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Analysis of the effects of surface stiffness on the contact interaction between a finger and a cylindrical handle using a three-dimensional hybrid model

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ABSTRACT

Contact interactions between the hand and handle, such as the contact surface softness and contact surface curvature, will affect both physical effort and musculoskeletal fatigue, thereby the comfort and safety of power tool operations. Previous models of hand gripping can be categorized into two groups: multi-body dynamic models and finite element (FE) models. The goal of the current study is to develop a hybrid FE hand gripping model, which combines the features of conventional FE models and multi-body dynamic models. The proposed model is applied to simulate hand-gripping on a cylindrical handle with covering materials of different softness levels. The model included three finger segments (distal, middle, and proximal phalanxes), three finger joints (the distal interphalangeal (DIP), proximal interphalangeal (PIP), and metacarpophalangeal (MCP) joint), and major anatomical substructures. The model was driven by joint moments, which are the net effects of all passive and active muscular forces acting about the joints. The finger model was first calibrated by using experimental data of human subject tests, and then applied to investigate the effects of surface softness on contact interactions between a finger and a cylindrical handle. Our results show that the maximal compressive stress and strain in the soft tissues of the fingers can be effectively reduced by reducing the stiffness of the covering material.

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1. Introduction

Musculoskeletal disorders of the hand and fingers are associated with occupational activities across all industrial sectors [1]. Since the handle serves as an interface between an operator and a machine or a tool, it is well accepted that an optimized design of the handle can reduce both physical effort and musculoskeletal fatigue, thereby improving comfort and reducing the risk of musculoskeletal disorders. Previous experimental studies indicate that grip strength, operator's comfort, and safety depend on the handle diameter [2–6], the properties of the surface materials [7,8], the handle shape [9,10], the friction of the contact surface [11], the stiffness of the contact surface [12], and also the posture of the operator [13]. It is difficult to objectively evaluate the biomechanical responses of the hand-arm system to the variations of the operating conditions in experiments because the forces in the musculoskeletal system cannot be easily measured in vivo. Therefore, biomechanical models of the system become essential tools for exploring the mechanical loading environment associated with injury mechanisms.

Researchers have developed multiple models of the hand and fingers for simulating different problems. Brook et al. [14] developed a biomechanical model of the dynamics of the index finger and applied their model to simulate the muscle forces in pinch grip and disc rotation. Biggs and Horch [15] proposed a three-dimensional (3D) kinematic long finger model and qualitatively validated their model via experimental data of tendon/muscle excursions for the motion of the MCP joint. Valero-Cuevas et al.'s [16] finger models included anatomically realistic tendon/muscle connections and musculoskeletal parameters. The whole-hand models proposed by Sancho-Bru et al. [17,18] were used to simulate the muscle loading for static gripping and free movements. Freund et al. [19] developed a hand model to investigate the dependence of the fingertip contact force on the gripping force, handle diameter, and hand size. All these hand models are multi-body dynamical models, in which the fingers are simulated using linkage systems composed of rigid finger segments linked by joints and connected by muscle/tendon

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units. Since these models do not contain passive soft tissues (i.e., skin and subcutaneous tissues), they cannot be applied to simulate the contact interactions between the fingers and objects, which are important for some practical problems.

For ergonomic designs of tool handles, it is important to understand the contact mechanics between the hand and handle, such as the effects of the contact surface softness and contact surface curvature on the comfort of the operators. The contact condition is known to be one of the essential factors that determine vibration resonance characteristics [20]. Therefore, hand contact mechanics are also important for understanding the biodynamic responses of the hand-arm system and to explore the mechanisms of hand-arm vibration syndrome [20,21]. Although contact pressures between the hand and a hard surface can be measured reliably using pressure sensor film, the same technique cannot be applied to evaluate the mechanics of the hand/handle contact. Since handles are typically covered with soft materials, which are usually much softer than the pressure sensor film, inserting the pressure sensor film between the hand and the handle will substantially alter the contact mechanics. Consequently, finite element (FE) models have been developed to examine contact conditions for such problems. Previously, we have proposed FE models to study the dynamic contact between a fingertip and a flat plate [22], the effects of the curvature of the contact surface on contact pressures [23], and the contact interactions between a fingertip and a vibrating plate [24]. In all these previous FE models, only one fingertip segment was included, and the simulations were driven by directly applying contact force or displacement. The contact force was prescribed as a model input and it was not related to the joint torques or muscle forces of the hand-arm in these models.

The goal of the current study is to develop a hybrid finger model to simulate hand gripping on a cylindrical handle with soft covering materials. The hybrid finger model will combine the features of the conventional FE models and the multi-body dynamic models; it includes three finger segments (distal, middle, and proximal phalanges), three joints [the distal interphalangeal (DIP), proximal interphalangeal (PIP), and metacarpophalangeal (MCP) joint], and contains the major anatomical substructures of the finger (i.e., soft tissues, nail, and bone). The model will be driven by the joint moments, which are net effects of passive and active forces (due to the effects of the connective tissues, ligaments, tendons, and muscles) acting about the joints. In this study, the proposed model is applied to investigate the effects of the softness of the contact surface on the contact interactions between a finger and a cylindrical handle.

