017	Vu	20 males	Control/Firefighter boots	Lumbar biomechanics
2018	Park	11 males & 3 females	Boot height	Range of motion

Regarding how different materials of the turnout boots may affect the performance of firefighters, three research teams were found to hold different opinions. Turner et al. (2010) reported that there is no significant effect on metabolic and respiratory characteristics due to the boots' material (leather or rubber). However, based on the physiological effects and gait-related characteristics, Huang et al. (2009) and Park et al. (2015) believed that *rubber boots are more effective than leather boots*. *Reducing boot weight and increasing flexibility* are critical for the turnout boots design which has a good influence on the lower extremity movement, gait patterns and physiological stresses of firefighter (Chiou et al., 2012; Park et al., 2019).

Based on safety concerns, the National Fire Protection Association (NFPA) standard for the height of firefighter boots was set to minimum 25 cm (Park et al., 2018). Two studies found that the comparing to the lower boots (25.4 cm), higher boots (35.56 cm) height would cause a different level of restriction in firefighter's performance based on the limit of the range of motion (Park et al., 2018; Park et al., 2019). Vu et al. (2017) found that when firefighters operate loading, comparing to wearing sport shoes, wearing turnout boots may lead the firefighter to a high risk of lumbar injuries. Two research groups have collected 203 online survey responses from firefighters to understand the performance of turnout boots based on users' feedback (Sokolowski et al., 2018; Park et al., 2014). The survey results collected from the users are holding the same opinion with the experiment result that size/fit and material selection are essential for the development of the next generation of the turnout boots.

Future direction. The findings of this review show that the current design of the firefighter turnout boots could achieve functional needs, but it is uncomfortable to wear and may cause safety and health issues. The future designs must better integrate the users' needs, human factors, and ergonomic concerns (Spratford et al., 2016; Park et al., 2019). Out of the twelve design components highlighted in Figure 1, only cushioning, traction qualify, structural foot support, stability and flexibility have been considered in the human participant studies. The future firefighter turnout boots designs should also consider the rest of the variables, such as: (a) functional need (level of protection), (b) waterproofness, (c) durability, and (d) thermal comfort. Also, a research gap was identified on how different current designs of the turnout boots influence the firefighter's performance. Future studies should consider firefighter performance along with additional design features, such as the structure of the boots, and different kind of sole types (Spratford et al., 2016; Turner et al., 2010).

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