



## Modeling the finger joint moments in a hand at the maximal isometric grip: The effects of friction

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### ABSTRACT

The interaction between the handle and operator's hand affects the comfort and safety of tool and machine operations. In most of the previous studies, the investigators considered only the normal contact forces. The effect of friction on the joint moments in fingers has not been analyzed. Furthermore, the observed contact forces have not been linked to the internal musculoskeletal loading in the previous experimental studies. In the current study, we proposed a universal model of a hand to evaluate the joint moments in the fingers during grasping tasks. The hand model was developed on the platform of the commercial software package AnyBody. Only four fingers (index, long, ring, and little finger) were included in the model. The anatomical structure of each finger is comprised of four phalanges (distal, middle, proximal, and metacarpal phalange). The simulations were performed using an inverse dynamics technique. The joint angles and the normal contact forces on each finger section reported by previous researchers were used as inputs, while the joint moments of each finger were predicted. The predicted trends of the dependence of the distal interphalangeal (DIP) and proximal interphalangeal (PIP) joint moments on the cylinder diameter agree with those of the contact forces on the fingers observed in the previous experimental study. Our results show that the DIP and PIP joint moments reach their maximums at a cylinder diameter of about 31 mm, which is consistent with the trend of the finger contact forces measured in the experiments. The proposed approach will be useful for simulating musculoskeletal loading in the hand for occupational activities, thereby optimizing tool-handle design.

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### 1. Introduction

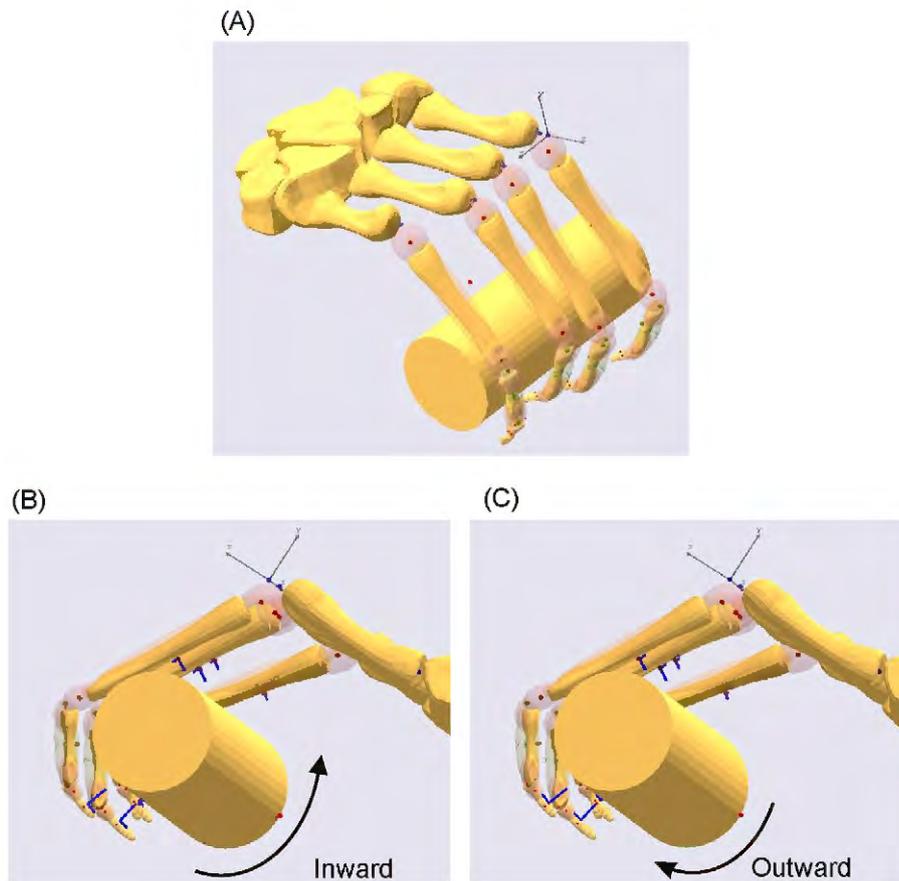
The interaction between the handle and operator's hand affects the comfort and safety of the tool operations. One of the major considerations in ergonomic design is the size of handles of power-tools [7]. Several previous experimental studies indicated that the grip strength depends on the handle diameter [2,8,11,10]. Lee and Rim [11] conducted comprehensive studies on the kinetics of gripping tasks. They measured the maximal contact forces acting on each finger section and joint angles in each finger for four subjects gripping cylinders of five different diameters. Their results indicated that the gripping forces reached the maximums at a diameter of about 31 mm. In most of the previous studies, the investigators measured only the normal contact forces between the fingers and the handle.

