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The effect of mechanical strains in soft tissues of the shoulder during load carriage

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ABSTRACT

Soldiers and recreational backpackers are often required to carry heavy loads during military operations or hiking. Shoulder strain appears to be one of the limiting factors of load carriage due to skin and underlying soft tissue deformations, trapped nerves, or obstruction of blood vessels. The present study was aimed to determine relationships between backpack weights and the state of loads in the shoulder's inner tissues, with a special focus on the deformations in the brachial plexus. Open-MRI scans were used for developing and then verifying a three-dimensional, non-linear, large deformation, finite element model of the shoulder. Loads were applied at the strap-shoulder contact surfaces of the model by pulling the strap towards the shoulder until the desired load was reached. Increasing the strap tensile forces up to a load that represents 35 kg backpack resulted in gradual increase in strains within the underlying soft tissues: the maximal tensile strain in the brachial plexus for a 25 kg backpack was 12%, and while carrying 35 kg, the maximal tensile strain increased to 16%. The lateral aspect of the brachial plexus was found to be more vulnerable to deformation-inflicted effects than the medial aspect. This is due to the anatomy of the clavicle that poorly shields the plexus from compressive loads applied during load carriage, while the neural tissue in the medial aspect of the shoulder is better protected by the clavicle. The newly developed model can serve as a tool to estimate soft tissue deformations in the brachial plexus for heavy backpack loads, up to 35 kg. This method will allow further development of new strap structures and materials for alleviating the strains applied on the shoulder soft tissues.

1. Introduction

Loss of upper-limb sensory-motor functions during heavy load carriage is common, is hampering performances, and is a potentially injurious medical condition (Bessen et al., 1987; Birrell and Hooper, 2007; Daube, 1969; Dillin et al., 1985; Makela et al., 2006; Wilson, 1987). Although clinical and epidemiological reports have addressed this issue since the 19th century (Renbourn, 1954), basic research designed to understand the underlying factors and mechanisms for this pathological condition is still lacking, due to the difficulties to study in situ nerve conduction of the brachial plexus.

It is hypothesized that the heavy load, transferred through the shoulder strap to the underlying soft tissues, might affect the neural performance of the upper limb due to trapped nerves or reduced blood supplies (Birrell and Hooper, 2007). Current load carriage systems designs, partially address this issue by transferring loads to the hip area through external rigid frames and belts, however, for high backpack loads, most of the load is still born by the shoulders (Lafiandra and Harman, 2004; Reid et al., 2004).

The first substantial study that provided some insights regarding the mechanisms underlying brachial plexus strains related to load carriage was recently reported by Hadid et al. (2012). In this study, open-MRI scans were used for reconstructing a three-dimensional (3D) geometrical model of an unloaded shoulder and for calculating the soft tissue deformations caused by a 25 kg backpack. These MRI scans revealed substantial deformations of the soft tissues of the shoulder, primarily in the area of the subclavian artery and the brachial plexus. The maximal skin pressure values exerted by a 25 kg load were substantial, and

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reached ~90 kPa. In the same study, a computational analysis using finite element (FE) modeling showed that in the muscle tissues surrounding the brachial plexus, the maximal compressive strain was 0.14, and the maximal tensile strain was 0.13 (Hadid et al., 2012). Such mechanical strains have been reported to hamper underlying neural tissues functions (Kwan et al., 1992; Takai et al., 2002). Noteworthy, even lower weights might have a deleterious effect. In this regard, recently, Kim et al. (2014) reported a decreased sensation in the upper extremity as well as a disturbance in macrovascular and microvascular hemodynamic values in healthy individuals who carried 12 kg for only 10 min. These authors suggested that the decreased hemodynamics may produce neurological dysfunctions, which probably affect fine motor control of the hands (Kim et al., 2014).

The copious amounts of studies and reviews published in the last 30 years on heavy load carriage were mainly descriptive, and did not include quantification of the effects of load on the inner soft tissues of the shoulder, and, specifically on the region of the brachial plexus and subclavian artery. The recent study by Hadid et al. (2012) demonstrated the feasibility to compute mechanical strains in the inner tissues of the shoulder, while carrying a relatively moderate load (25 kg) that is less than the realistic loads carried e.g., by soldiers (Knapik et al., 2004; US Department of the Army, 1990). In addition, the strap used in the previous study was tied to the skin, such that only normal pressures could be applied at the skin-strap interface (Hadid et al., 2012). In reality, the strap also applies shear forces and stresses that may contribute to the total effective subdermal tissue strains, resulting in greater magnitudes of skin pressures as well as internal soft tissue deformations at and under the hotspots, respectively. The present study was aimed to extend that previous modeling in two aspects: a) to determine relationships between backpack weights and the state of loads in the shoulder's soft tissues, taking into consideration heavy loads (up to 35 kg) with a special focus on the deformations and potential damages in the brachial plexus, and b) to develop a tool that will enable to study the effect exerted by an independent backpack strap structure.

