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ORIGINAL PAPER

A review on finite element modelling of finger and hand mechanical behaviour in haptic interactions

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Abstract
Touch perception largely depends on the mechanical properties of the soft tissues of the glabrous skin of fingers and hands. The correct modelling of the stress–strain state of these tissues during the interaction with external objects can provide insights on the exteroceptual mechanisms of human touch, offering design guidelines for artificial haptic systems. However, devising correct models of the finger and hand at contact is a challenging task, due to the biomechanical complexity of human skin. This work presents an overview of the use of Finite Element analysis for studying the stress–strain state in the glabrous skin of the hand, under different loading conditions. We summarize existing approaches for the design and validation of Finite Element models of the soft tissues of the human finger and hand, evaluating their capability to provide results that are valuable in understanding tactile perception. The goal of our work is to serve as a reference and provide guidelines for those approaching this modelling method for the study of human haptic perception.

Keywords Finite element analysis · Tactile perception · Haptic contact · Touch interactions · Biomechanical modelling

1 Introduction

The significant capabilities of the human somatosensory system are strongly connected to the physical properties of the skin, which is the sensory organ of touch. The skin covers approximately two square meters of the adult body surface and responds to interactions with external objects or limb movements with a complex viscoelastic mechanical behaviour (Wiertlewski and Hayward 2012; Biswas and Visell 2019). The mechanical properties of its different tissue layers are highly nonlinear and time-dependent, with large variations within and between persons, which depend on both biological, e.g., sex and age (Abdouni et al. 2018) and environmental factors, e.g., friction or moisture (Serhat et al. 2022). The mechanics of the glabrous skin, which covers the palmar surfaces of our fingers and hands, strongly determine the way tactile stimuli are processed and encoded into neural signals via mechanoreceptors, ultimately reaching the somatosensory regions of the brain (Johansson and Flanagan 2009; Deflorio et al. 2022). Accurate modelling of skin mechanics can be used to predict the activation of mechanoreceptors and to shed light on the mechanisms underpinning touch perception; such knowledge can then inform the design of effective haptic displays and sensors (Biswas and Visell 2021). However, fully grasping the several nuances of skin mechanics represents a challenging task. In recent years, a multi-disciplinary effort has been devoted to tackling this issue by developing accurate methods to estimate the mechanical properties of the skin and designing mathematical and numerical models to study the complex stress–strain interplay that occurs in human skin layers during the interaction with external objects (Wei et al. 2022a; Serhat et al. 2022).

This survey focuses on the methods that have been proposed in the literature to simulate the mechanical behaviour of human fingers and hands at contact, focusing on the glabrous skin. These methods often take advantage of available experimental data to achieve adherence to

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the mechanics of hands and fingers *in vivo* (Gerling et al. 2014; Kumar et al. 2015). *Finite Element (FE)* analysis offers a useful approach for the numerical resolution of highly nonlinear problems, usually relying on multivariate differential equations whose solution cannot be achieved in a closed form. FE analysis exploits a piecewise approximation, i.e., dividing the region of interest of the domain (a 3D spatial region plus time) into smaller elements with simple geometry. Within each element, field variables such as mechanical stress or strain are approximated using polynomial shape functions. This allows for the representation of complex variable distributions within the domain in a piecewise manner, simplifying the solution of otherwise complex equations. Although other analytical (Srinivasan 1989) or numerical (Ho and Hirai 2015) solutions exist, they often suffer from heavily restrictive assumptions, such as requiring an axis-symmetric geometry (Serina et al. 1998), and are difficult to extend to different situations or loading types (Serina et al. 1998). On the other hand, FE analysis is a powerful analytical tool for the simulation of different problems in the field of haptic contact interactions (Wu et al. 2004; Khojasteh et al. 2018; Wei et al. 2022a). In this work, we conducted a survey on the FE models that have been proposed for the simulated evaluation of the mechanical response of human fingers and hands, considering mechanical interactions and focusing on the modelling of the soft tissues of the glabrous skin. As detailed in Sect. 2.2, previous reviews delved into the biomechanical modelling of the human skin and on the role played in the field by FE analysis (Deflorio et al. 2022; Biswas and Visell 2021; Mostafavi Yazdi and Baqersad 2022). However, to the authors' best knowledge, none of the previous works focused on the design of the FE models themselves. For this reason, we directed our effort towards a systematic organization and comparison between the relevant models existing in the literature. By summarizing and discussing the common design choices and assumptions, we gained useful insights that can be used by others to develop models in line with the state of the art. The next section describes the methodology used to collect the studies considered in our survey and further details its contribution with respect to similar papers in the state of the art. The structure of the rest of this paper is as follows. Section 3 provides a brief overview of the biology of the mechanoreceptors and the skin, as well as of the relevant mechanical properties and parameters of human skin, fingers, and hands, highlighting those that are relevant to haptic interactions. Section 4 then reviews the main types of FE models of the human hand and finger at contact, based on the type of desired touch-related information to be estimated. Finally, in Section 4 we provide a critical analysis of the existing methods, highlighting their pros and cons for the different targeted research questions, and offering possible suggestions on how to proceed along this interesting research direction.

2 Scope

When in contact with external objects, the human hand is subjected to external stimuli such as vibrations, frictional and compressive forces, and the mechanical state of the hand soft tissues is translated into neural signals that are interpreted as tactile perception. In our survey, we considered existing FE models that are endowed with the capability to realistically simulate the mechanical response of the fingers or the hand during contact with external mechanical stimuli. Hereinafter, we refer to these models as *haptically focused*, i.e., they focus on simulating the stress–strain state of skin and soft tissues under different loading conditions, targeting the linking of this state to tactile perceptual response. Of note, the mechanical state that originates from these interactions has been proven to propagate via mechanical energy waves also far from the contact zone, eliciting mechanoreceptors-mediated responses in other skin areas not directly involved in the haptic interaction (Shao et al. 2016). However, this aspect is not taken into account in FE modelling, given that the majority of touch-sensitive neurons are located in the hand (Ryan et al. 2021), and that the complexity of an appropriately detailed FE model with such a wide scope would be prohibitive. In the next section, the criteria for the collection and screening of the studies included in this survey are detailed.

2.1 Study selection

Haptically focused FE models can be found in the literature, with varying degrees of complexity, ranging from simple 2D time-invariant models of fingertip sections (Maeno et al. 1998b), to realistic and multi-layered dynamic simulators for the entire hand, such as the example shown in Fig. 1 (Wei et al. 2020). It is worth mentioning that FE models of human fingers and hands have also been proposed for visual rendering in Virtual Reality (VR), where FE methods are used for simulating soft tissue deformation during contact with virtual objects (Tong et al. 2023). The main goal of these models is striking a balance between the visual realism of the behaviour of the hand, and tight temporal constraints for real-time rendering with reduced computational costs. To achieve this, the actual biomechanics and the separation of tissue layers are often simplified, sacrificing the accuracy of the internal mechanical state during the interactions (Hirota and Tagawa 2016). Another category of FE models of hands available in the literature are the anatomically accurate musculoskeletal ones, which are developed for realistic simulation of the kinaesthetic behaviour of the

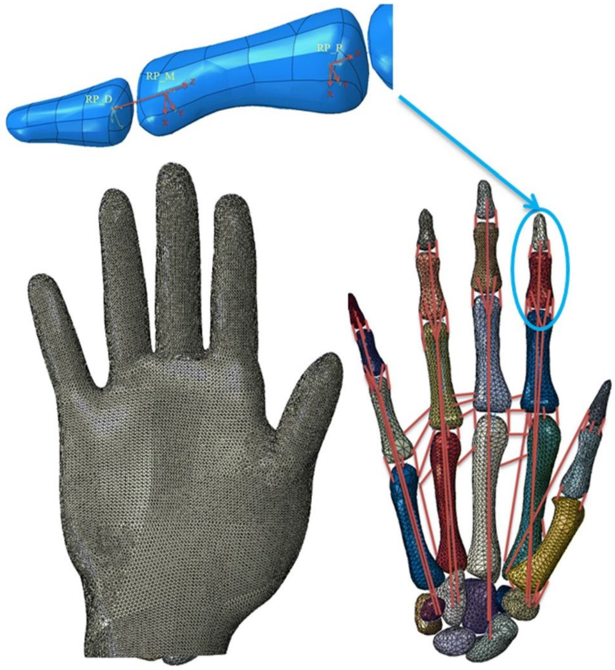

Fig. 1 FE model of the whole hand from (Wei et al. 2020), used to simulate grasp and tactile exploration (Wei et al. 2022a), with the directions of ligaments and tendons drawn in red (not included in the model). On top, the detail of the finger joint model is shown, evidencing the local axes defined for each bone which are constrained to only rotate relative to one another. evidenced in red. In the image, RP is 'reference point', and individual reference points are identified by a Latin character (D, M, P)

hand or the hand-arm complex (Lv et al. 2022). Although accurate in representing the mechanical properties of the biological components, these models usually focus less on the skin, which is sometimes discarded, and more on the rigid elements in the hands and arms, such as the bones as well as the joints and tendons that interconnect them. The studies presenting models of these types cannot be described as haptically focused and, because of this, they were not included in our survey.

Studies were initially collected using *Scopus* (Elsevier Ltd., Oxford, United Kingdom); the *Cadima* online service (Julius Kühn-Institut, Quedlinburg, Germany) was used to track the results of the initial search and to remove duplicates. The search strings for the initial collection of studies were created by selecting one keyword from each of the four lists in Table 1, combined using "AND". All possible keyword combinations were employed, with the exception that synonymous terms (e.g., "touch"/"tactile," "model"/"modelling") were grouped together and linked by "OR". A total of 113 studies were collected, of which 14 duplicates. Additionally, 16 studies were deemed out of scope during initial screening, based on abstract review, leaving 83 studies for full-text assessment. The excluded

Table 1 List of keywords used to build search strings for the initial collection of studies. The words in "Scope" referred to the anatomy targeted by the model; those in "FE method" were used to signify the focus of the search, i.e., studies on FE modelling of the mechanics of the human hand and its skin; those in "Biomechanics" concerned specific mechanical properties of the modelled tissues, and of their response to external loads; those in "Interaction" included possible types of contact loads that exist in the context of active or passive touch

Scope	*"skin", "hand", "finger", "fingertip"*
FE method	*"FEM", "finite element", "model", "modelling" "response", "simulation", "numeric"*
Biomechanics	*"biomechanics", "mechanics", "hyperelastic" "viscoelastic", "elasticity", "viscosity" "stiffness", "friction", "dynamics" "frequency", "vibration", "quasi-static"*
Interaction	*"haptic", "touch", "tactile", "contact" "compression", "pressing", "tapping", "sliding" "grip", "grasp", "exploration", "texture" "surface", "compliance", "softness", "rough" "edge", "curvature", "shape"*

works focused on artificial skin or robotic fingertips, or employed computational methods other than FE analysis. Of the initial batch, only 52 studies were included in the final paper, according to the criteria detailed in this section. 24 more sources were either identified from citation searching or were added to further detail the work of already cited authors. Compliance with the PRISMA standard (Preferred Reporting Items for Systematic Reviews and Meta-analyses (Page et al. 2021)) was ensured by compiling the associated checklist; the standard PRISMA flowchart is used in Fig. 2 to summarize the study selection process.

2.2 Contribution

Our survey is not the first effort present in the scientific literature regarding the analysis and simulation of biomechanical properties of human skin and hands. In this section, we refer to pre-existing surveys on the same broad topic, highlighting their differences with our work to clarify our contribution to the state of the art.

An existing review by Deflorio et al. (Deflorio et al. 2022) focuses on modelling the touch-induced activation of the mechanoreceptors, and how it can be related to the mechanical deformation of the skin. FE analysis is brought up in the review as one of the potential methods for simulating the mechanical behaviour of the tissues, to the extent that is necessary to estimate the quantities (e.g., strain) that trigger and drive responses in the neural afferents. The authors compare FE with alternative modelling techniques, citing the FE model from Gerling et al. (Gerling et al. 2014) as a meaningful example. The specific characteristics of the example are not compared with other FE models, which

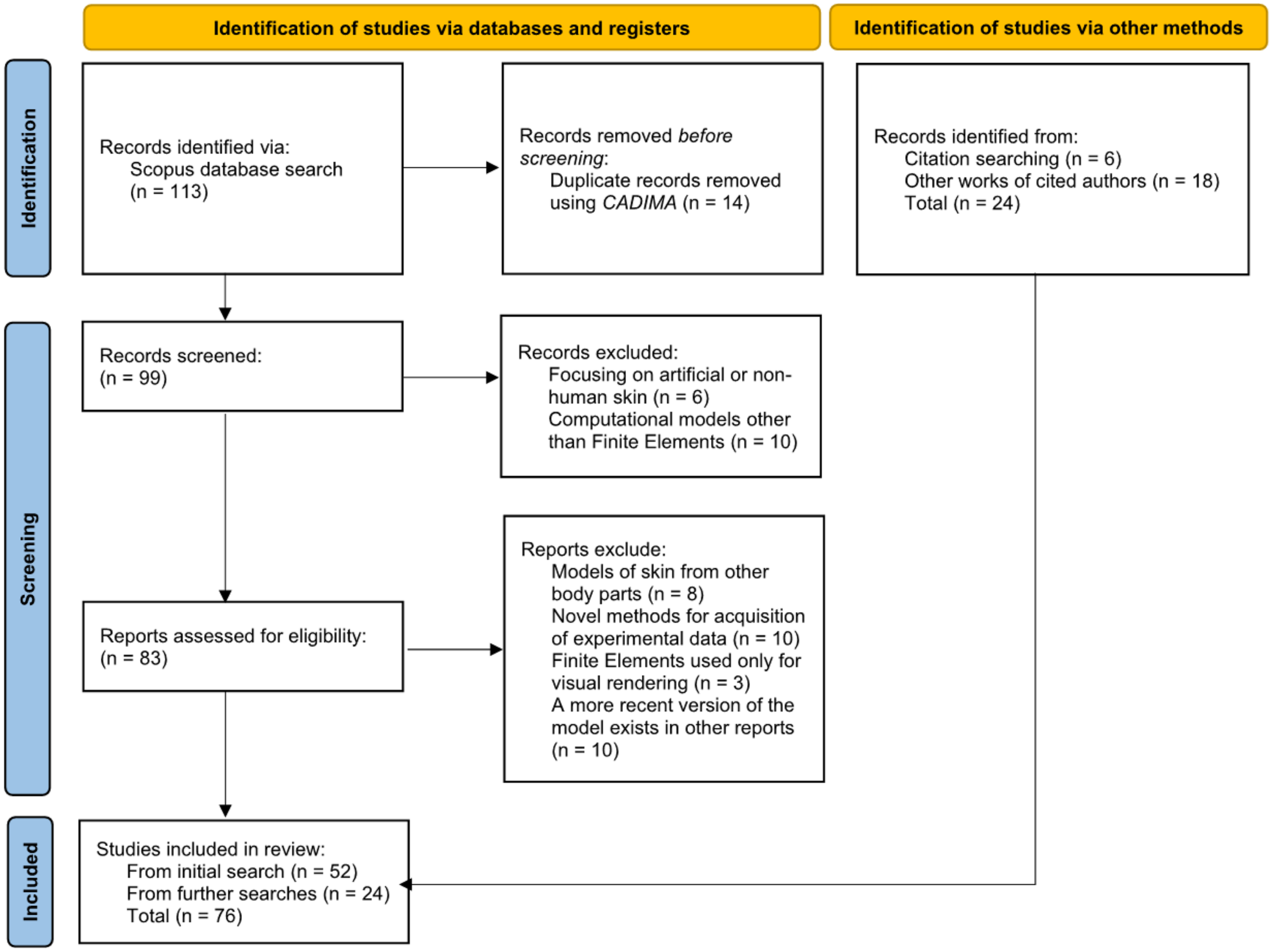

Fig. 2 PRISMA flow chart summarizing the study selection process (Page et al. 2021)