In a few studies, the investigators quantified the frictional forces between the fingers and the handle. For example, Amis [3] measured both normal and shear contact forces between the fingers and the cylindrical handles in the maximal isometric grasping on

cylinders of diameters from 31 to 116 mm. Grip-only tests were performed in their studies—the subjects were instructed not to apply torques on the cylinders. Recently, Seo et al. [13,12] investigated the effects of the frictional torque on the gripping efforts. The subjects were instructed to apply their maximal isometric torques in the tests. Their results suggested that the effects of the torque on the distal interphalangeal (DIP) joint in a fingertip depend on the direction of the exertion: the torque in the outward direction tends to decrease the DIP joint moment while that in the inward direction tends to increase the DIP joint moment. They concluded from their study that the maximal torques can be applied in the outward direction. The effects of friction on the proximal interphalangeal (PIP) and metacarpophalangeal (MCP) joints were not analyzed in their study.

The friction between the skin and objects of different materials has been studied by several researchers. Adams et al. [1] tested the friction of the skin at the fingertip using glass and polypropylene in the dry and wet conditions. They found that the static and dynamic coefficients of friction are similar and independent of the normal contact force in the dry condition, while they are different and dependent on the contact force in the wet condition. They found that the friction coefficient in dry condition is approximately 0.25 and 0.40, respectively, for the skin/glass and skin/polypropylene

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**Fig. 1.** The hand model developed on the platform of the commercial software package AnyBody (A). The effects of the torque directions (B and C) are simulated by varying the directions of the frictional forces.

contact. More extensive study for the friction between the skin and different materials was conducted recently by Tomlinson et al. [14]. They examined the friction characteristics of the contact of the skin at the fingertip with the probes of 12 different materials: 3 metals, 5 plastics, and 4 elastomers. The friction coefficients for the tested metals and plastics are in a range from 0.14 to 0.29, while those for the elastomers are between 0.41 and 0.83.

From a biomechanical-point-of-view, the goal for the optimized design of a tool handle should be the minimization of the operation efforts and musculoskeletal fatigue, thereby improving comfort and reducing musculoskeletal disorders in the hand. Because it is not feasible to experimentally measure the musculoskeletal loadings in a power grip task, biomechanical models of the hand and fingers are useful for exploring such problems. Although there are some biomechanical models of the hands and fingers that have been developed to simulate different problems (e.g., Sancho-Bru et al. [15,16]), the effects of the friction on the musculoskeletal loading in the fingers in a gripping task have not been analyzed.

In the current study, we develop an inverse dynamic model of a hand on the basis of the experimental data reported by Lee and Rim [11]. The joint angles of each finger and the contact forces on each finger sections obtained in the experiments [11] are applied as inputs, while the joint moments of each finger are predicted. The objective of the present study is to investigate: (1) the joint moment in fingers in power grip, (2) the effects of friction on the joint moments in the fingers, and (3) the dependence of the joint moment in fingers on the diameter of the cylinders. Our hypotheses are that the dependence of the joint moments in the fingers on the diameter of the cylinders is consistent in trend with those observed in the gripping forces [11], and that the effects of friction on the DIP joint are different from those on PIP and MCP joints.