2. Methods

2.1. Finite element model

The proposed 3D FE model of the grip features a finger and a cylindrical handle, as illustrated in Fig. 1. The FE model was developed to simulate a middle finger, which consists of a distal, a middle, and a proximal phalanx (Fig. 1B). The finger model included soft tissues, bone, and nail. External shapes of all three finger segments were considered to be rotationally symmetrical. The middle and proximal phalanges were conical frustums, whereas the distal phalange was a conical frustum connected with a hemispherical-like fingertip. The dimensions of the finger segments were adjusted to match the average of all subjects. The dimensions of the bony cross-sections were determined based on published experimental measurements [25].

The DIP and PIP joints were modeled as hinges with one degree of freedom (DOF, flexion/extension). The MCP joint was modeled as a universal joint with two DOFs (flexion/extension

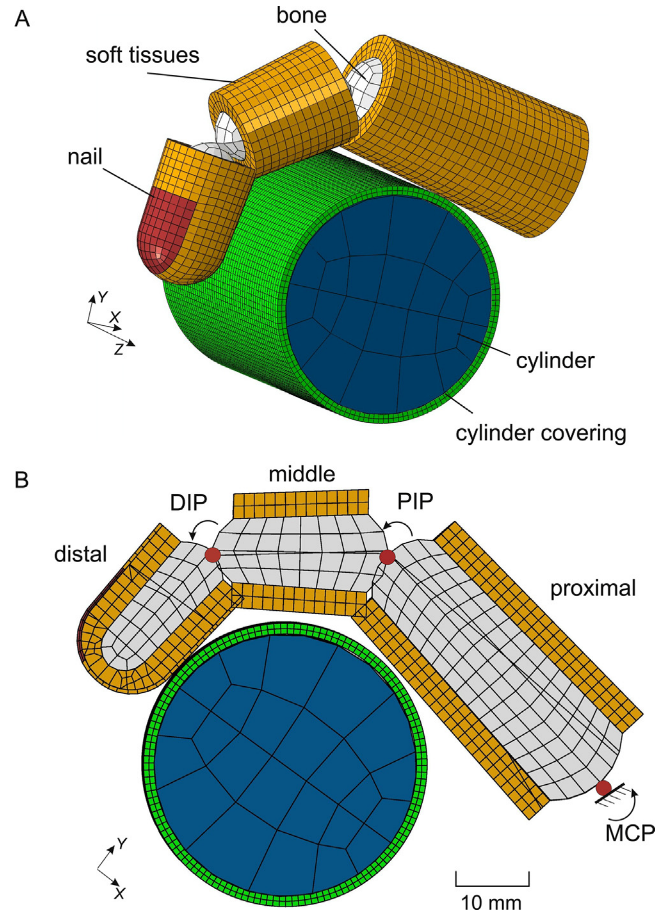

Fig. 1. Proposed finger model mimicking a gripping task. (A) Three dimensional sketch of the model. (B) Cross-sectional view of the model. The finger model consisted of three segments, i.e., distal, middle, and proximal segments. The finger segments contain three different materials: bone, soft tissues, and nail. In order to simulate the effects of the contact surface stiffness, the cylindrical handle was considered to be covered with different materials. The finger was driven by the moments applied at the DIP, PIP, and MCP joints. The cylinder was fixed at its axial center, and it can rotate around its axis.

and adduction/abduction) (Fig. 1B); however, the DOF in adduction/abduction has been constrained in the study. The proximal phalanx is linked to ground via the MCP joint. The system is mechanically equivalent to the case where a metacarpal bone is fixed in space. In the current problem, all finger joints exhibited rotational motions only around the z-axis (the motion of adduction/abduction in the MCP joint was constrained). The finger joints were built on the apexes of the bony segments. Each apex was constrained by the end surface of the corresponding bony segment.

The soft tissues were considered to be connected to the side surfaces of the bony segments. The effects of the passive stiffness due to the deformation of the soft tissues around the joint creases were neglected, i.e., the ends the finger segments could penetrate into each other without resistance. The contact pairs were built between the external surface of the cylinder covering and the external side surfaces of the finger segments. The friction coefficient between the skin/cylinder contact interface was considered to be 0.30 [26,27]. The FE model is geometrically nonlinear to cope with large deformation. The FE model was developed using a commercial software package ABAQUS.

For all simulations of cylinders with or without soft covering materials, the external diameter of the cylinder was 40 mm. The cylinder was of aluminium and was considered to be covered with three different materials (thickness 1.5 mm): synthetic viscoelastic