is what our manuscript focuses on instead, discussing the design choices made in the creation of each cited FE model with respect to related ones. We intend to provide guidelines that, once FE is selected as the appropriate solution for a given application, can be used to inform the construction of a new FE model, tailored to a specific research question. Tong et al. (Tong et al. 2023) carried out a survey on the haptic simulation of deformable human hands in VR environments, in the context of rendering a virtual hand avatar. FE analysis is mentioned as one of the tools used in this type of model, but the implementation of hand FE models is not discussed in detail. As discussed in section 2.1, in these applications, the main goal is not biomechanical accuracy, and as such they cannot be considered haptically focused. Another review by Biswas and Visell (Biswas and Visell 2021) refers to the biomechanics of active tactile exploration, and how the properties of the hand allow for the varied capabilities of human touch perception. The paper details the interplay between the various mechanical and kinaesthetic stimuli during tactile interactions, and how these stimuli could be replicated in haptically-endowed *Extended Reality (XR)* systems. Simulation models for these relationships are only briefly mentioned, and the FE method is not taken into consideration. Lastly, the survey by Mostafavi Yazdi and Baqersad (Mostafavi Yazdi and Baqersad 2022), while not specifically concerned with FE analysis, provides a detailed summary of commonly used constitutive laws for modelling the biomechanics of the human skin, and of the experimental tests that are typically carried out to experimentally derive the model parameters. It is worth mentioning that the design of haptically focused FE models requires the inclusion of accurate constitutive models of the skin, as well as the usage of experimental data, usually acquired *in vivo*. The mentioned survey discusses constitutive models which are apt for this purpose, and also collects publicly available sets of parameters for each type of model. However, very few of the given parameter sets are devised specifically for the skin of the human hand.

In light of these comparisons, and to the best of our knowledge, our review appears to be the only one focused on FE models of the human finger and hand and their soft tissues that are specifically created to study and model human haptic interaction. Our contribution concerns the comparison between the variety of published models, based on their adherence to real human biomechanics and on their capability to estimate a variety of mechanical behaviours. From this comparison, we try to design and provide guidelines for researchers who need to develop FE models of this type.

3 Biomechanics of touch

Tactile perception is produced in human skin by the activation of *mechanoreceptors*, specific cells that are scattered throughout the skin and are sensitive to mechanical stimuli such as strain and vibration (Biswas and Visell 2019). In humans, the glabrous skin of the hands has an especially high density of mechanoreceptors, which increases from the palm to the distal phalanges (Ryan et al. 2021). Mechanoreceptive afferent neurons are classically categorized into two main classes: *slowly activating (SA)*, which are mainly activated in response to low-frequency stimuli, and *rapidly activating (RA)*, prominently sensitive to transient and oscillating stimuli up to a wide high-frequency range. The two relevant types of SA afferents are those that end respectively in *Merkel cells*, which are sensitive to static skin deformation, but also respond to transient deformations; and those with *Ruffini endings*, which are mainly located around the nail and are sensitive to skin stretch. RA afferents also comprise two main categories, consisting of those ending in *Meissner corpuscles*, responsive to oscillating frequencies up to 100 Hz, and those ending in *Pacini corpuscles*, sensitive to stimuli ranging from 10 up to 1000 Hz, located in deeper skin tissues and endowed with very large receptive fields. In hairy skin, C tactile (CT) afferents are also worth mentioning, which are fundamental in encoding touch-enabled stimuli with an affective or social valence (Ryan et al. 2021).

The glabrous human skin, which is the focus of our work, is composed of two main layers, called epidermis and dermis. The *epidermis* is the most external layer, which is the stiffer part of the skin and includes structures such as the fingerprint ridges. The *dermis* is the deeper, softer layer, which houses most of the mechanoreceptors (Deflorio et al. 2022). The interface between epidermis and dermis is not smooth but instead composed of undulations called *papillae*, which are believed to help in the transmission of tactile signals to the mechanoreceptors. Indeed, the stiffness gradient in going from epidermis to dermis and the related restriction of the capability for deformation of the skin are thought to provoke an amplification of mechanical stimuli (Gerling and Thomas 2005). The lower part of the dermis is called *reticular region* because of the dense structure of *elastomeric* and *collagen fibres*, which act as a support structure for the skin and limit its capability for deformation, allowing it to return to its original shape after being loaded (Daly 1982). The mechanical behaviour of these fibres is highly dependent on the direction of loading, showing a stiffer response along the so-called *Langer's lines* (Langer 1861; Ní Annaidh et al. 2012). The mass of tissue below the dermis is usually denoted as *subcutaneous*; it has a high content of liquids (e.g., water, blood, or globules of fat) and greater compliance than the skin, demonstrating relevant properties of viscosity. In Fig. 4, the separation between the tissue layers of a human fingertip is shown represented in an FE model (Serhat et al. 2022). For an extensive review of the properties of mechanoreceptive afferent neurons, mechanoreceptors, and the layers of the skin, the interested reader is invited to refer to, e.g., Johnson (Johnson 2001), Biswas and Visell (Biswas and Visell 2021), Ryan et al. (Ryan et al. 2021) and Deflorio et al. (Deflorio et al. 2022).

The *constitutive law* of a material can be defined as the relationship between stresses and strains during loaded deformation. FE models require the introduction of constitutive laws which describe the mechanical response of the associated solid material to imposed loads. In the majority of cases, and especially, where nonlinear constitutive laws are required, the parameters that characterize them are determined by fitting the constitutive equations to experimental data (Fung 1993), such as the force-displacement curves obtained by compressing a fingertip pulp (Maeno et al. 1998b). The rest of this section details the most relevant mechanical properties of the soft tissues of the hand and fingers that can be replicated in FE models, and the constitutive laws that have been used in examples taken from the literature. Figure 3 provides a synthesis of the content of the following sections. In the majority of FE models, tissues are assumed to be *homogeneous*, i.e., the materials have identical properties at all internal points, and *isotropic*, i.e., the properties are the same in all directions within the material. Neither of these assumptions is conservative; indeed, many biological tissues including the skin are well known to be neither homogeneous nor isotropic due to the complex nature of their composition (Fung 1993; Ní Annaidh et al. 2012).

3.1 Tissue elasticity

As is well known, the *elasticity* of a material is its capability to deform under an external load, and completely recover its original shape and size once the load has been removed. It is the first and most significant property that must be taken into account when modelling the biomechanical behaviour of a material. *Linear elasticity (LE)* is the simplest constitutive model and follows directly from a generalization

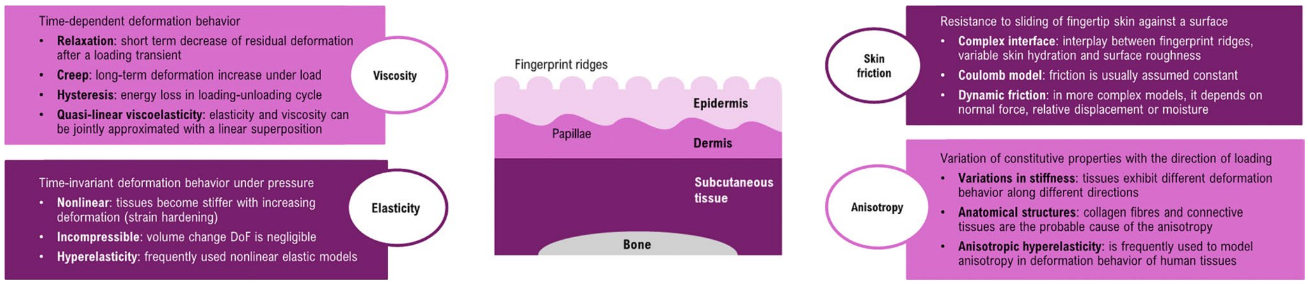

Fig. 3 Synthesis of the most relevant biomechanical properties of the soft tissues of the human hands, and the typical constitutive models used to describe them

of Hooke's law, that is, the strains are proportional to the stresses that cause them. The fixed ratio of stress to strain is called the material's Young's modulus E. For multiaxial loading, all stress–strain relationships remain linear and the entirety of a homogeneous LE material can be characterized just by two parameters: Young's modulus E and Poisson's ratio ν, i.e. the ratio of lateral strain to axial strain. Experimental observations from multiple sources have shown that the human skin only behaves like a linearly elastic body when undergoing limited deformations (Mostafavi Yazdi and Baqersad 2022). Indeed, it exhibits mostly nonlinear behaviour in touch-related contact interactions, which generally involve forces up to 10 N and/or indentations up to 5 mm. The stiffer elements present in the human hand, namely bones and nails, are generally considered linearly elastic in the range of deformations associated with these interactions. The nonlinear elastic behaviour of the glabrous skin is instead mainly caused by the soft tissues. It is often described in terms of *strain hardening*, i.e., the stiffness increases with increasing deformation (Wang and Hayward 2007). In practice, this results in force-deformation relationships, where great strains are induced from the undeformed state with small loads, up to approximately 1 N, but the force required to increase the strains grows sharply with the deformation itself (Pawluk and Howe 1999; Serina et al. 1998). The commonly adopted solution to describe a material that has fully elastic behaviour, but does not follow a linear law, is *hyperelasticity* (Lapeer et al. 2010). Hyperelastic materials are usually described using a function of *strain energy (SE)*, a form of potential energy associated with elastic deformation of solids (Ali et al. 2010). In bodies that undergo large deformations, SE can be related to the local deformation gradient by means of an SE density function. The main assumption of the theory of hyperelasticity is that the behaviour of the solid is *time-invariant*; this assumption is usually not verified with the human skin. Commonplace hyperelastic constitutive laws are usually written under the additional hypothesis of *incompressibility* of the material (Rivlin 1992). In FE simulations of hand soft tissues under quasi-static conditions, the hypothesis of incompressibility holds since the degree of freedom of volume change tends to be negligible with respect to the shear deformation (Wu et al. 2004). Most formulations of the SE density function were originally developed to describe the elastic behaviour

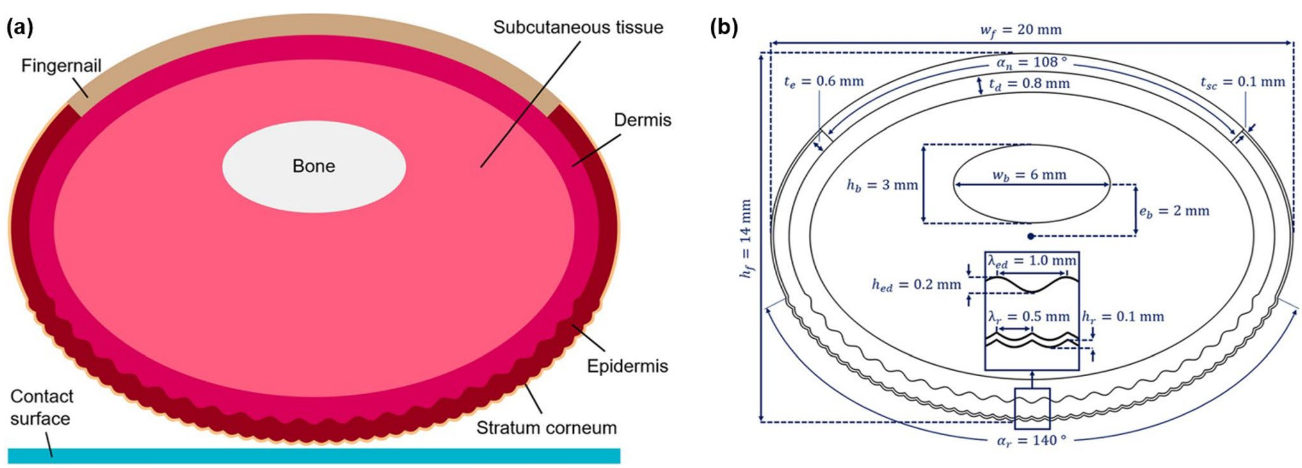

Fig. 4 Geometry of the FE fingertip model from (Serhat et al. 2022), used to investigate the effect of moisture on the contact areas generated when compressing the finger.**a** Detail of the tissue layers included in the model. **b** Size of the fingertip and of the individual layers, with detail of the dermal papillae and epidermal ridges

of artificial rubbers (Ali et al. 2010), but have then been applied to other compliant materials, and are apt for the characterization of highly deformable biological tissues like skin (Lapeer et al. 2010). Among these models, the most commonly used are the Ogden-Storakers (Ogden 2003), the Mooney-Rivlin (Rivlin 1992), the Neo-Hookean (Kossa et al. 2023) and the Yeoh (Yeoh 1993) formulations. The first two are the most commonly used for finger and hand models, with the widest availability of published parameter sets (Harih and Tada 2019; Wei et al. 2020; Wu et al. 2010; Khojasteh et al. 2018). Although significantly less common, parameter sets for Yeoh and Neo-Hookean models can be found in the literature (Vodlak et al. 2015; Almagirby et al. 2018). Yeoh and Neo-Hookean SE density functions have a smaller number of coefficients, and are therefore suitable when there is scarce availability of experimental data (Vodlak et al. 2015), or the available data is not specific for the type of loading studied (Almagirby et al. 2018).