## 2. Methods

### 2.1. Hand model

Only four fingers – index, long, ring, and little finger – were included in the model. The anatomical structure of each finger comprised four phalanges – distal, middle, proximal, and metacarpal phalange. These four phalanges were connected by three joints: DIP, PIP, and MCP joints. The DIP and PIP joints were considered as hinges with one degree of freedom (DOF), simulating flexion/extension motion; whereas the MCP joint was modeled as a universal joint with two DOFs, simulating adduction/abduction and flexion/extension motions. The hand model was developed on the platform of the commercial software AnyBody (version 3.0, AnyBody Technology, Aalborg, Denmark) (Fig. 1), which is a universal software tool for the modeling of the musculoskeletal system. The model is developed from scratch by defining bones (segments), joints, movements, constraints, and external forces. The model is written in AnyScript code, which is an object-oriented programming language of the AnyBody System. In order to better visualize the contact forces on the finger sections, the 3D bony section meshes were implemented into the model.

### 2.2. Finger section dimensions

The external dimensions of the fingers have been measured on a large sample basis by several previous researchers, e.g. [6,5]. The dimensions of the finger sections have been summarized in a scale to the hand width and breadth by Buchholz et al. [17]. Assuming ‘unisex’ hand dimensions (hand length = 177 mm; hand breadth = 77 mm), which are the means of typical adult male and

**Table 1**

Dimensions of the phalangeal sections of the fingers. The phalangeal sections are approximated by cylindrical bodies with ellipsoidal cross sections: *a*, *b* and *l* are half width, half depth, and length of the cylinder.

Sections	Finger tissue external (m)		
	<i>a</i> (breadth/2)	<i>b</i> (depth/2)	<i>l</i> (length)
Index			
Distal	0.0076	0.0063	0.0170
Middle	0.0084	0.0074	0.0253
Proximal	0.0089	0.0087	0.0434
Long			
Distal	0.0078	0.0067	0.0191
Middle	0.0083	0.0076	0.0301
Proximal	0.0086	0.0094	0.0471
Ring			
Distal	0.0074	0.0064	0.0189
Middle	0.0077	0.0073	0.0293
Proximal	0.0081	0.0093	0.0432
Little			
Distal	0.0068	0.0057	0.0165
Middle	0.0072	0.0068	0.0207
Proximal	0.0076	0.0082	0.0361

female hand dimensions based on Buchholz et al.'s (1992) study, we have determined the dimensions of each finger section, as listed in Table 1. The dimensional ratios of the finger sections and joint locations have been normalized using the definition of the normative finger model [4], as in Table 2. The data of the original normative finger model [4] are also listed in the table for comparison.

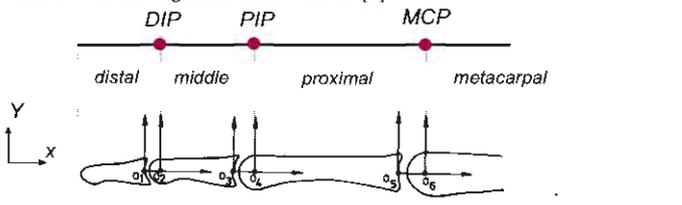
**2.3. Simulation procedure**

The simulations were performed using an inverse dynamics technique. The joint angles and the normal contact forces on each finger section reported by Lee and Rim [11] were used as inputs, while the joint moments of each finger were predicted using AnyBody. The normal contact forces on each finger section were applied at the locations defined by the local coordinates of each section [11].