2. Methods

2.1. General

An advanced load bearing shoulder model was developed, building upon the model that was previously developed by our group (Hadid et al., 2012). The 3D anatomy of the shoulder was obtained from a sagittal MRI set of an unloaded scan acquired from one person, who was scanned in a sitting position (T1-weighted, 4-mm-thick slices using 0.5 T scanner, Signa SP; GE, Fairfield, CT). The shoulder geometry was reconstructed in 3D using the ScanIP version 6 software (Simpleware, UK). The model included all the anatomical compartments that support load carriage over the shoulder area: the skin, fat, muscles (as one merged compartment), clavicle, acromion, acromioclavicular joint (as a cartilaginous tissue at the bony interface), and the rib cage. The subclavian artery was added as the marker for the brachial plexus position. The strap was added to the geometrical model as well, and positioned as observed in the experimental setting based on the loaded MR scan. The dimensions of the shoulder model were defined so that volume of interest (VOIs) in the soft tissues below the shoulder strap-subclavian artery, in its region below the shoulder strap, is sufficiently far from the coronal and sagittal boundary surfaces (which is not more than 1/3 of the shortest distance between the model's opposing external boundaries, according to the St. Venant theory). The 3D model of the undeformed shoulder with the strap was imported to a FE solver, FEBio version 1.6 (Musculoskeletal Research Laboratories, Utah, USA, http://mrl.sci.utah.edu/software/febio) (Maas et al., 2012) for non-linear, large deformation stress–strain analyses.

The novel approach of the present study was based on using an independent strap that was pulled towards the body gradually (by assigning displacement to both its ends) compared to the normal pressure applied to the skin as if the strap was tied to the skin, which we have assumed in our previous work. This allowed the following extensions to the model: a) reaching a higher load bearing simulation of up to 35 kg compared to 25 kg in our previous model, and b) providing the capability to use different strap geometries and material properties.

2.2. Meshing

The model was meshed in ScanIP version 6 (Simpleware, Exeter, UK) using 859,059 linear tetrahedral elements, optimized so that in/out aspect ratios for all elements were higher than 0.2. A maximal edge length of 10 mm was allowed, assuming that contact regions and volumes of interest (VOI) have a maximal edge length of 4 mm (Fig. 1). Final mesh densities were chosen following convergence analyses, which showed that for a 30% denser mesh (1,458,773 elements compared to 859,059) the difference for the average tensile strain was $<1\%$ for the same loading state.

The meshed model was imported to PreView (FEBio) for setting the boundary conditions, constitutive laws and material properties, and loading mode.

2.3. Material properties

The rib cage, clavicle, the acromioclavicular joint and the acromion were considered as isotropic elastic materials, and the subclavian artery, muscle tissues, skin tissues and subdermal fat were taken as Mooney–Rivlin-type materials. The specific mechanical properties of muscle and fat tissues were chosen from within the physiological ranges reported in the literature (Elsner and Gefen, 2008; Fung, 1993; Gefen and Haberman, 2007; Linder-Ganz and Gefen, 2004; Magnenat-Thalmann et al., 2002; Palevski et al., 2006). To provide the best fit with the MRI-measured tissue deformations for 25 kg loaded backpack, the whole range of reported mechanical properties for the subdermal fat and muscles was tested in sensitivity analyses, in increments of one standard deviation, until the tissue deformations predicted by the modeling were the closest to the deformations measured by means of the MRI. The final mechanical properties assigned to each tissue type are listed in Table 1.

The backpack strap was considered as a neo-Hookean material, and assigned an experimentally-measured modulus, based on uniaxial compression and tensile tests using an Instron electromechanical materials testing machine (Instron 5544, High Wycombe, UK). The compressive elastic modulus was measured as described by Hadid et al. (2012). Tensile testing was performed by gripping the strap at both ends, and measuring the force versus extension at a 0.5 mm/s rate. It should be noted that the tensile modulus (~2 MPa) of the strap was found to be greater than its compressive modulus (81 kPa), meaning that the strap is stronger in the axial

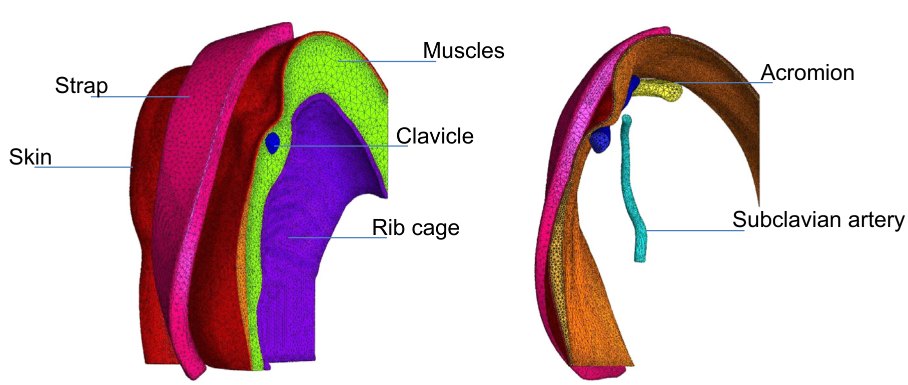

Fig. 1. The model of the shoulder for investigation of brachial plexus strains during backpack carriage: (a) the meshed model – medial view of the rib cage, muscle tissue, the clavicle, subdermalfat skin tissue and the backpack strap. (b) The meshed model – inside view of the subclavian artery, clavicle and the acromion.