3.2 Tissue viscosity

It is well-documented that, depending on the distribution in time of the application of the external loads, the soft tissues of the hand exhibit time-dependent behaviour that cannot always be fully captured even by a nonlinear elastic law (Serina et al. 1998). This behaviour is usually called *viscosity*, and the tissues that demonstrate it are commonly referred to as *viscoelastic*. The viscous behaviour of soft tissues is usually described through three phenomena: relaxation, creep, and hysteresis, of which an exhaustive experimental characterization was carried out by Wang and Hayward (Wang and Hayward 2007). In detail, *relaxation* refers to the progressive stabilization of the mechanical state of the fingertip after a transient in the mechanical loading (Jindrich et al. 2003). The imposed load, usually contact force, required to maintain a certain configuration or deformation, rapidly decreases after the transient phase and then reaches a lower, stable value in the span of a few seconds (Pataky et al. 2005). Additional relaxation also happens slowly over time after the finger is unloaded: noticeable amounts of deformation persist in the fingertip after the unloading transient and its original shape is only recovered after some seconds (Pataky et al. 2005). In opposition, *creep* consists in the slow increase of deformation in the soft tissue when the external load is kept constant over time. Agache and Humbert (Agache and Humbert 1995) observed three phases of skin creep (an initial purely elastic deformation, a viscoelastic phase, and a constant creep phase) and pointed to the realignment of the dermal collagen fibres as the origin of this behaviour. Wang and Hayward observed creep to happen twice as slowly as relaxation, and suggested instead that both could be caused by motion of fluids in and out of the body part (Wang and Hayward 2007). Lastly, *hysteresis* refers to the loss in strain energy that occurs in the fingertip in the span of a full loading-unloading cycle, thought to be caused by internal friction (Capace et al. 2021). As an observable effect of hysteresis, deformation decreases during unloading more slowly than it increases during loading. Wang and Hayward observed that this dissipation is highly repeatable and independent of the period of the cycle as long as it is greater than 10 s, but cycles faster than that tend to express minor losses (Wang and Hayward 2007). For the purpose of joint modelling of the viscous and elastic response of soft tissues, Fung proposed a *quasi-linear viscoelasticity (QLV)*, which treats the elastic and the viscous behaviours as two separate, additive stress components (Fung 1993). In the case of finger glabrous skin models, Wu et al. (Wu et al. 2003) support the idea that the constitutive stress–strain relationship can be written as a linear superposition of an elastic and a viscous term, even where one or both components are internally nonlinear. For these applications, the viscous term is often formulated via a Prony series (Soussou et al. 1970; Tschoegl 2012), while the elastic law can be chosen independently as linear or hyperelastic to fit the specific application. Multiple parameter sets for QLV constitutive laws used in FE modelling of the soft tissues of the hand are available. These models integrate with viscosity various formulations of elasticity: linear (Tang et al. 2016), or nonlinear, such as Ogden (Wu et al. 2003), Mooney-Rivlin (Wu et al. 2010), Neo-Hookean (Almagirby et al. 2018) and Yeoh (Vodlak et al. 2016) strain energy potentials.

3.3 Material anisotropy

As noted previously, neglecting mechanical *anisotropy* is known to be too restrictive when dealing with many biomechanical properties of tissues (Langer 1861; Ní Annaidh et al. 2012). The human fingertip, in particular, has been shown to possess anisotropic elasticity and stiffness, associated among other factors with the superficial ridges of the epidermis (Wang and Hayward 2007) or with dermal structures such as the collagen fibres (Daly 1982). This element is often neglected when dealing with the FE modelling of fingers and hands; however, it would be beneficial to take it into account if striving for adherence of the behaviour of a model to the real anatomy (Dallard et al. 2014). As a starting point for studies going in this direction, linear anisotropic models are easy to implement and could provide a valuable approximation of directional properties of the glabrous skin: *orthotropic* or *transversally isotropic* models can be used to reduce the number of parameters required for the constitutive law, under the assumption of existence of symmetry planes for the mechanical behaviour (Ogden 2003). On the other hand, using linearly anisotropic models for biomechanical modelling retains most issues presented by all linear elastic constitutive laws, and requires the additional hypothesis of knowing the local principal directions of the material, so mindful use is required (Serina et al. 1998). Although usually applied to different anatomy with respect to the tissues of the human hand, elastic constitutive laws exist that are based on anisotropic hyperelastic SE density functions, most notably the *Holzapfel-Gasser-Ogden (HGO)* (Holzapfel et al. 2000; Gasser et al. 2005). Duprez et al. used an HGO potential to investigate the inclusion of the directional properties of collagen fibres in an FE model of a human fingertip (Duprez et al. 2024). Chamoret et al. (Chamoret et al. 2013) also developed an FE simulation of contact between a human hand and a soft material, both treated as nonlinear and anisotropic, using a version of the HGO constitutive law. To the best of our knowledge, these are the only FE models of the human hand that take nonlinear anisotropic elasticity into account.

3.4 Skin friction

While not strictly a constitutive property, but rather an emergent behaviour of the interaction between different materials, *friction*, i.e., the relationship between the component of the contact force normal to the contact surface and the tangential force component, is another relevant factor in modelling the biomechanics of tactile interactions. Finger pad friction is a highly complex phenomenon whose characteristics vary with physiological factors, e.g., age or skin elasticity and properties of the interface, such as roughness and moisture (André et al. 2010; Amaied et al. 2015; Pasumarty et al. 2011). In FE models, the coefficient of friction at the interface with the skin is usually taken as a constant value chosen based on the touched object material and its superficial properties (e.g., roughness) (Battaglia et al. 2015; Khojasteh et al. 2018; Wei et al. 2020). An example of more complex model of dynamic finger pad friction is that used by André et al. (André et al. 2009), in which the coefficient of friction is determined as a negative exponential of the normal component of the contact force (Barrea et al. 2016; Delhaye et al. 2024). Previous experimental observations also supported the idea of modelling the coefficient of friction of the fingertip skin as an exponential function of the normal contact force (Han and Kawamura 1996; Sivamani et al. 2003), and the validation of a similar friction law using FE is proposed in a study by Yoshida et al. (Yoshida et al. 2011). Other studies investigated the relationship between superficial textures, such as ridges, gratings or reliefs, and frictional forces in the context of relative sliding motion (Janko et al. 2018b; Peng et al. 2021). Another factor which has an impact on friction in tactile contact is interface moisture, whether caused by the skin or present on the touched surface (Adams et al. 2013; Peng et al. 2021). These studies intended, through extensive experimental campaigns, to characterize the nonlinear, dynamic variations of the frictional forces according to the properties of the contact interface. However, the implementation of any complex frictional law in an FE model of the human hand is still an under-explored topic.

4 Finite Element models of human hands and fingers

Haptically focused FE models must achieve realistic simulation of mechanical behaviour to accurately estimate deformations, pressures, vibration responses, and contact areas, because these quantities directly inform the output of the receptors in the skin (Gerling et al. 2014). Contact problems are among the most complex to represent in FE analysis, and they add other nonlinearities on top of those intrinsic to the biomechanical system (Robert et al. 2012). As a consequence of such complexity, any FE analysis conducted on this topic must select a subset of questions to be answered by the model, making assumptions about the issues that are not focal to the problem at hand or justifying their removal using experimental observations. To achieve accurate results through FE simulation, it is therefore desirable to develop models that are specifically geared towards the intended goal. In this section, we review some of the most relevant results that can be achieved via FE analysis of haptic interactions, comparing existing models built for this purpose and providing guidelines on how to create new ones for similar cases. Design choices pertaining to each model will be described according to the three following criteria:

- *Geometric complexity*: the degree of accuracy of the shape of the FE model with respect to a real human finger or hand. This includes the dimensionality (2D or 3D), the number and shape of the skin layers, the inclusion of structures such as fingerprints or dermal ridges, or the adherence of the geometry to medical images of real patients.
- *Biomechanical complexity*: the implementation of nonlinearities, time-dependencies, and anisotropies in the constitutive models chosen for each type of material. This also includes the presence of functional structures such as bone joints, tendons, or ligaments.
- *Interaction complexity*: the amount of detail and realistic properties considered when modelling contact. It includes elements such as boundary conditions, vibrations, whether the simulation is static or dynamic, what types of loads are imposed, etc.

Whenever applicable, in the next paragraphs, models will be presented and compared with respect to the three given criteria. The majority of the FE models discussed in this section are limited in scope to a single fingertip, e.g., the distal phalanx of an index finger. Haptically focused models of a whole finger or the entire hand are on the other hand few in the literature (Wu et al. 2017; Harih and Tada 2019), due to the complexity added by the presence of joints and tendons between finger bones, whose kinaesthetic properties are interwoven with the mechanical behaviour of the soft tissues. The content of this section with the suggested design practices is shown in Table 2.

4.1 Static contact modelling

A first use-case for FE models of human hands is simulating the mechanical behaviour of a finger pad pressed against a surface, estimating its mechanical stress–strain state. Frequently, the application of such loads can be assumed to happen slowly over time, i.e., in a timespan of the order of a few seconds; under this assumption, the interaction can be simulated in quasi-static conditions (Harih and Dolšak 2014; Hokari and Pramudita 2023). In practice, this simplifies the model, allowing to neglect the transmission of mechanical vibrations through the materials and the time-dependent, viscous properties of the soft tissues, the effect of which is negligible when loads are applied slowly, as mentioned in Sect. 4.2. Experimental data from different sources can be more easily compared with a quasi-static simulation, because the actual time-dependency of the application of the load can also be abstracted away in the simulation. Care should always be taken in verifying that the neglected aspects of the interactions do not significantly affect the simulation results, by validating the simplified model against experimental data. Especially at higher loading speeds, a comparison in accuracy between a quasi-static and a dynamic simulation can also be carried out to verify the model's adherence to the real biomechanics. Data from simulated quasi-static loading of a human finger pad can be used to carry out ergonomic analysis (Chamoret et al. 2010; Harih and Tada 2015), to be compared with data acquired via novel experimental methods as a ground truth (D'Angelo et al. 2019; Logozzo et al. 2022b), or to investigate the potential relationship between mechanical quantities and perceived tactile properties, such as softness (Battaglia et al. 2015; Hokari and Pramudita 2023). This type of FE analysis is often focused on the relationship between contact forces and resulting contact areas (Logozzo et al. 2022b; Xu et al. 2018), distributions of contact pressures (Harih and Tada 2015; D'Angelo et al. 2017) or of elastic strains (Hokari and Pramudita 2023) in the finger volume. Under the quasi-static assumption, elasticity is the main factor in selecting the constitutive laws for the soft tissues. Many such analyses choose to implement the soft tissues as linear materials (Shimawaki and Sakai 2007; Logozzo et al. 2022b) but in the majority of the recent studies hyperelasticity was introduced (with the exception of bones and nails) to achieve higher adherence to real behaviour (Battaglia et al. 2015; D'Angelo et al. 2019). Structures such as epidermal ridges and dermal papillae are most frequently neglected instead, opting for smooth separation surfaces between tissues (Battaglia et al. 2015; Logozzo et al. 2022b); indeed, the effect of these microstructures on the stress–strain states is highly localized (Shao et al. 2010). On the other hand, the different mechanical properties of the relevant soft tissues affect the overall behaviour of the finger or hand (Shimawaki and Sakai 2007), therefore models in this category should include multiple tissue layers differing in constitutive model. The touched surfaces are usually assumed flat, unless the effect of texture or curvature is the specific focus of the study (Xu et al. 2018). They can be either rigid (D'Angelo et al. 2019) or compliant (Battaglia et al. 2015; Hokari and Pramudita 2023), frictionless (D'Angelo et al. 2017) or rough (Vodlak et al. 2015), again depending on which parameters are being investigated through the simulation. When present, frictional properties are usually expressed via a constant coefficient of friction (Vodlak et al. 2015; Battaglia et al. 2015). In the majority of cases, problems of this category can be addressed by considering only a single fingertip (D'Angelo et al. 2019; Hokari and Pramudita 2023), although limiting the model to a 2D section of the fingertip is not recommended, as it reduces accuracy in the computation of the pressure distributions (Harih et al. 2016). An example of such a 3D fingertip model is shown in Fig. 5 (D'Angelo et al. 2017). Models in this category are simple to create, when compared with analyses that take into account dynamics or multi-finger interactions. However, the user should be wary of the relevant number of assumptions that are usually made in modelling, comparing simulation results to experimental data to evaluate their accuracy, and keeping in mind that the results are often not conservative. Examples of published experimental data that can be used to validate these simulations include contact

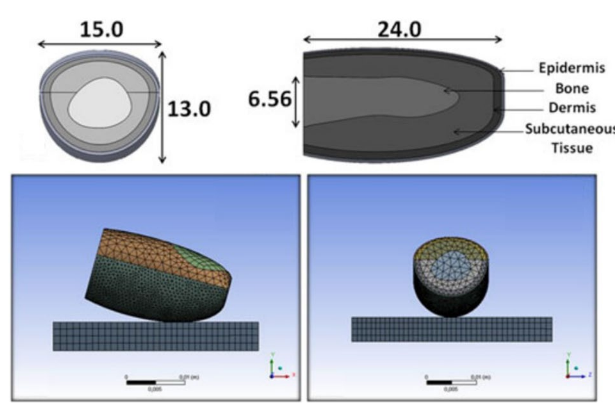

Fig. 5 Geometry and mesh of the FE fingertip model from (D'Angelo et al. 2017), developed as a comparison with a novel experimental method for measuring contact areas and pressures. Dimensions are expressed in mm

Table 2 Summary of Sect. 4, highlighting for each category the characteristics of the main cited FE models. The evaluation follows the three design criteria described at the beginning of Sect. 4

