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Effects of an improved biomechanical backpack strap design on load transfer to the shoulder soft tissues

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ABSTRACT

The aim of the present study was to characterize shoulder strap structure and mechanical properties that may alleviate strains and stresses in the soft tissues of the shoulder. Utilizing a finite element model of the shoulder constructed from a single subject, we have quantified skin stresses exerted by backpack straps and the strains at the subclavian artery (SCA). For this end, standard shape straps with stiffness of 0.5, 1.2, and 5 MPa, were compared to the effects of optimized straps; a double-layered (soft outer layer and reinforced internal supporting layer) and newly-designed anatomically-shaped strap. Compared to the standard 0.5 MPa strap, the 5 MPa strap resulted in 4-times lower SCA strains and 2-times lower Trapezius stresses. The double-layered strap resulted in 40% and 50% reduction in SCA strains and skin stresses, respectively, with respect to the softer strap. The newly-designed anatomical strap exerted 4-times lower SCA strains and 50% lower skin stresses compared to the standard strap. This demonstrates a substantial improvement to the load carriage ergonomics when using a composite anatomical strap.

1. Introduction

From childhood through adulthood, people use backpacks in their daily routine. For children, a backpack weight equalling 10–15% of their own body weight is the recommended limit (Brackley, 2004), which frequently is exceeded (Negrini, 2002; Negrini et al., 1999; Negrini et al., 2004; Sheir-Neiss et al., 2003). For combat soldiers, loads can reach approximately 100% of their own bodyweight (Dean, 2004; Knapik and Reynolds, 2016). While carrying a backpack, the shoulders were found to be the region with the highest ratings of pain and discomfort, and shoulder discomfort was rated as the most limiting factor for failing to complete a load carriage task (Birrell and Hooper, 2007; Holewijn, 1990; Wettenschwiler et al., 2015).

Mao et al. (2015) have recently found that backpack loads as low as 5 kg decrease shoulder muscle oxygenation and skin microvascular flow, which become more significant with 10 kg load (Mao et al., 2015). This has been corroborated by our group in a series of studies, which revealed that the deep tissues below the shoulder strap are significantly deformed in a way that can hamper the neural and hemodynamic performances (Hadid et al., 2015; Hadid et al., 2012). Furthermore, in healthy adults carrying a backpack for short duration of 10 to 45 min, there was a significant decrease in upper extremity sensation, as well as reduced macrovascular and microvascular hemodynamic values. These effects were observed across the board, regardless of different body dimensions and geometries (Hadid et al., 2017; Kim et al., 2014). In more severe cases, paralysis of the upper limb may occur (Bessen et al., 1987; Birrell and Hooper, 2007; Daube, 1969; De Luigi et al., 2008; Dillin et al., 1985; Knapik and Reynolds, 2016; Makela et al., 2006; Wilson, 1987).

Realizing that most of the loads are still borne by the shoulders (Lafiandra and Harman, 2004; Reid et al., 2004), efforts are being made to alleviate the adverse effects of load carriage, particularly by improving the weight distribution over the body. Mackie et al. (2005) recommended the use of hip-belts and shoulder strap adjustments, as these may have significant effects on the demands

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placed on backpack users. For heavy backpack loads, Martin and Hooper (2000) demonstrated a reduction in skin pressure hotspots by utilizing different mesh materials for the strap. They also suggested that the use of a plastic insert could improve the skin pressure distribution by increasing the strap-body contact area. However, no bioengineering analyses or quantitative data were provided regarding the different materials that were compared.

Although many studies have been published over the last few decades on the adverse effects associated with load carriage and the advances already made in load carriage systems, the loss of upper-limb sensorimotor functions still remains a common phenomenon experienced mainly by soldiers and backpackers who carry heavy loads for extended periods. With the understanding that the straps are still a weak point in the backpack ergonomic design, the aim of the present study was to quantitatively characterize the effects that shoulder strap structures and mechanical properties have on strains and stresses in the soft tissues of the shoulder. Such understanding facilitates optimization of the load carriage system as a whole, and the strap design specifically, for minimizing exposure to sustained tissue strains and stresses.

2. Methods

2.1. General

Experimental and computational methods were applied consecutively. The initial steps included characterization of the relevant mechanical properties of the backpack straps and their components. The data obtained were then used to develop a computational analysis, comparing the effects of different strap structures and material properties on soft tissue strains and stresses in the shoulder area. Finally, the effect of a novel, anatomically-shaped strap design on the strains and stresses in the soft tissues of the shoulder was computationally evaluated.

