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Technical note

An analysis of contact stiffness between a finger and an object when wearing an air-cushioned glove: The effects of the air pressure☆

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ABSTRACT

Air-cushioned gloves have the advantages of lighter weight, lower cost, and unique mechanical performance, compared to gloves made of conventional engineering materials. The goal of this study is to analyze the contact interaction between fingers and object when wearing an air-cushioned glove. The contact interactions between the the fingertip and air bubbles, which is considered as a cell of a typical air-cushioned glove, has been analyzed theoretically. Two-dimensional finite element models were developed for the analysis. The fingertip model was assumed to be composed of skin layers, subcutaneous tissue, bone, and nail. The air bubbles were modeled as air sealed in the container of nonelastic membrane. We simulated two common scenarios: a fingertip in contact with one single air bubble and with two air cushion bubbles simultaneously. Our simulation results indicated that the internal air pressure can modulate the fingertip–object contact characteristics. The contact stiffness reaches a minimum when the initial air pressure is equal to 1.3 and 1.05 times of the atmosphere pressure for the single air bubble and the double air bubble contact, respectively. Furthermore, the simulation results indicate that the double air bubble contact will result in smaller volumetric tissue strain than the single air bubble contact for the same force.

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1. Introduction

Gloves are commonly used as a primary means to protect workers from acute traumatic occupational hand injuries. Epidemiological studies indicated that glove use could help to lower the risk of the injuries associated with lacerations and punctures by 60–70% [13]. However, many other studies showed that workers' performance could be compromised when gloves are used [3], partially due to the increased effort in submaximal tasks and reduced sensitivity [15]. Wearing a work glove was found to contribute to hand-grip fatigue [6]. Lariviere et al.'s [9] study indicated that the surface electromyography (EMG) activity in the forearm, which reflected muscle forces, was related to glove types used. Mital et al. [10] investigated the effects of glove use on muscle loading for operating non-powered hand tools and found that the magnitude of torque exerted on the workpiece varied by glove type. These results were further confirmed by Kinoshita et al. [7], who found that glove thickness and materials, which presumably modify the cutaneous sensation and glove/object friction, influence grip force regulation, and thereby affect the precision handling of small objects. Kovacs et al.'s [8] studies indicated significant differences in the effects of different glove types on the peak force, ratio of peak force to normalized flexor muscle EMG activity, and the ratio of peak force to muscle co-activity. Material stiffness and thickness have been identified as the primary concerns in glove design [11]. All previous studies suggest that there is a need to improve glove design using an ergonomic approach, such that gloves serve not only safety protection means, but also help improve productivity.

The air-cushioned glove is among recent glove products developed for anti-vibration protection. Air bubble cushions have been widely used in cases of the contact interactions between human and equipment, for example, the seat cushion, air bed mattresses, sports shoes, and shock-absorption gloves. In a representative air-cushioned glove, the finger segments are cushioned by separated air bubbles (Fig. 1A). Air cushions have the advantages of light weight, low cost, and unique mechanical performance, compared with other conventional glove materials, such as rubbers and polymers. However, the contact interaction between the finger and air bubbles is not well understood.

One of the most important considerations in ergonomic design of a tool handle is the contact stiffness between the hand and tool handle [4,12,14], i.e., the ratio of the contact force to the local deformations of the contacting bodies. Previous experimental studies