Model	Geometric complexity	Biomechanical complexity	Interaction complexity
4.1. *Static contact*			
(Maeno et al. 1998b)	2D transverse fingertip section, 3 soft tissue layers with fingertip ridges and papillae	Linear elastic, inviscous materials, no friction	Quasi-static pressing of a flat, rigid indenter against the fingertip
(D'Angelo et al. 2017)	3D fingertip model, 3 soft tissue layers, no microstructures	Hyperelastic, inviscous, Mooney-Rivlin materials, no friction	Quasi-static pressing of a flat, rigid indenter against the fingertip
(Logozzo et al. 2022b)	3D fingertip model, 3 soft tissue layers, no microstructures	Linear elastic, inviscous materials, no friction	Quasi-static displacement-controlled indentation of the fingertip in a soft, flat material sample
(Hokari and Pramudita 2023)	3D fingertip model, 3 soft tissue layers, no microstructures	Hyperelastic, inviscous, Ogden materials, Coulomb friction	Quasi-static force-controlled indentation of the fingertip in a soft, flat material sample
4.2. *Dynamic contact*			
(Wu et al. 2004)	2D transverse fingertip section, 2 soft tissue layers, no microstructures	Hyperelastic, Ogden materials with additive Prony viscoelastic term, hydraulic permeability model for subcutaneous tissue, no friction	Dynamic, displacement-controlled pressing of different pointed, rigid indenters against the fingertip
(Wu et al. 2006b)	3D fingertip model, 3 soft tissue layers, no microstructures	Hyperelastic Mooney-Rivlin materials with additive Prony viscoelastic term, no friction	Dynamic, displacement-controlled pressing of flat and pointed rigid indenters against the fingertip
(Giavazzi et al. 2010)	2D transverse fingertip section, 3 soft tissue layers with fingertip ridges and papillae	Hyperelastic Yeoh materials with additive Prony viscoelastic term, Coulomb friction	Dynamic suction of fingertip skin in a rigid cavity
(Kumar et al. 2015)	3D fingertip model, 3 soft tissue layers, no microstructures	Linear elastic materials with additive Prony viscoelastic term, no friction	Dynamic, displacement-controlled pressing of cylindrical and pointed rigid indenters against the fingertip
4.3. *Vibration transmission*			
(Wu et al. 2017)	3D FE finger model and lumped element model for the rest of the hand, one soft tissue layer, connective tissue at joints, no microstructures	Hyperelastic Mooney-Rivlin materials with additive Prony viscoelastic term, finger joints as hinges and universal joints with torsional springs and dampers, Coulomb friction	Transmission of vibrations induced by oscillating cylindrical soft object gripped by the finger
(Almagirby et al. 2018)	2D transverse fingertip section, 2 soft tissue layers, no microstructures	Hyperelastic Neo-Hookean materials with additive Prony viscoelastic term, no friction	Transmission of vibrations induced by oscillating flat, rigid surface pressed on the fingertip
(Noël 2018)	3D finger model, one soft tissue layer, connective tissue at joints, no microstructures	Hyperelastic Ogden materials with additive Prony-like viscoelastic term, finger joint properties are neglected, no friction	Transmission of vibrations induced by oscillating cylindrical rigid object pressed on the fingertip
(Serhat and Kuchenbecker 2024)	3D fingertip model, 3 soft tissue layers, no microstructures	Linear elastic, inviscous materials, no friction	Vibrations induced in the fingertip by harmonic point forces applied on the skin
4.4. *Tribologic properties*			
(Shao et al. 2010)	2D transverse fingertip section, 3 soft tissue layers with fingerprint ridges, no microstructures	Linear elastic, inviscous materials, no adhesive friction	Quasi-static displacement-controlled sliding of the fingertip against textured surfaces
(Amaied et al. 2015)	2D transverse fingertip section, 3 soft tissue layers with fingerprint ridges	Linear elastic materials with additive Prony viscoelastic term, no adhesive friction	Dynamic, displacement-controlled sliding of the fingertip against textured surfaces
(Khojasteh et al. 2018)	2D transverse fingertip section, 3 soft tissue layers with fingerprint ridges	Hyperelastic, inviscous, Mooney-Rivlin materials, Coulomb friction	Dynamic, displacement-controlled sliding of the fingertip against textured surfaces

Table 2 (continued)

(Serhat et al. 2022)	2D transverse fingertip section, 4 soft tissue layers with fingerprint ridges and papillae	Linear elastic, inviscous materials, modified Coulomb friction model	Quasi-static displacement-controlled pressing of the fingertip against surfaces of different friction
4.5. *Grasp analysis*			
(Chamoret et al. 2016)	3D hand model, one soft tissue layer, detailed joint synovial capsules, no microstructures	Linear elastic, inviscous materials, torsional springs and dampers at finger joints, Coulomb friction	Dynamic cylindrical grasping of a rigid object with imposed kinematics
(Hokari et al. 2019)	3D hand model, one soft tissue layer, no microstructures	Linear elastic, inviscous materials, finger joints as hinges, Coulomb friction	Quasi-static cylindrical grasping of rigid and soft objects with imposed kinematics
(Harih et al. 2021)	3D hand model, one soft tissue layer, no microstructures	Hyperelastic, inviscous, Ogden materials, finger joints as hinges with tendon force actuation, no friction	Quasi-static cylindrical and precision grasping of rigid objects with imposed kinematics and tendon forces
(Wei et al. 2020)	3D hand model, 3 soft tissue layers, detailed anatomy of the finger extensor mechanism, no microstructures	Hyperelastic, inviscous, Ogden materials, finger joints as hinges with tendon force actuation, Coulomb friction	Quasi-static cylindrical, spherical and precision grasping of rigid objects with imposed kinematics and tendon forces
4.6. *Mechanoreceptor response*			
(Gerling et al. 2014)	3D fingertip model, 3 soft tissue layers with no microstructures	Hyperelastic, inviscous, Mooney-Rivlin materials, no friction	Quasi-static pressing of a rigid pointed indenter against the fingertip
(Tang et al. 2016)	2D longitudinal fingertip section, 3 soft tissue layers with fingerprint ridges	Hyperelastic Ogden materials with additive Prony viscoelastic term, Coulomb friction	Dynamic, displacement-controlled sliding of the fingertip against textured surfaces
(Vodlak et al. 2016)	2D transverse fingertip section, 4 soft tissue layers with fingerprint ridges and papillae	Hyperelastic Yeoh materials with additive Prony viscoelastic term, no friction	Dynamic, displacement-controlled sliding of the fingertip against textured surfaces
(Ishizuka et al. 2022)	2D transverse fingertip section, 4 soft tissue layers with fingerprint ridges and papillae	Linear elastic, inviscous material model, Coulomb friction	Quasi-static pressing of a rigid pointed indenter against the fingertip

force-indentation (Maeno et al. 1998b; Serina et al. 1997), contact force-areas (Li and Gerling 2023; Logozzo et al. 2022a), contact pressure distributions (D'Angelo et al. 2019; Hokari et al. 2019) and more; for a meaningful comparison with quasi-static simulation, the loads should be applied at low speeds, e.g., less than 1 mm/s.

4.2 Dynamic contact modelling

Following what was said in Sect. 4.1 concerning static contact loading, it may be useful to build FE models capable of estimating the stress–strain states of finger pads also under dynamic conditions, taking into account their time-variant response (Wu et al. 2003). Most observations made in the previous case can be translated to the dynamic one, for example concerning friction and compliance of the touched objects or the inclusion of mechanically separate tissue layers. The most relevant increase in complexity is associated with the inclusion of time-variant material properties, requiring the use of a viscoelastic constitutive law to accurately predict, e.g., relaxation behaviour (Wu et al. 2003) (Kumar et al. 2015). In the majority of examples, the chosen constitutive law is a QLV model (see Sect. 3.2), composed of a Prony series to model viscosity and a hyperelastic potential as the elastic law (Wu et al. 2004) (Giavazzi et al. 2010). Due to the interplay between viscous and elastic behaviour in such cases, the use of hyperelastic constitutive laws is recommended (Wu et al. 2004). Indeed, simulations relying on linear elasticity have been shown to fail to capture relaxation or other viscous effects (Wang et al. 2012). The importance of viscous behaviour of the soft tissue is especially evident when considering different loading types which are not limited to normal compression, such as indentation (Wu et al. 2006b) (Kumar et al. 2015) or suction (Hendriks et al. 2003) (Giavazzi et al. 2010). Due to the large number of parameters in nonlinear, viscoelastic material laws, a comparison of the simulations with experimental data should be carried out (Wang et al. 2012). A wide variety of experimental test types return data that is apt for the purpose of validating these simulations, including dynamic compression (Pawluk and Howe 1999) (Nam and Kuchenbecker 2021) or indentation (Srinivasan 1989) (Iravanimanesh et al. 2021), suction (Hendriks et al. 2004) (Giavazzi et al. 2010), lateral displacement (Pataky et al. 2005) (Wang and Hayward 2007) and more. The greatest accuracy in stress–strain distributions with respect to a real finger is obtained only via 3D simulations (Wu et al. 2006b) (Kumar et al. 2015), although 2D analyses limited to a fingertip section can still offer valuable insights (Wu et al. 2004). Of note, Chamoret et al. developed an FE model of the entire hand to characterize its biomechanical behaviour during dynamic impact with a material sample having hyperelastic, anisotropic properties (Chamoret et al. 2013). Although the complexity of the modelled interaction is certainly remarkable, viscous properties are missing in the material models, and there is no attempt to model the behaviour of the finger joints. The simulated contact pressure results are not compared to any experimental data, therefore lacking validation (Harih and Tada 2019).

4.3 Vibration absorption and transmission

An inherently dynamic property of mechanical systems, which is relevant for the human hand in the context of tactile interactions, is the transmission of externally induced vibrations through the system. When interacting with a vibrating object or surface, or during sliding against rough or textured surfaces, the soft tissues of the human hand are subjected to vibrations which propagate through the hand and up the arm (Shao et al. 2016; Tummala et al. 2024). Modelling the transmission of such vibrations via FE (within computational limits, and therefore usually restricted to the hand and neglecting the effects on the rest of the arm) is useful in understanding these tactile interactions and how they are physiologically perceived and interpreted (Wu et al. 2006a), but also to derive considerations on the topic of ergonomics and safety of the interaction of human hands with vibrating objects (Robert et al. 2012). Often, such analyses are conducted assuming an external vibrating object or surface (Wu et al. 2017), or an otherwise oscillating exciting load (Serhat and Kuchenbecker 2024), although examples exist of simulation of transmission of friction-induced vibrations (Amaied et al. 2015). Although most studies tackle this issue using 2D (Wu et al. 2010; Almagirby et al. 2018) or 3D (Wu et al. 2008; Serhat and Kuchenbecker 2024) models of a single fingertip, including the rest of the finger or the hand is suggested when transmission of the vibration to the hand is relevant to the analysis (two such examples are shown in Fig. 6 and Fig. 7 (Wu et al. 2010; Noël 2018)). Fingertip models usually include 5 mechanically separate tissue layers (epidermis, dermis, subcutaneous, nail and bone) (Wu et al. 2008; Amaied et al. 2015), or even more in the case of Serhat and Kuchenbecker (Serhat and Kuchenbecker 2021). Tissue interfaces are usually modelled as smooth, although Amaied et al. take into account epidermal ridges (Amaied et al. 2015) for a more realistic representation of friction-induced vibrations. Skin elasticity can influence vibration transmission greatly, therefore care must be taken in its modelling (Almagirby et al. 2018; Amaied et al. 2015). Overall, when tackling this issue, complex constitutive models that fully capture the spectrum of mechanical behaviours of the skin should be used, concerning both elasticity (Serhat and Kuchenbecker 2021), viscosity (Wu et al. 2010; Almagirby et al. 2018) and mechanical properties of finger joints when included (Wu et al. 2017). Another relevant aspect

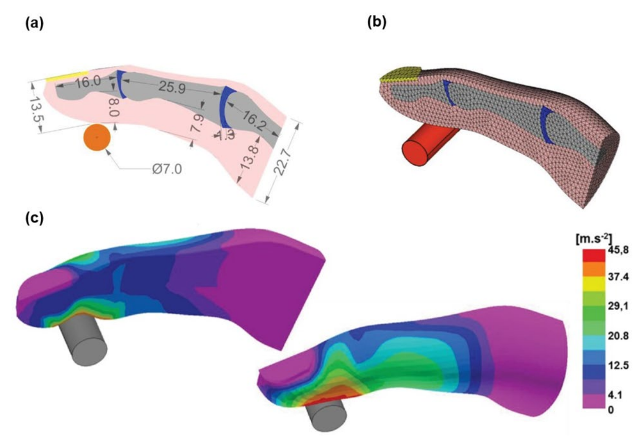

Fig. 6 Finger model from (Noël 2018), in contact with a cylindrical object. **a** Geometry of the finger, bones and connective tissues of the joints, with dimensions in mm. **b** Mesh of the model. **c** Example of propagation of vibrations through the finger, induced by oscillations of the cylindrical object, pressed against the fingertip

when modelling the transmission of vibrations induced by an external object is the pre-compression of the object against the finger, whose configuration (Wu et al. 2009) and intensity (Wu et al. 2007) greatly impact the response. This pre-compression can usually be assumed to happen following quasi-static behaviour (Noël 2018). Friction is usually represented via a constant coefficient (Wu et al. 2017) or even neglected when vibrations are transmitted normally to the contact interface by an oscillating object (Noël 2018), as it was shown to have negligible effects (Wu et al. 2007).