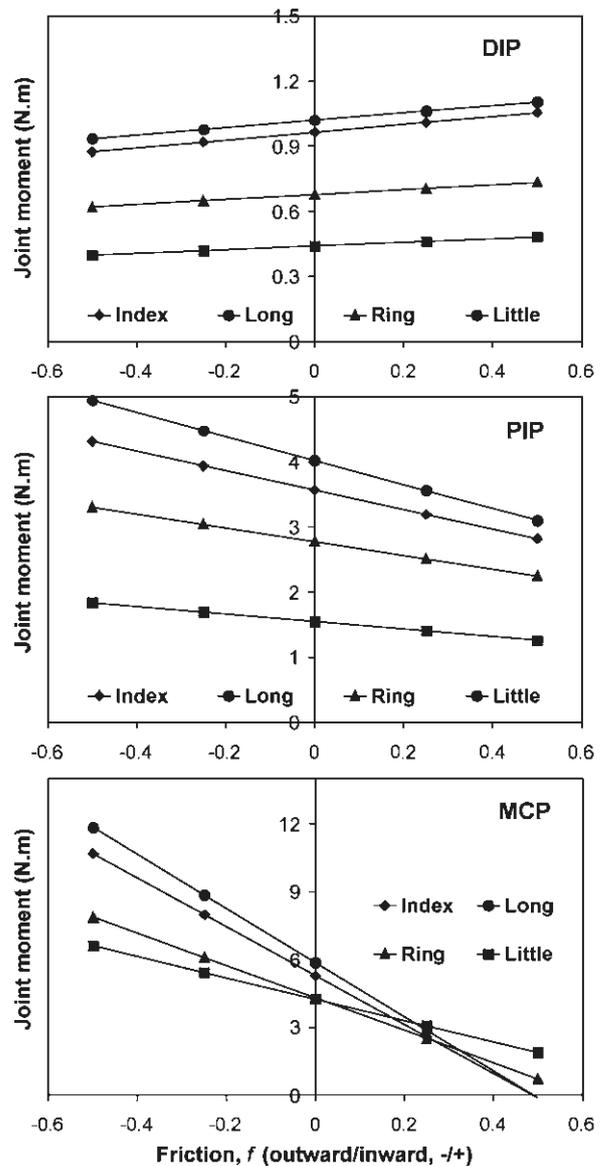
The friction effects on the joint moments were simulated by applying frictional forces to each finger section. The magnitudes of the frictional forces were calculated by multiplying the normal contact forces by a friction coefficient. The frictional forces were applied at the same locations on each finger section as the normal

**Table 2**

Comparison of the scaling parameters of the finger sections of the current study with those in the original normative model [4]



	Index	Long	Ring	Little
Scale of the normative model [4]				
O102	0.2240	0.1840	0.1660	0.2300
O203	1.0000	1.0000	1.0000	1.0000
O304	0.2880	0.2330	0.2240	0.3040
O405	1.9190	1.6080	1.5760	1.7970
O506	0.4320	0.3650	0.3460	0.5060
Revised scale of the current model				
O102	0.2240	0.1840	0.1660	0.2300
O203	1.0000	1.0000	1.0000	1.0000
O304	0.2880	0.2330	0.2240	0.3040
O405	1.8012	1.5724	1.4788	1.7741
O506	0.4055	0.3569	0.3247	0.4995