All mechanical tests were performed using an electromechanical materials testing machine (Instron 5544, High Wycombe, UK). By converting the outputs of load and extension into stress-strain curves using Matlab (version R2010a, MathWorks^{TM}, MA, US), the elastic moduli of the strap as an intact unit and each of its components were calculated as described below.

2.2. Compression testing of intact straps

The straps of six backpacks, three commercial backpacks and three military backpacks, all designed for heavy load carriage, were evaluated (Table 1). A compression test was performed using a circular compression plate (46 mm diameter) and a 2 kN load cell. The straps were compressed at an extension rate of 250 mm/min in accordance with ASTM D3574-11 protocol. Since the tested materials behave non-linearly, a Matlab algorithm was used to detect the first phase before the “knee” is observed, which effectively limited the strain to 25% compressive strain. The average modulus for this phase of the test was reported as the compressive modulus.

2.3. Characterization of the mechanical properties of the strap components

The range of the mechanical properties of materials used for manufacturing the backpack straps were evaluated (Table 2). Open cell foam, closed cell foam, and airmesh, constructing the inner cushioning parts of the straps, were tested utilizing compressive tests, as described above. Then, two Cordura textiles and airmesh materials were chosen as representatives of the outer strap layers. Their tensile properties were evaluated in accordance with ASTM D5034 protocol, using a 2 kN load cell and sample fixation clamps. Two different specimens of each material were stretched at a constant pace of 300 mm/min until a rupture has occurred. The modulus was detected as described above.

Table 1
The compressive modulus of the tested backpacks straps (Average ± SD).

Backpack	Type and manufacturer	Compressive modulus (MPa)
A	Gregory Baltoro, 75 L (Gregory Mountain Products, UT, US)	0.22 ± 0.03
B	NICE frame, supporting up to 107 L backpacks, (Mystery Ranch Backpacks, MT, US)	0.13 ± 0.01
C	Gregory Palisade, 80 L (Gregory Mountain Products, UT, US)	0.21 ± 0.01
D	Military backpack prototype, 90 L (Lior Textile, IL)	0.10 ± 0.01
E	Second military backpack prototype, 90 L, (Lior Textile, IL)	0.25 ± 0.01
F	Standard IDF Backpack design 90 L (Hagor, IL)	0.53 ± 0.05

2.4. Computational analysis

A finite element (FE) computational model that was developed and experimentally verified by Hadid et al. (2015) was used to calculate the soft tissue stresses and strains exerted by the backpack straps. In short, Open-MRI was used for developing and verifying a three-dimensional, non-linear, large-deformation, FE model of the shoulder. The model included the shoulder strap of a current military backpack, the skin, fat, muscles, bones, and subclavian artery of a single patient. The mesh was comprised of ~900,000 tetrahedral elements (Fig. 1). Each simulated strap was gradually pulled from both ends to reach a desirable reaction force (i.e. strap tension), and these forces were translated into loads applied on the straps, using linear regression fit between shoulder strap tension and backpack mass (Hadid et al., 2015). Incorporating into the model several strap mechanical properties and 3D structures, the discrete and combined effects of the strap materials on the stresses and strains in the regions of interests (ROIs) of the soft tissues of the shoulder were assessed. For the computational steps the models were exported to the Preview module of the FE software FEBio (version 1.17) for assigning material properties, boundary and loading conditions, and the model was then exported to FEBio solver version 2.3 for analyses. Results were analysed using PostView version 1.9 (Both Preview, FEBio, and PostView were provided by Musculoskeletal Research Laboratory, University of Utah). The runtime of each model variant was 5–40 h using a 64-bit Windows 7-based workstation with Intel Core i7-5820K 3.30 GHz CPU, and 32 GB of RAM.

2.5. Optimizing the mechanical properties of the strap

Various strap properties of an isotropic, 15 mm thick strap construction were assigned to the original model described by Hadid et al. (2015). The clavicle and the trapezius ROIs where the high-pressure hot spots were noted were examined for effective stresses on the skin under the shoulder strap. In addition, an ROI in the subclavian artery (Fig. 1c), which provides an indication of the strains that develop on the brachial plexus (Hadid et al., 2012), was analysed for total effective Lagrange strains.

The model relies on neo-Hookean constitutive law, with a single elastic modulus as opposed to the compressive or tensile moduli that were measured experimentally (Hadid et al., 2015; 2012). The assigned elastic modulus value is the effective modulus, representing the contribution of both the compressive and tensile stiffness components. Therefore, the effective moduli of the strap

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