4.4 Tribologic properties

Another specific subset of haptic interactions that have been analysed through FE modelling is that of static or sliding contacts involving complex textures, friction and moisture at the interface (Khojasteh et al. 2018; Serhat et al. 2022). Here, the potential purposes of this modelling effort may include the identification of a nonlinear friction coefficient law that resembles the real behaviour of the fingertip interface (Yoshida et al. 2011); the estimation of friction force oscillations at the skin-texture interface (Shao et al. 2010; Khojasteh et al. 2018); or the modelling of moisture and its effect on interface friction (Nam and Kuchenbecker 2021; Serhat et al. 2022). Most of the examples cited in this section consist of 2D sections of fingertips, longitudinal (Tang et al. 2016) or transverse, such as the example shown in Fig. 8 (Khojasteh et al. 2018). These models have a large number of similarities, like including a large number of mechanically separate tissue layers (Amaied et al. 2015; Khojasteh et al. 2018; Serhat et al. 2022), with micro-scale geometric features such as epidermal ridges (Amaied et al. 2015; Khojasteh et al. 2018) and dermal papillae (Serhat et al. 2022). Indeed, the effect of such microstructures is relevant when investigating the highly local friction effects happening at the interface (Shao et al. 2010; Khojasteh et al. 2018; Serhat et al. 2022). Material models used for the fingertip soft tissues are sometimes linear elastic (Amaied et al. 2015; Nam and Kuchenbecker 2021) but more often hyperelastic (Yoshida et al. 2011; Tang et al. 2016; Khojasteh et al. 2018), and can include viscosity (Amaied et al. 2015; Tang et al. 2016), where dynamic effects are believed to significantly affect the results. In the 2D models, the friction coefficient is treated as a constant (Tang et al. 2016; Khojasteh et al. 2018), and the complexity of the contact behaviour emerges from the simulated interaction. As an exception, Serhat et al. implement a spring-like friction model, where the friction coefficient is the product of a constant and the relative sliding between the fingertip and the surface; different values of the constant are used to represent different moisture conditions (Serhat et al. 2022). Touched surfaces

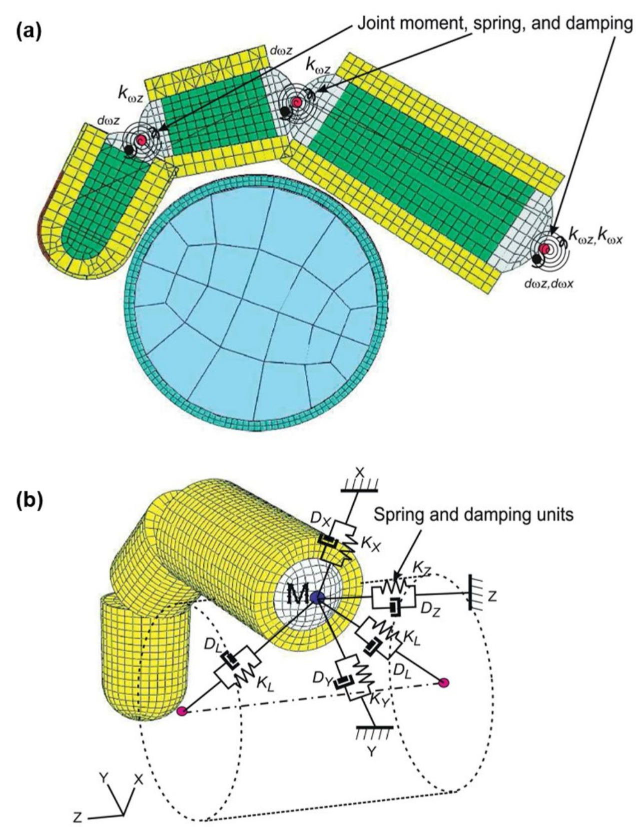

Fig. 7 Finger model from (Wu et al. 2017), designed to simulate the effect of grasp force on the transmission of vibrations provoked by a grasped oscillating object. **a** Mesh of the model, showing the mechanical representation of the finger joints as torsional spring-damper systems. **b** Schematic representation of the spring and damper connections between the finger model, the grasped object and the ground, used as an abstract representation of the rest of the hand, not included in the model

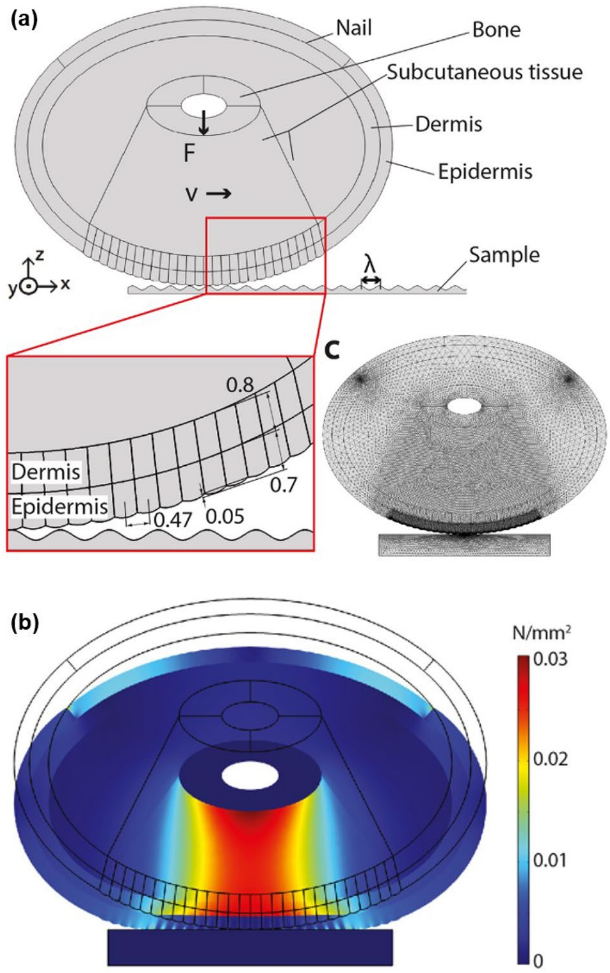

Fig. 8 FE model from (Khojasteh et al. 2018), designed to estimate friction force oscillations during sliding of the fingertip over textured surfaces. **a** Geometry of the model and the textured sample, showing in detail the epidermal ridges (dimensions in mm). Force F and velocity v imposed on the fingertip are shown. **b** Mechanical stress induced in the fingertip when pressed against the textured sample

are often treated as rigid (Khojasteh et al. 2018; Serhat et al. 2022) and flat (Nam and Kuchenbecker 2021; Serhat et al. 2022), unless the texture is the focus of the study (Tang et al. 2016; Shao et al. 2010; Khojasteh et al. 2018). A notable exception to the observations made above is the study by Yoshida et al. (Yoshida et al. 2011), which presents a 3D model including the two phalanges, sliding above a rigid flat surface, for the purpose of identifying a nonlinear friction coefficient law. Following models used for rubber-like materials, the study proposed describing the tangential friction force as an exponential function of normal force, to replicate experimental data acquired by sliding a plate against a fingertip. Lastly, because the properties investigated by these studies are highly dependent on the specific finger-surface pair, their results are frequently compared with ad-hoc acquired data, whose experimental conditions the simulation tries to replicate (Yoshida et al. 2011; Khojasteh et al. 2018; Nam and Kuchenbecker 2021).

4.5 Grasp analysis

As an extension of the static contact case, a study on the tactile interactions involved in the context of **grasp** can be carried out using an FE model. A simpler example involves the analysis of a finger wrapped around an object, like a tool handle (Tony and Alphin 2019; Wu et al. 2017), but the majority of grasp types involve multi-finger interactions around the object, and therefore their simulation requires a model of the entire hand (Hokari et al. 2019; Harih et al. 2021; Wei et al. 2020). An element which is fundamental in the context of grasp analysis is the modelling of finger joints, specifically the characterization of kinematic constraints and forces exerted via the tendons (Harih and Tada 2019; Wei et al. 2020). Typically, models take into account a revolute degree of freedom for the flexion-extension rotation of each joint, and an additional rotational degree of freedom at the knuckles which allows for relative separation of the fingers; this simplified model can be represented via simple kinematic constraints as two revolute joints (for the finger joints) and a universal joint (for the knuckle) on each finger (Wu et al. 2017; Harih and Tada 2019). Some models take into account a mechanically separate material for the connective tissue at each joint (Tony and Alphin 2019; Wu et al. 2017), or include the synovial membrane around it (Chamoret et al. 2016), while others abstract these structures away as part of a general 'soft tissue' model (Hokari et al. 2023; Harih and Tada 2019). Stiffness and damping can be assigned to each joint to attune its behaviour to that of the real joint, to account for the physiological elements that are neglected (Wu et al. 2017). Recent hand models (Harih et al. 2021; Wei et al. 2020) implement a 'tendon-like' connection between adjacent bones, as shown in Figs. 1a and Fig. 9c, where force loads can be applied in a direction which mimics the physiological function of the tendons, to improve the accuracy of the load model with respect to the real human hand. Of interest, Wei et al. utilized their FE model of the human hand (Wei et al. 2020) to investigate how the inclusion in the modelling procedure of different anatomical parts of the finger extensor mechanism (lateral band, extensor hood) increases the realism in the simulated transmission of grasp force throughout the finger (Wei et al. 2022b). They implemented on the same model two different finger joint models (a rigid one based on hinge joints, and an anatomically accurate flexible model), demonstrating an increase in quality of the simulated grasp with the anatomically accurate configuration (Wei et al. 2023). To the best of our knowledge, existing studies concerning hand

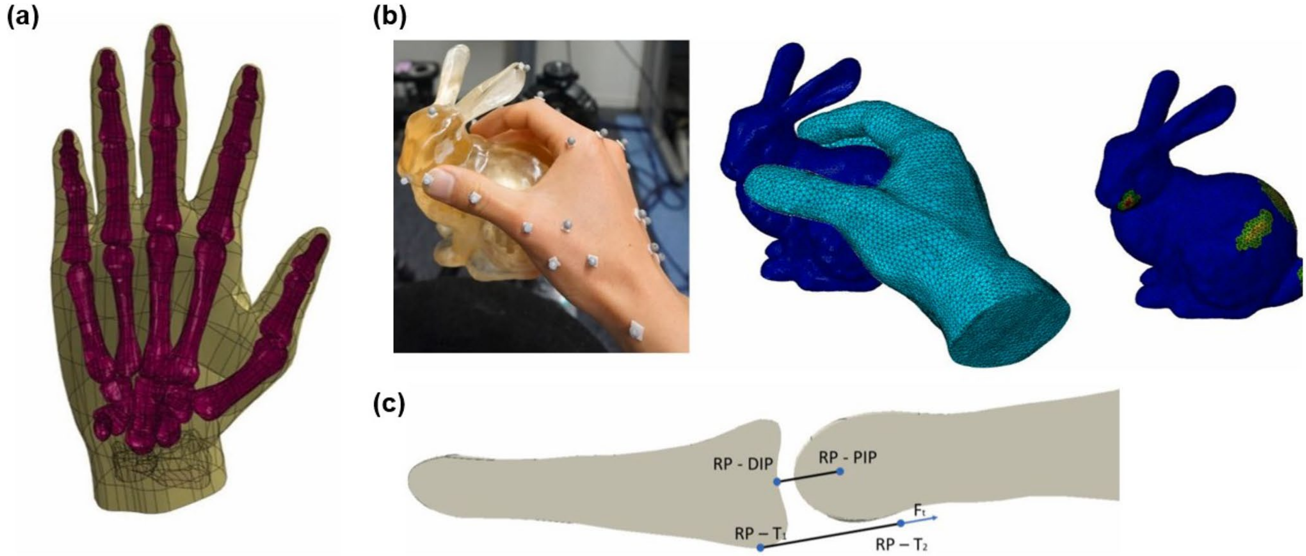

Fig. 9 FE model of the human hand for grasp simulation (Harih et al. 2021). **a** Geometry of the model, showing the distinction between bones and soft tissue. **b** Example of grasping simulation, performed using motion-captured trajectories measured on a human subject. **c** Model of the finger joint, composed of a passive constraint, which restricts relative movement between bones to a single revolute degree of freedom, and a 'tendon-like' actuation represented by a force applied on the distal bone. In the image, RP is 'reference point', DIP and PIP are respectively 'distal' and 'proximal inter-phalangeal'

models for grasp analysis choose to implement inviscous, hyperelastic constitutive laws for the soft tissues, assuming quasi-static conditions (Harih and Tada 2019; Wei et al. 2020). With the exception of Wei et al. (Wei et al. 2020), the majority also opts to lump all soft tissues in a single solid part with uniform properties (Hokari et al. 2019; Harih and Tada 2019). The only grasp model which takes viscosity into account is the one limited to a single finger (Tony and Alphin 2019; Wu et al. 2017), as this study is also concerned with the transmission of vibrations from the grasped object to the finger itself, under dynamic conditions (Wu et al. 2017). Lastly, the outer surfaces of the touched objects are usually assumed smooth (i.e., no gratings or coarse texture), with constant friction or frictionless.

4.6 Mechanoreceptor response to strain

As discussed in Sect. 3, it is a well-documented fact that mechanoreceptive afferents produce neural signals in response to certain characteristics within the stress–strain state of the skin, for example, shear strain and vibrations. In the literature, a long list of studies exist which investigated the opportunity of linking an FE mechanical model of the human finger to analytical models of neuron activation, in such a way that the model would be capable of predicting the response of the mechanoreceptors to loads applied on the virtual fingertip. Hereinafter, we refer to such models as *micro-focused*. Ground truths exist in the form of experimental data on neuron activation, such as that carried out by Srinivasan (Srinivasan and Neuroscience 1987) for indentation loading. Such micro-focused finger models can be 2D (i.e., representing a longitudinal (Wang et al. 2015) or transverse (Vodlak et al. 2016; Chen et al. 2016) section of the fingertip), or 3D (Wu et al. 2006a; Gerling et al. 2014). Most, if not all, the significant examples of such models include multiple, individual skin layers (Wu et al. 2004; Lesniak and Gerling 2009) and also take microstructures into account, such as epidermal ridges and dermal papillae, such as shown in the example in Fig. 10 (Ishizuka et al. 2022). Indeed, as it was shown for example by Gerling et al. (Gerling et al. 2005), interfaces between tissues and micro-geometries cause a localized amplification of the mechanical signals in the vicinity of the mechanoreceptors, an effect which should be taken into account in the model. Material models should take into account hyperelasticity (Tang et al. 2016; Gerling et al. 2014) and, when dynamic load components are relevant, viscosity (Kumar et al. 2015; Chen et al. 2016). Distributions of strain energy density (Chami et al. 2010; Gerling et al. 2014; Wei et al. 2022a) or other functions of elastic strain (Wu et al. 2006a; Vodlak et al. 2016) are the most frequently used descriptors to predict activation of the mechanoreceptors. The cited studies investigated neural response under a large variety of loading types, including static compression (Maeno et al. 1998a), static and dynamic indentation (Lesniak and Gerling 2009) (Kumar et al. 2015; Ishizuka et al. 2022), sliding against frictional (Wang et al.