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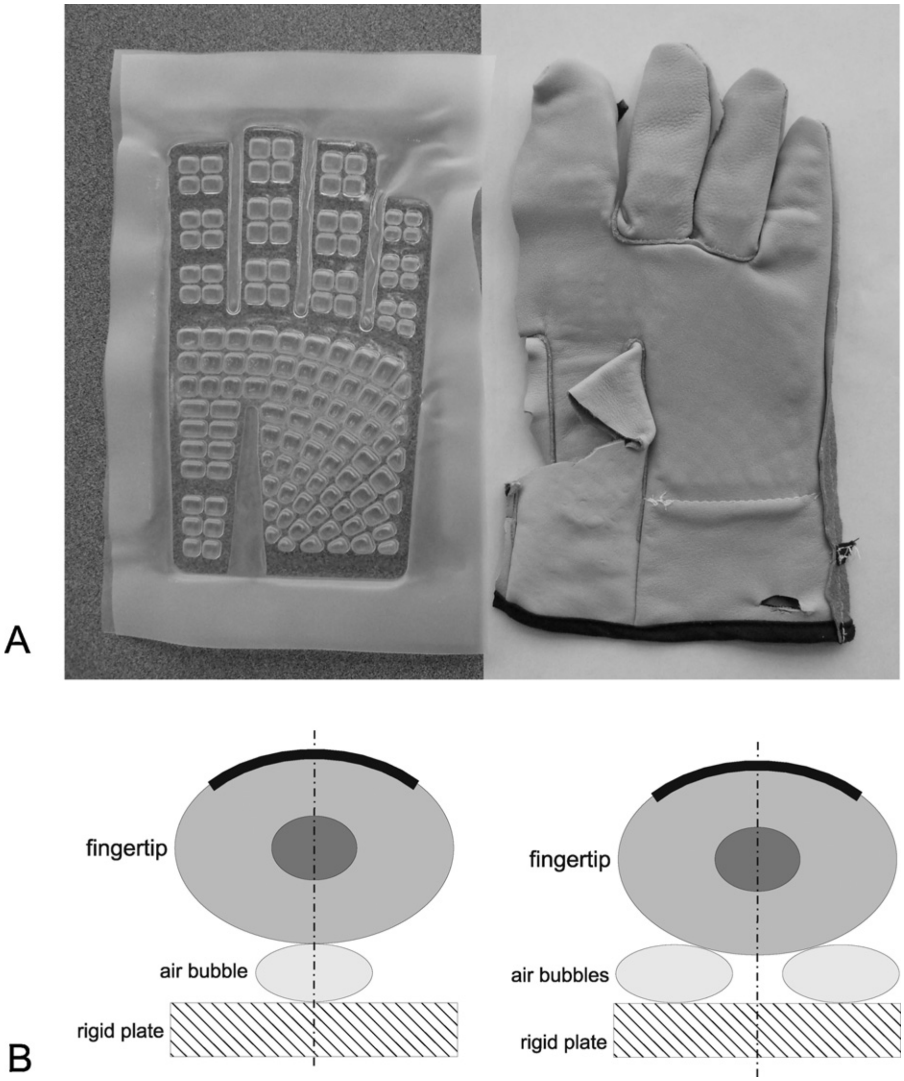

Fig. 1. Illustration of a typical air-cushioned glove and the conceptual models. (A) Typical air-cushioned glove. Left: a piece of air bubble underlay. Right: an air-cushioned glove. (B) Conceptual models. Left: a fingertip contacted with a single air-bubble. Right: a fingertip contacted with two air-bubbles.

indicated that the grip force and the tactile sensitivity of the fingers are effectively affected by the glove thickness [15]. Since glove wearing affects the contact stiffness between the hand and tool handle, these studies suggested that the contact stiffness may affect the manipulations of hand-held tools. The goal of the current study was to analyze the contact interaction between a fingertip and air bubbles, which represents a contact element in an air-cushioned glove. Our hypothesis is that the initial air pressure in the air bubble of the glove will affect the contact stiffness between the fingertip and object.

2. Method

2.1. Finite element models

The mechanical behavior of one cell of a typical air-cushioned glove is analyzed in the current study – the contact interactions between the fingertip and air bubbles. Two scenarios have been simulated, as illustrated in Fig. 1B. In the first case, the fingertip is in contact with a single air bubble (Fig. 1B-left), whereas in the second case, the fingertip is in contact with two air bubbles (Fig. 1B-right) simultaneously. The air-cushion element models are representative for the glove linings that are typically used in mechanic or anti-vibration gloves (e.g., Mechanic, Anti-Vibration Gloves, IMPACTO, Belleville, Canada). The finite element models illustrated in Fig. 2A and B are for these two cases. For the second scenario, only half of the model was considered due to the symmetric nature of the problem (Fig. 1B-right vs. Fig. 2B); the horizontal displacement at the symmetric line was constrained (Fig. 2B). The two-dimensional fingertip model represents a section of the distal finger segment. The section is assumed to be in the middle between the tip of the finger segment and the distal-intermediate phalangeal (DIP) joint line, where the cross-sectional shape variation is considered to be small. The finite element models were developed using a commercial software package COMSOL MultiPhysics (version 3.5a, COMSOL, Inc., Burlington, MA, US).

The fingertip model was assumed to be composed of skin layers, subcutaneous tissue, bone, and nail. The dimensions of the fingertip were assumed to be representative of the index finger of an average male subject [5]. The nail is considered to have a thickness of 0.60 mm [2]. The skin is assumed to be composed of two layers: the outer skin (100 μm thick) and inner skin (1.26 mm thick). The outer skin layer contains stratum corneum (SC) and a part of the viable epidermis; and it is considered as linearly elastic (Young's modulus of 2 MPa and Poisson's ratio of 0.30); whereas the inner skin layer is composed of dermis and a part of the viable epidermis,