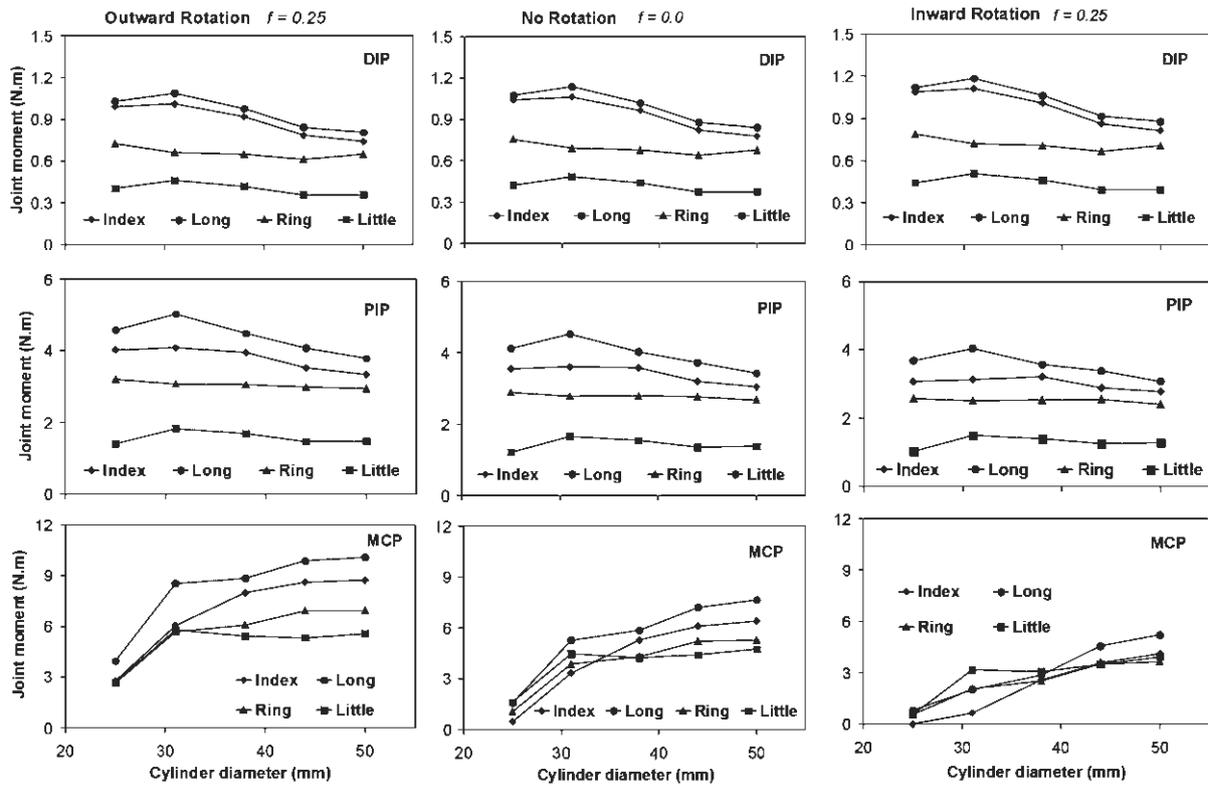
**Fig. 2.** The simulated effects of the friction coefficient on the finger joint moments. The minus and plus frictions represent the outward and inward torque directions, respectively. The same cylinder diameter (38 mm) was applied for the calculations.

contact forces, and at a tangential direction towards the trend of the relative sliding. By varying the directions of the frictional forces, the effects of the torque direction can be simulated (Fig. 1). The coefficient of the friction is assumed to vary from 0.0, for the “frictionless” grip, to 0.50, which is in a range observed in the experiments [1, 14].

**3. Results**

**3.1. Effects of friction**

In the first set of numerical tests, we studied the effects of friction on the finger joint moments. The effects of friction on the joint moments are analyzed by using the same cylinder diameter (38 mm) while applying different friction coefficients and torque direction, as shown in Fig. 2. It is generally accepted and recommended that the optimal handle diameter is around 40 mm [9]. The simulations results showed that the effects of the torsional friction force on the DIP joint are different from those for the PIP and MCP joints. The maximal joint moments in DIP joint increases from the



**Fig. 3.** The simulated effects of the cylinder diameter on the finger joint moments. The figures show the joint moments in each of the four fingers as a function of cylinder diameter. The central column shows the results for the grip with zero friction coefficient, while the left and right columns show the results for the grip with a friction coefficient 0.25 when rotating outward and inward, respectively. The simulations were performed using five cylindrical diameters: 25, 31, 38, 44, and 50 mm.

outward to inward torsion, while those in the PIP and MCP joints decrease from the outward to inward torsion.