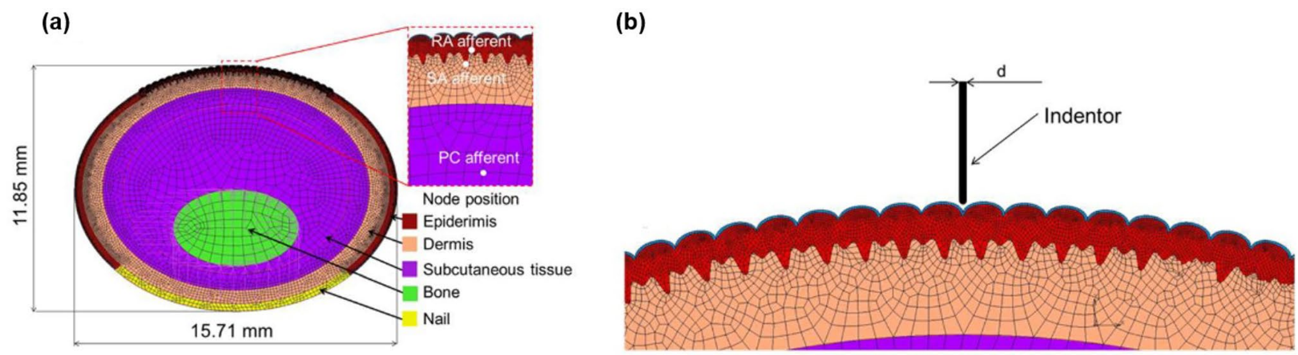

Fig. 10 2D FE model of a human fingertip, used to simulate its mechanical response to indentation as the base for an activation model of skin mechanoreceptors (Ishizuka et al. 2022). **a** Model mesh, showing the different tissue layers and locations for three types of mechanoreceptors. **b** Detail of the indenter of diameter *d*, the epidermal ridges and the dermal papillae

2015) or textured (Tang et al. 2016) surfaces, and vibrations (Wu et al. 2006a). It is worth mentioning that very few examples take into account 'active' behaviour on the part of the human (Wang et al. 2015; Tang et al. 2016), while in all other cases the load is passively applied on the finger. Among these, Wei et al. took advantage of their FE hand model, already mentioned in Sect. 4.5, to estimate afferent signals during an active curvature discrimination task. A human participant performed the task, and the model replicated the participant's motion-captured movements, and estimated the strain energy density at the location of the mechanoreceptors (Wei et al. 2022a). The study focused on validating the afferent activation model by demonstrating that the simulated accuracy in the discrimination task (based on the afferent signal) was comparable with that experimentally observed. In a recent development, this FE-driven afferent activation model was used to transform pressure signals coming from a sensorized robotic hand into equivalent human afferent activations, to endow the robotic hand with human-like sensorimotor mechanisms (Wei et al. 2024).

5 Discussion and conclusions

In the last section, we have listed and described some commonplace categories of Finite Element models of the human hand that can be used to simulate tactile interactions. The significant effort required to accurately model this complex system is certainly of value, as it returns valuable knowledge on what mechanical states are induced in the hand tissues during the interactions, and how they are distributed within the hand itself. In Sect. 4, studies on FE simulation of human hands and fingers have been described, grouped according to their intended goal, providing insight into important aspects of the modelling process. The proposed classification is not as clear-cut, and some models can serve multiple purposes, e.g., a simulation of dynamic frictional forces generated in a fingertip sliding on a textured surface can also be used to estimate the transmission of said vibrations throughout the finger. Although it is always possible, within computational limits, to increase complexity, we set out to provide suggestions on how to build a simple yet effective FE model based on its main intended purpose. The insights gained from our systematic review are shown in Table 3. As a general guideline, the use of one of the available hyperelastic material laws for the soft tissues is recommended, as is viscous modelling with a Prony series in cases of dynamic loading. The target anatomy should be replicated in the model with the maximum accuracy, including elements such as finger joints, epidermal ridges and dermal papillae whenever possible. Models should include 4-5 individual tissue layers, i.e., bone, nail, subcutaneous mass, and skin, potentially divided into dermis and epidermis. Touched objects can usually be treated as flat, smooth and rigid unless a different feature (e.g., softness, texture or curvature) is the focus of the specific study. Friction can be modelled with a combination of a constant coefficient and, where texture is relevant, surface geometry.

Aspects of human biomechanics emerged from our effort, which have not yet been fully explored via FE and may be worth investigating further. For example, the presence of the finger joints affects not just the kinematics of the hand, but also the distribution of contact forces and the transmission of vibrations throughout the finger itself, impacting the mechanical response to contact loads. As previously mentioned, this phenomenon has been investigated via FE in the context of propagation of external vibrations (Noël 2018; Wu et al. 2017) and grasp analysis (Wei et al. 2023, 2022b). On the other hand, it could be worth modelling its effects in the context of, e.g., sliding interactions with textured surfaces and their friction-induced vibrations. Similarly, friction has often been neglected in FE models, or modelled as

Table 3 Design guidelines for FE simulation of haptic interactions, listed according to the three design criteria described at the beginning of Sect. 4

	Geometric complexity	Biomechanical complexity	Interaction complexity
4.1. **Static contact**	2D or 3D fingertip model, with at least 3 soft tissue layers (epidermis, dermis and subcutaneous tissue). Inclusion of epidermal ridges is encouraged	Soft tissues should be modelled as hyperelastic. Viscosity can be neglected. Inclusion of Coulomb friction is encouraged	Quasi-static problems involve the pressing of a fingertip against a flat or pointed indenter. Contact can be achieved by imposing either displacement or normal force
4.2. **Dynamic contact**	2D or 3D fingertip model, with at least 3 soft tissue layers (epidermis, dermis and subcutaneous tissue). Inclusion of epidermal ridges is encouraged	Soft tissues should be modelled as hyperelastic. Viscosity can be modelled as an additive term (e.g., with QLV paradigm) using Prony series. Inclusion of Coulomb friction is encouraged	Dynamic problems involve the pressing and/or relative sliding of a fingertip against a flat or pointed object. Contact is usually achieved by imposing displacement, especially if the loading speed must be controlled
4.3. **Vibration transmission**	2D or 3D fingertip or finger model, with at least 2 soft tissue layers (skin and subcutaneous tissue). For finger models, joint connective tissue and dynamic properties of joints (e.g., torsional stiffness, damping) should be taken into account	Soft tissues should be modelled as hyperelastic. Viscosity can be neglected in quasi-static analyses, or modelled as an additive term (e.g., with QLV paradigm) using Prony series. Inclusion of Coulomb friction is encouraged	Vibration analysis involves pressing of the finger against an oscillating object. Contact is usually achieved by imposing displacement. Effects of pre-loading of the objects against the finger should be investigated
4.4. **Tribologic properties**	2D fingertip model, with at least 3 soft tissue layers (epidermis, dermis and subcutaneous tissue). Inclusion of epidermal ridges and dermal papillae is encouraged	Soft tissues should be modelled as hyperelastic. Viscosity can be neglected in quasi-static analyses, or modelled as an additive term (e.g., with QLV paradigm) using Prony series. Friction should be included; use of dynamic coefficients (e.g., dependent on normal force or relative sliding) is encouraged	Vibration analysis involves sliding of the fingertip against rough or textured objects. Contact is usually achieved by imposing displacement. Effects of pre-loading of the fingertip against the object should be investigated
4.5. **Grasp analysis**	3D finger or hand model, with at least 2 soft tissue layers (skin and subcutaneous tissue). Joint connective tissue and dynamic properties of joints (e.g., torsional stiffness, damping) should be taken into account. Inclusion of realistic joint actuation (e.g., via tendon forces) is encouraged	Soft tissues should be modelled as hyperelastic. Viscosity can be neglected in quasi-static analyses, or modelled as an additive term (e.g., with QLV paradigm) using Prony series. Inclusion of Coulomb friction is encouraged	Grasp analysis concerns the squeezing of an object within a finger or hand. Contact can be achieved by imposing either joint displacements and velocities or tendon forces
4.6. **Mechanoreceptor response**	2D or 3D fingertip model, with at least 3 soft tissue layers (epidermis, dermis and subcutaneous tissue). Inclusion of epidermal ridges and dermal papillae is encouraged	Soft tissues should be modelled as hyperelastic. Viscosity can be neglected in quasi-static analyses, or modelled as an additive term (e.g., with QLV paradigm) using Prony series. Inclusion of Coulomb friction is encouraged	The characteristics of the interaction strongly depend on the type of perceptual test being simulated. Dynamic analyses are preferred to ensure realistic transmission of load throughout the tissues

a constant coefficient, but it has been shown that the real behaviour of the skin is more complex (André et al. 2009; Peng et al. 2021). More complex kinematic models for the human hand are available (Gabiccini et al. 2013), which could potentially be integrated within an FE simulation to achieve greater realism. It is worth investigating the integration of nonlinear friction laws, which may focus on modelling, e.g., surface roughness, fingertip moisture or adhesion effects, in simulations of static and dynamic tactile interactions, which may lead to insights into how these laws apply to the behaviour of the real anatomy. Lastly, anisotropy of the viscoelastic properties of the skin and the fingertip pulp is well-documented (Langer 1861; Ní Annaidh et al. 2012), but it has largely been neglected in FE applications. Some sources of anisotropy, such as the collagen fibres in the subcutaneous mass, could be included in the elastic constitutive laws, to investigate whether this significantly changes the resulting behaviour, as has been previously suggested (Duprez et al. 2024).

A topic which has been tangentially mentioned in this review is that of the experimental acquisition of biomechanical data, required to select parameters for the constitutive laws used in an FE model. Examples of apt experimental procedures can be found in many of the cited studies (D'Angelo et al. 2019; Kumar et al. 2015; Logozzo et al. 2022a), and in the other reviews cited in Sect. 2.2. It is possible to use published sets of constitutive parameters (Wu et al. 2004; Gerling et al. 2014; Almagirby et al. 2018) or published biomechanical datasets (Serina et al. 1997; Janko et al. 2018a; Tummala et al. 2024), provided that the type of loading or contact interaction resembles the one that is simulated in the FE model. In particular, higher ($\geq$ 1 mm/s) loading speed and noticeable relaxation effects should be present in the data used to fit parameters of viscoelastic laws; indentation (Kumar et al. 2015) or suction (Giavazzi et al. 2010) tests have been shown to provide apt results.

There is a distinctive absence of openly accessible FE models, possibly due to how each is specifically tailored to its application. To compensate for this, we believe it would be beneficial to identify design guidelines and performance standards for benchmarking and assessing newly developed models, also with respect to real human biomechanics. As discussed in Sect. 3, the biomechanics of touch involves different aspects (e.g., finger joint kinematics, tendon-driven force transmission, exchange of contact and frictional forces, strain- and time-dependency of soft tissue stiffnesses), each of them coming with its own modelling challenges. To lay down the foundations of a benchmark for FE hand models, we could take inspiration from what has been done in the field of neuromusculoskeletal models, which encompass a comparable amount of independent, but equally important, constitutive elements. Hicks et al. introduced a general process of model validation, and a set of practical guidelines concerning each aspect of the modelling effort (Hicks et al. 2015). New models that follow these instructions can then be considered well-validated, and their simulated results can be used to draw conclusions about real human anatomy and biomechanics (Ravera et al. 2019). Furthermore, we believe that a series of benchmark tests could be designed to further empower researchers with reliable quantitative validation methods for their FE finger or hand models. Currently, for each new model, the designer is tasked with selecting appropriate, publicly available experimental data against which comparing the model's outcomes (Gerling et al. 2014; Duprez et al. 2024), or with autonomously collecting new data for this specific purpose (Kumar et al. 2015; Wei et al. 2020). The latter point comes with the arbitrary selection of the simulation boundary conditions to fit the experiments. A standardized benchmark test would solve the issue by preselecting the setup for the simulations, and providing the desired simulation results in the form of either experimental data sets collected following well-defined guidelines, or collections of simulated results from already well-validated models. Precedents for this exist, such as the benchmark designed by Land et al. for the numeric simulation of cardiac mechanics (Land et al. 2015). The benchmark is composed of three standardized tests (i.e., simulations) to be carried out, and of simulated results from 11 different FE implementations. To validate a new model, its performance in all three tests is compared with the aforementioned simulated results (Lluch et al. 2019). Benchmark tests (i.e. simulations) for a finger or hand FE model could be designed to include, for example, quasi-static passive compression of the finger pad, dynamic sliding of the fingertip against a textured surface, active tendon-driven tapping of the fingertip on a flat surface and cylindrical grasping, each supplemented with reference contact force, pressure, area or deformation data, obtained from already validated models or experimentally gathered. For the latter point, defining repeatable and clearly specified experimental conditions is of pivotal importance. At the same time, it would be fundamental to promote an open access approach to the experimental datasets, as done e.g. in (Averta et al. 2021), where a multi-modal, multi-centre database on arm motion control in healthy and post-stroke conditions is made publicly available. Summarizing, we do believe that the introduction of uniform validation methods or benchmarking tests, together with an open access approach, could enrich and enhance research on FE modelling of touch biomechanics, by easing the design of new models, guaranteeing accuracy with respect to real anatomy, and allowing for direct quantitative comparison between existing models.

The majority of the FE models mentioned in this survey have their implementation in one specific FE software described in the related paper, as writing custom FE code from scratch is rarely feasible. Models and simulations are hardly ever cross-compatible or portable to different software, worsening the overall lack of publicly accessible examples. Different FE software possess different features, and some desirable for the application may be missing; care should be taken in selecting the optimal software for the task, due to lack of portability. The availability of in-software scripting, as present, e.g., in *Ansys* (Ansys Inc., Canonsburg, Pennsylvania, United States), can be useful in integrating missing features, such as constitutive models or complex nonlinearities.

We have reviewed and summarized the available literature on FE modelling of human hands and fingers and their biomechanical response to tactile interactions. By collecting and comparing the relevant studies, we have identified shared traits which have allowed us to provide suggestions on how to design new FE models for research on the biomechanics of touch. We have identified gaps and neglected topics that, if delved into, may reward with novel and otherwise unnoticed insights. We hope that our effort will help researchers who intend to contribute and help challenge common assumptions to discover new paths in research on this topic.

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Declarations

Conflict of interest The authors have no Conflict of interest to declare that are relevant to the content of this article.

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References

Abdouni A, Moreau G, Vargiolu R et al. (2018) Static and active tactile perception and touch anisotropy: aging and gender effect. Scientific Reports 8(1):14240. https://doi.org/10.1038/s41598-018-32724-4

Adams MJ, Johnson SA, Lefèvre P et al. (2013) Finger pad friction and its role in grip and touch. Journal of the Royal Society Interface 10(80):20120467. https://doi.org/10.1098/RSIF.2012.0467

Agache PG, Humbert P (1995) Noninvasive assessment of the physical properties of the skin. In: Wound Healing and Skin Physiology, Berlin, Heidelberg, pp 497–503, https://doi.org/10.1007/978-3-642-77882-7_46

Ali A, Hosseini M, Sahari BB (2010) A review of constitutive models for rubber-like materials. American J of Engineering and Applied Sciences 3(1):232–239. https://doi.org/10.3844/AJEASSP.2010.232.239

Almagirby A, Rongong JA, Carré MJ (2018) The development of a new artificial model of a finger for assessing transmitted vibrations. Journal of the Mechanical Behavior of Biomedical Materials 78:20–27. https://doi.org/10.1016/j.jmbbm.2017.11.005

Amaied E, Vargiolu R, Bergheau JM et al. (2015) Aging effect on tactile perception: Experimental and modelling studies. Wear 332–333:715–724. https://doi.org/10.1016/J.WEAR.2015.02.030

André T, Lefèvre P, Thonnard JL (2009) A continuous measure of fingertip friction during precision grip. Journal of Neuroscience Methods 179(2):224–229. https://doi.org/10.1016/J.JNEUMETH.2009.01.031

André T, Lefèvre P, Thonnard JL (2010) Fingertip moisture is optimally modulated during object manipulation. Journal of Neurophysiology 103(1):402–408. https://doi.org/10.1152/JN.00901.2009

Averta G, Barontini F, Catrambone V, et al. (2021) U-limb: A multi-modal, multi-center database on arm motion control in healthy and post-stroke conditions. GigaScience 10(6):giab04. https://doi.org/10.1093/gigascience/giab043

Barrea A, Bulens DC, Lefevre P et al. (2016) Simple and reliable method to estimate the fingertip static coefficient of friction in precision grip. IEEE Transactions on Haptics 9(4):492–498. https://doi.org/10.1109/TOH.2016.2609921

Battaglia E, Bianchi M, D'Angelo ML, et al. (2015) A finite element model of tactile flow for softness perception. In: 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), pp 2430–2433, https://doi.org/10.1109/EMBC.2015.7318884

Biswas S, Visell Y (2019) Emerging material technologies for haptics. Advanced Materials Technologies 4(4):190042. https://doi.org/10.1002/admt.201900042

Biswas S, Visell Y (2021) Haptic perception, mechanics, and material technologies for virtual reality. Advanced Functional Materials 31(39):2008186. https://doi.org/10.1002/adfm.202008186

Capace A, Cosentino C, Abidi H et al. (2021) Modelling and identification of the asymmetric hysteresis in the viscoelastic response of the fingertip under indentation: A multistate friction model with switching parameters. Mechatronics 77:102578. https://doi.org/10.1016/j.mechatronics.2021.102578

Chami A, Ohka M, Yussof H (2010) An investigation of the reason of velvet hand illusion perception using FEM analysis. In: 2010 Fourth Asia International Conference on Mathematical/Analytical Modelling and Computer Simulation, pp 118–122, https://doi.org/10.1109/AMS.2010.36

Chamoret D, Peyraut F, Gomes S et al. (2010) Finite element approach applied to human digital model for biomechanical modeling. International Journal on Interactive Design and Manufacturing (IJIDeM) 4(1):75–82. https://doi.org/10.1007/s12008-009-0087-3

Chamoret D, Roth S, Feng ZQ et al. (2013) A novel approach to modelling and simulating the contact behaviour between a human hand model and a deformable object. Computer Methods in Biomechanics and Biomedical Engineering 16(2):130–140. https://doi.org/10.1080/10255842.2011.608662

Chamoret D, Bodo M, Roth S et al. (2016) A first step in finite-element simulation of a grasping task. Computer Assisted Surgery 21:22–29. https://doi.org/10.1080/24699322.2016.1240294

Chen H, Shuai L, Zhu W (2016) Preliminary study on sed distribution of tactile sensation in fingertip. MATEC Web of Conferences 45:04006. https://doi.org/10.1051/MATECCONF/20164504006

Dallard J, Duprey S, Bernard C et al. (2014) Fingertip finite element modelling - on choosing the right material property. Computer Methods in Biomechanics and Biomedical Engineering 17:30–31. https://doi.org/10.1080/10255842.2014.931084

Daly CH (1982) Biomechanical properties of dermis. Journal of Investigative Dermatology 79(1):17–20. https://doi.org/10.1038/jid.1982.4

D'Angelo ML, Cannella F, Bianchi M et al. (2017) An integrated approach to characterize the behavior of a human fingertip in contact with a silica window. IEEE Transactions on Haptics 10(1):123–129. https://doi.org/10.1109/TOH.2016.2614679

D'Angelo ML, Cannella F, D'Imperio M, et al. (2019) A preliminary approach to study the behavior of human fingertip at contact via experimental test and numerical model. ACTA IMEKO 6(2):81–88. https://doi.org/10.21014/ACTA_IMEKO.V6I2.393

Deflorio D, Di Luca M, Wing AM (2022) Skin and mechanoreceptor contribution to tactile input for perception: a review of simulation models. Frontiers in Human Neuroscience 16:862344. https://doi.org/10.3389/FNHUM.2022.862344

Delhaye BP, Schiltz F, Crevecoeur F, et al. (2024) Fast grip force adaptation to friction relies on localized fingerpad strains. Science Advances 10(3):eadh9344. https://doi.org/10.1126/sciadv.adh9344

Duprez G, Delhaye BP, Laurent D (2024) Anisotropic subcutaneous response during fingertip normal and tangential loadings. IEEE Transactions on Haptics 17(4):753–760. https://doi.org/10.1109/TOH.2024.3406251

Fung YC (1993) Biomechanics. Springer, New York,. https://doi.org/10.1007/978-1-4757-2257-4

Gabiccini M, Stillfried G, Marino H, et al. (2013) A data-driven kinematic model of the human hand with soft-tissue artifact compensation mechanism for grasp synergy analysis. In: IEEE/RSJ International Conference on Intelligent Robots and Systems, p 3738-3745, https://doi.org/10.1109/IROS.2013.6696890

Gasser TC, Ogden RW, Holzapfel GA (2005) Hyperelastic modelling of arterial layers with distributed collagen fibre orientations. Journal of The Royal Society Interface 3(6):15–35. https://doi.org/10.1098/RSIF.2005.0073

Gerling G, Thomas G (2005) The effect of fingertip microstructures on tactile edge perception. In: First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics Conference, pp 63–72, https://doi.org/10.1109/WHC.2005.129

Gerling GJ, Rivest II, Lesniak DR et al. (2014) Validating a population model of tactile mechanotransduction of slowly adapting type i afferents at levels of skin mechanics, single-unit response and psychophysics. IEEE Transactions on Haptics 7(2):216–228. https://doi.org/10.1109/TOH.2013.36

Giavazzi S, Ganatea M, Trkov M et al. (2010) Inverse determination of viscoelastic properties of human fingertip skin. Materials and Geoenvironment 57:1–16

Han HY, Kawamura S (1996) Analysis of stiffness of human fingertip and comparison with artificial fingers. In: 1999 IEEE International Conference on Systems, Man, and Cybernetics, p 3061-3066, https://doi.org/10.1109/ICSMC.1999.825364

Harih G, Dolšak B (2014) Recommendations for tool-handle material choice based on finite element analysis. Applied Ergonomics 45(3):577–585. https://doi.org/10.1016/J.APERGO.2013.07.014

Harih G, Tada M (2015) Finite element evaluation of the effect of fingertip geometry on contact pressure during flat contact. International Journal for Numerical Methods in Biomedical Engineering 31(6):e02712. https://doi.org/10.1002/CNM.2712

Harih G, Tada M (2019) Development of a feasible finite element digital human hand model. DHM and Posturography 1:273–286. https://doi.org/10.1016/B978-0-12-816713-7.00021-0

Harih G, Tada M, Dolšak B (2016) Justification for a 2d versus 3d fingertip finite element model during static contact simulations. Computer Methods in Biomechanics and Biomedical Engineering 19(13):1409–1417. https://doi.org/10.1080/10255842.2016.1146712

Harih G, Kalc M, Vogrin M et al. (2021) Finite element human hand model: Validation and ergonomic considerations. International Journal of Industrial Ergonomics 85:103186. https://doi.org/10.1016/J.ERGON.2021.103186

Hendriks FM, Brokken D, van Eemeren JT et al. (2003) A numerical-experimental method to characterize the non-linear mechanical behaviour of human skin. Skin Research and Technology 9(3):274–283. https://doi.org/10.1034/J.1600-0846.2003.00019.X

Hendriks FM, Brokken D, Oomens CW et al. (2004) Influence of hydration and experimental length scale on the mechanical response of human skin in vivo, using optical coherence tomography. Skin Research and Technology 10(4):231–241. https://doi.org/10.1111/J.1600-0846.2004.00077.X

Hicks JL, Uchida TK, Seth A et al. (2015) Is my model good enough? best practices for verification and validation of musculoskeletal models and simulations of movement. Journal of Biomechanical Engineering 137(2):020905. https://doi.org/10.1115/1.4029304

Hirota K, Tagawa K (2016) Interaction with virtual object using deformable hand. Proceedings - IEEE Virtual Reality pp 49–56. https://doi.org/10.1109/VR.2016.7504687

Ho VA, Hirai S (2015) A novel model for assessing sliding mechanics and tactile sensation of human-like fingertips during slip action. Robotics and Autonomous Systems 63:253–267. https://doi.org/10.1016/J.ROBOT.2014.09.009

Hokari K, Pramudita JA (2023) Investigation of mechanical responses in fingertip using finite element model for softness perception. Advanced Experimental Mechanics 8:87–93. https://doi.org/10.11395/aem.8.0_87

Hokari K, Arimoto R, Pramudita JA, et al. (2019) Palmar contact pressure distribution during grasping a cylindrical object: Parameter study using hand finite element model. Advanced Experimental Mechanics 4:135–140. https://doi.org/10.11395/AEM.4.0_135

Hokari K, Pramudita JA, Okada K et al. (2023) Development of a gripping comfort evaluation method based on numerical simulations using individual hand finite element models. International Journal of Human Factors and Ergonomics 10(2):187–206. https://doi.org/10.1504/IJHFE.2023.130538

Holzapfel GA, Gasser TC, Ogden RW (2000) A new constitutive framework for arterial wall mechanics and a comparative study of material models. Journal of Elasticity and the Physical Science of Solids 61:1–48. https://doi.org/10.1023/A:1010835316564

Iravanimanesh S, Nazari MA, Jafarbeglou F et al. (2021) Extracting the elasticity of the human skin in microscale and in-vivo from atomic force microscopy experiments using viscoelastic models. Computer Methods in Biomechanics and Biomedical Engineering 24(2):188–202. https://doi.org/10.1080/10255842.2020.1821000

Ishizuka H, Kitaguchi S, Nakatani M, et al. (2022) Computational models for sa, ra, pc afferent to reproduce neural responses to dynamic stimulus using fem analysis and a leaky integrate-and-fire model. arXiv:2208.00615 2208.00615. https://doi.org/10.48550/arXiv.2208.00615

Janko M, Wiertlewski M, Visell Y (2018) Contact geometry and mechanics predict friction forces during tactile surface exploration. Scientific Reports 8(1):1–10. https://doi.org/10.1038/s41598-018-23150-7

Janko M, Zhao Z, Kam M, et al. (2018b) A partial contact frictional force model for finger-surface interactions. In: IEEE Haptics Symposium, pp 255–261, https://doi.org/10.1109/HAPTICS.2018.8357185

Jindrich DL, Zhou Y, Becker T et al. (2003) Non-linear viscoelastic models predict fingertip pulp force-displacement characteristics during voluntary tapping. Journal of Biomechanics 36(4):497–503. https://doi.org/10.1016/S0021-9290(02)00438-4

Johansson RS, Flanagan JR (2009) Coding and use of tactile signals from the fingertips in object manipulation tasks. Nature Reviews Neuroscience 10(5):345–359. https://doi.org/10.1038/nrn2621

Johnson KO (2001) The roles and functions of cutaneous mechanoreceptors. Current Opinions in Neurobiology 11(4):455–461. https://doi.org/10.1016/S0959-4388(00)00234-8

Khojasteh B, Janko M, Visell Y (2018) Complexity, rate, and scale in sliding friction dynamics between a finger and textured surface. Scientific Reports 8(1):1–10. https://doi.org/10.1038/s41598-018-31818-3

Kossa A, Valentine MT, McMeeking RM (2023) Analysis of the compressible, isotropic, neo-Hookean hyperelastic model. Meccanica 58(1):217–232. https://doi.org/10.1007/s11012-022-01633-2

Kumar S, Liu G, Schloerb DW et al. (2015) Viscoelastic characterization of the primate finger pad in vivo by microstep indentation and three-dimensional finite element models for tactile sensation studies. Journal of Biomechanical Engineering 137(6):061002. https://doi.org/10.1115/1.4029985/444888

Land S, Gurev V, Arens S et al. (2015) Verification of cardiac mechanics software: benchmark problems and solutions for testing active and passivematerial behaviour. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 417(2184):20150641. https://doi.org/10.1098/rspa.2015.0641

Langer K (1861) On the anatomy and physiology of the skin: I. the cleavability of the cutis. British Journal of Plastic Surgery 31(1):3–8. https://doi.org/10.1016/0007-1226(78)90003-6

Lapeer RJ, Gasson PD, Karri V (2010) Simulating plastic surgery: From human skin tensile tests, through hyperelastic finite element models to real-time haptics. Progress in Biophysics and Molecular Biology 103(2–3):208–216. https://doi.org/10.1016/J.PBIOMOLBIO.2010.09.013

Lesniak DR, Gerling GJ (2009) Predicting SA-i mechanoreceptor spike times with a skin-neuron model. Mathematical Biosciences 220(1):15–23. https://doi.org/10.1016/J.MBS.2009.03.007