### 3.2. Effects of cylinder diameter

In the second set of numerical tests, we analyzed the effects of cylinder diameter on the finger joint moments. The predicted joint moments in each of the four fingers as a function of cylinder diameter are shown in Fig. 3. The central column shows the results for the “frictionless grip” (the numerical test condition with a zero friction coefficient), whereas the left and right columns of the figure show the results for the grip with a friction coefficient 0.25 when rotating outwards and inwards, respectively. The theoretical results show that the descending order for the magnitude of the maximal joint moments in DIP and PIP in the fingers is: long, index, ring, and little finger. For the MCP joint, the trends in the joint moment for large cylinder ( $D \geq 38$  mm) are the same as in DIP and PIP joints, while that for small cylinder ( $D \leq 31$  mm) the descending order for the magnitude of the maximal joint moments changes to: long, little, ring, and index finger. For the DIP and PIP joints, the maximal joint moment as a function of the cylinder diameter reaches the maximum at a cylinder diameter of about 31 mm, while the maximal MCP joint moment increases with an increasing cylinder diameter. The friction and torque directions do not vary the general trends of the dependence of the joint moments on cylinder diameter.

## 4. Discussion and conclusion

The trends of the dependence of the DIP and PIP joint moments on cylinder diameter predicted in the current study agree with those of the finger contact forces observed experimentally [11]. Our results show that the DIP and PIP joint moments reach their maximums at a cylinder diameter of about 31 mm, which is consistent

with the trend of the finger contact forces measured in the experiments [11]. However, in the experimental study, the observed contact forces were not linked to the internal musculoskeletal loading. In the current study, we have confirmed that the contact forces on the fingers are associated with the PIP and DIP joint moments. Assuming that the DIP and PIP joint moments are predominant when gripping a cylinder, subjects should be able to apply the maximum gripping force at a cylinder diameter of about 31 mm.

Our simulation results for the effect of friction on the DIP joint moment agree with Seo et al.'s [13] hypothesis that outward torque tends to reduce the DIP joint moment while inward torque tends to increase the DIP joint moment. However, the current simulations further indicate that the effect of friction on the PIP and MCP joint moments is opposite to that for the DIP joint: outward torque tends to increase the joint moments while inward torque tends to reduce the joint moments. Our simulations suggest that the effects of friction on musculoskeletal loading depend on the task. By comparing our results with those reported by Seo et al. [13,12] and Lee and Rim [11], one would speculate that for maximum isometric gripping tests, the DIP and PIP joint moments will be predominant; while in maximum isometric twisting tests, the DIP joint moments will be predominant since the majority of the contact forces are distributed at the fingertips. An outward twist will tend to reduce the musculoskeletal loading when a subject is applying the maximum isometric torque, but could increase the musculoskeletal loading when the subject is applying the maximum isometric grip. The latter scenario can happen when a power-tool operator intends to hold a tool handle still while the power tool generates a sudden torque.

In the current study, the normal contact forces were assumed to be unchanged and independent of the torque direction. Therefore, the simulated cases represent the maximum isometric grip, in which the subjects try to hold the handle still and do not intend to rotate it. If the subjects exert maximum isometric torque, the nor-

mal contact force distributions among the fingers will vary with the torque direction [12].

The contact forces between the fingers and the cylindrical handle were measured using Fuji film in Lee and Rim's [11] study. Consequently, the reported contact forces represent the maximal values during the entire gripping process. In practical cases, the magnitudes of the contact forces do not reach their maximums simultaneously in time sequence. Therefore, the current simulations are estimations of the maximal joint moment in the fingers that can occur during a power grip.

A further limitation of this study is that constant friction coefficients were applied in the calculations. The friction coefficient between the skin and handle may be dependent on the contact surface area and hence the magnitude of the normal contact force [1]. Consequently, the friction coefficient may be different on each finger section. The effects of this non-linear contact condition has not been analyzed in our study.

In the current study, we proposed a universal model of a hand with four fingers to simulate grasping tasks. The current model is developed with a commercially available software package (AnyBody), the researchers and bioengineers can apply it as a universal tool for solving practical problems. The proposed approach will be useful for simulating musculoskeletal loading in the hand for occupational activities, thereby optimizing tool designs.

#### Disclaimers

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

#### Conflict of interest statement

All authors of this manuscript have no conflict of interest.

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