Li B, Gerling GJ (2023) An individual's skin stiffness predicts their tactile acuity. The Journal of Physiology 601(24):5777–5794. https://doi.org/10.1101/2023.07.17.548686

Lluch E, De Craene M, Bijnens B et al. (2019) Breaking the state of the heart: meshless model for cardiac mechanics. Biomechanics and Modeling in Mechanobiology 18:1549–1561. https://doi.org/10.1007/s10237-019-01175-9

Logozzo S, Valigi MC, Malvezzi M (2022) A methodology to evaluate contact areas and indentations of human fingertips based on 3d techniques for haptic purposes. MethodsX 9:101781. https://doi.org/10.1016/J.MEX.2022.101781

Logozzo S, Valigi MC, Malvezzi M (2022) Modelling the human touch: A basic study for haptic technology. Tribology International 166:107352. https://doi.org/10.1016/J.TRIBOINT.2021.107352

Lv Y, Zheng Q, Chen X et al. (2022) Analysis on synergistic cocontraction of extrinsic finger flexors and extensors during flexion movements: A finite element digital human hand model. PLOS ONE 17(5):e0268137. https://doi.org/10.1371/JOURNAL.PONE.0268137

Maeno T, Kawai T, Kobayashi K (1998) Analysis and design of a tactile sensor detecting strain distribution inside an elastic finger. IEEE International Conference on Intelligent Robots and Systems 3:1658–1663. https://doi.org/10.1109/IROS.1998.724836

Maeno T, Kobayashi K, Yamazaki N (1998) Relationship between the structure of human finger tissue and the location of tactile receptors. JSME International Journal Series C Mechanical Systems, Machine Elements and Manufacturing 41(1):94–100. https://doi.org/10.1299/JSMEC.41.94

Mostafavi Yazdi SJ, Baqersad J (2022) Mechanical modeling and characterization of human skin: A review. Journal of Biomechanics 130:110864. https://doi.org/10.1016/J.JBIOMECH.2021.110864

Nam S, Kuchenbecker KJ (2021) Optimizing a viscoelastic finite element model to represent the dry, natural, and moist human finger pressing on glass. IEEE Transactions on Haptics 14(2):303–309. https://doi.org/10.1109/TOH.2021.3077549

Noël C (2018) A three-dimensional visco-hyperelastic FE model for simulating the mechanical dynamic response of preloaded phalanges. Medical Engineering and Physics 61:41–50. https://doi.org/10.1016/J.MEDENGPHY.2018.08.007

Ní Annaidh A, Bruyère K, Destrade M et al. (2012) Characterization of the anisotropic mechanical properties of excised human skin. Journal of the Mechanical Behavior of Biomedical Materials 5(1):139–148. https://doi.org/10.1016/j.jmbbm.2011.08.016

Ogden RW (2003) Nonlinear elasticity, anisotropy, material stability and residual stresses in soft tissue. Springer Vienna. https://doi.org/10.1007/978-3-7091-2736-0_3

Page MJ, McKenzie JE, Bossuyt PM et al. (2021) The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. Systematic Reviews 372:n71. https://doi.org/10.1186/s13643-021-01626-4

Pasumarty SM, Johnson SA, Watson SA et al. (2011) Friction of the human finger pad: Influence of moisture, occlusion and velocity. Tribology Letters 44(2):117–137. https://doi.org/10.1007/S11249-011-9828-0

Pataky TC, Latash ML, Zatsiorsky VM (2005) Viscoelastic response of the finger pad to incremental tangential displacements. Journal of Biomechanics 38(7):1441–1449. https://doi.org/10.1016/J.JBIOMECH.2004.07.004

Pawluk DTV, Howe RD (1999) Dynamic contact of the human fingerpad against a flat surface. Journal of Biomechanical Engineering 120(6):605–611. https://doi.org/10.1115/1.2800860

Peng Y, Serfass CM, Kawazoe A et al. (2021) Elastohydrodynamic friction of robotic and human fingers on soft micropatterned substrates. Nature Materials 20(12):1707711. https://doi.org/10.1038/s41563-021-00990-9

Ravera EP, Crespo MJ, Catalfamo Formento PA (2019) Assessment of the energy-related cost function over a range of walking speeds. Biomechanics and Modeling in Mechanobiology 18:1837–1846. https://doi.org/10.1007/s10237-019-01180-y

Rivlin RS (1992) The elasticity of rubber. Rubber Chemistry and Technology 65(3):51–66. https://doi.org/10.5254/1.3538628

Robert A, Roth S, Chamoret D et al. (2012) Functional design method for improving safety and ergonomics of mechanical products. Journal of Biomedical Science and Engineering 5:457–468. https://doi.org/10.4236/jbise.2012.58058

Ryan CP, Bettelani GC, Ciotti S et al. (2021) The interaction between motion and texture in the sense of touch. Journal of Neurophysiology 126(4):1375–1390. https://doi.org/10.1152/jn.00583.2020

Serhat G, Kuchenbecker KJ (2021) Free and forced vibration modes of the human fingertip. Applied Sciences 11(12):5709. https://doi.org/10.3390/app11125709

Serhat G, Kuchenbecker KJ (2024) Fingertip dynamic response simulated across excitation points and frequencies. Biomechanics and Modeling in Mechanobiology 23:1369–1376. https://doi.org/10.1007/s10237-024-01844-4

Serhat G, Vardar Y, Kuchenbecker KJ (2022) Contact evolution of dry and hydrated fingertips at initial touch. PLOS ONE 17(7):e0269722. https://doi.org/10.1371/journal.pone.0269722

Serina ER, Mote CD, Rempel D (1997) Force response of the fingertip pulp to repeated compression-effects of loading rate, loading angle and anthropometry. Journal of Biomechanics 30(10):1035–1040. https://doi.org/10.1016/S0021-9290(97)00065-1

Serina ER, Mockensturm E, Mote CD et al. (1998) A structural model of the forced compression of the fingertip pulp. Journal of Biomechanics 31(7):639–646. https://doi.org/10.1016/S0021-9290(98)00067-0

Shao F, Childs TH, Barnes CJ et al. (2010) Finite element simulations of static and sliding contact between a human fingertip and textured surfaces. Tribology International 43(12):2308–2316. https://doi.org/10.1016/J.TRIBOINT.2010.08.003

Shao Y, Hayward V, Visell Y (2016) Spatial patterns of cutaneous vibration during whole-hand haptic interactions. Proceedings of the National Academy of Sciences of the United States of America 113(15):4188–4193. https://doi.org/10.1073/pnas.1520866113

Shimawaki S, Sakai N (2007) Quasi-static deformation analysis of a human finger using a three-dimensional finite element model constructed from CT images. Journal of Environment and Engineering 2(1):56–63. https://doi.org/10.1299/jee.2.56

Sivamani RK, Goodman J, Gitis NV et al. (2003) Friction coefficient of skin in real-time. Skin Research and Technology 9(3):235–239. https://doi.org/10.1034/j.1600-0846.2003.20361.x

Soussou JE, Moavenzadeh F, Gradowczyk MH (1970) Application of prony series to linear viscoelasticity. Transactions of The Society of Rheology 14(4):573–584. https://doi.org/10.1122/1.549179

Srinivasan M, Neuroscience RL (1987) Tactile discrimination of shape: responses of slowly and rapidly adapting mechanoreceptive afferents to a step indented into the monkey fingerpad. Journal of Neuroscience 7(6):1682–1697. https://doi.org/10.1523/JNEUROSCI.07-06-01682.1987

Srinivasan MA (1989) Surface deflection of primate fingertip under line load. Journal of Biomechanics 22(4):343–349. https://doi.org/10.1016/0021-9290(89)90048-1

Tang W, Zhang J, Shi X et al. (2016) Investigation of mechanical responses to the tactile perception of surfaces with different textures using the finite element method. Advances in Mechanical Engineering 8(7):168781401666045. https://doi.org/10.1177/1687814016660453

Tong Q, Wei W, Zhang Y et al. (2023) Survey on hand-based haptic interaction for virtual reality. IEEE Transactions on Haptics 16(2):154–170. https://doi.org/10.1109/TOH.2023.3266199

Tony BJA, Alphin MS (2019) Finite element analysis to assess the biomechanical behavior of a finger model gripping handles with different diameters. Biomedical Human Kinetics 11(1):69–79. https://doi.org/10.2478/BHK-2019-0009

Tschoegl NW (2012) The phenomenological theory of linear viscoelastic behavior: an introduction. Springer Science & Business Media

Tummala N, Reardon G, Fani DS, Goetz, et al. (2024) Skinsource: A data-driven toolbox for predicting touch-elicited vibrations in the upper limb. IEEE Haptics Symposium 2024:53–60. https://doi.org/10.1109/HAPTICS59260.2024.10520852

Vodlak T, Vidrih Z, Fetih D, et al. (2015) Development of a finite element model of a finger pad for biomechanics of human tactile sensations. In: 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), pp 909–912, https://doi.org/10.1109/EMBC.2015.7318510

Vodlak T, Vidrih Z, Sustaric P et al. (2016) Computational assessment of mechanical triggers for spiking activity during surface exploration: From finite element analysis to firing-rate. Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) 9775:406–415. https://doi.org/10.1007/978-3-319-42324-1_40

Wang Q, Hayward V (2007) In vivo biomechanics of the fingerpad skin under local tangential traction. Journal of Biomechanics 40(4):851–860. https://doi.org/10.1016/J.JBIOMECH.2006.03.004

Wang Z, Wang L, Ho VA et al. (2012) A 3-d nonhomogeneous FE model of human fingertip based on MRI measurements. IEEE Transactions on Instrumentation and Measurement 61(12):3147–3157. https://doi.org/10.1109/TIM.2012.2205102

Wang Z, Chathuranga DS, Hirai S (2015) Study on the human perception of incipient and overall slippages using a 2d FE fingertip model. In: Proceedings of the Annual International Conference of the (IEEE) Engineering in Medicine and Biology Society, (EMBS), pp 5764–5767, https://doi.org/10.1109/EMBC.2015.7319702

Wei Y, Zou Z, Wei G et al. (2020) Subject-specific finite element modelling of the human hand complex: muscle-driven simulations and experimental validation. Annals of Biomedical Engineering 48(4):1181–1195. https://doi.org/10.1007/S10439-019-02439-2

Wei Y, McGlone FP, Marshall AG et al. (2022) From skin mechanics to tactile neural coding: predicting afferent neural dynamics during active touch and perception. IEEE Transactions on Biomedical Engineering 69(12):3748–3759. https://doi.org/10.1109/TBME.2022.3177006

Wei Y, Zou Z, Qian Z et al. (2022) Biomechanical analysis of the effect of the finger extensor mechanism on hand grasping performance. IEEE Transactions on Neural Systems and Rehabilitation Engineering 30:360–368. https://doi.org/10.1109/TNSRE.2022.3146906

Wei Y, Zou Z, Qian Z et al. (2023) Biomechanical analysis of the effect of finger joint configuration on hand grasping performance: Rigid vs flexible. IEEE Transactions on Neural Systems and Rehabilitation Engineering 31:606–619. https://doi.org/10.1109/TNSRE.2022.3229165

Wei Y, Marshall AG, McGlone FP et al. (2024) Human tactile sensing and sensorimotor mechanism: from afferent tactile signals to efferent motor control. Nature Communications 15(1):6857. https://doi.org/10.1038/s41467-024-50616-2

Wiertlewski M, Hayward V (2012) Mechanical behavior of the fingertip in the range of frequencies and displacements relevant to touch. Journal of Biomechanics 45(11):1869–1874. https://doi.org/10.1016/j.jbiomech.2012.05.045

Wu JZ, Dong RG, Smutz WP et al. (2003) Modeling of time-dependent force response of fingertip to dynamic loading. Journal of Biomechanics 36(3):383–392. https://doi.org/10.1016/S0021-9290(02)00427-X

Wu JZ, Dong RG, Rakheja S et al. (2004) A structural fingertip model for simulating of the biomechanics of tactile sensation. Medical Engineering & Physics 26(2):165–175. https://doi.org/10.1016/J.MEDENGPHY.2003.09.004

Wu JZ, Krajnak K, Welcome DE et al. (2006) Analysis of the dynamic strains in a fingertip exposed to vibrations: Correlation to the mechanical stimuli on mechanoreceptors. Journal of Biomechanics 39(13):2445–2456. https://doi.org/10.1016/J.JBIOMECH.2005.07.027

Wu JZ, Welcome DE, Dong RG (2006) Three-dimensional finite element simulations of the mechanical response of the fingertip to static and dynamic compressions. Computer Methods in Biomechanics and Biomedical Engineering 8(1):55–63. https://doi.org/10.1080/10255840600603641

Wu JZ, Welcome DE, Krajnak K et al. (2007) Finite element analysis of the penetrations of shear and normal vibrations into the soft tissues in a fingertip. Medical Engineering & Physics 29(6):718–727. https://doi.org/10.1016/J.MEDENGPHY.2006.07.005

Wu JZ, Krajnak K, Welcome DE et al. (2008) Three-dimensional finite element simulations of the dynamic response of a fingertip to vibration. Journal of Biomechanical Engineering 130(5):054501. https://doi.org/10.1115/1.2947199/455135

Wu JZ, Krajnak K, Welcome DE et al. (2009) Analysis of the biodynamic interaction between the fingertip and probe in the vibrotactile tests: The influences of the probe/fingertip contact orientation and static indentation. Journal of Biomechanics 42(2):116–124. https://doi.org/10.1016/J.JBIOMECH.2008.10.033

Wu JZ, Dong RG, Welcome DE et al. (2010) A method for analyzing vibration power absorption density in human fingertip. Journal of Sound and Vibration 329(26):5600–5614. https://doi.org/10.1016/J.JSV.2010.07.022

Wu JZ, Welcome DE, McDowell TW et al. (2017) Modeling of the interaction between grip force and vibration transmissibility of a finger. Medical Engineering & Physics 45:61–70. https://doi.org/10.1016/J.MEDENGPHY.2017.04.008

Xu C, Wang Y, Hauser SC et al. (2018) In the tactile discrimination of compliance, perceptual cues in addition to contact area are required. Proceedings of the Human Factors and Ergonomics Society Annual Meeting 62(1):1535–1539. https://doi.org/10.1177/1541931218621347

Yeoh OH (1993) Some forms of the strain energy function for rubber. Rubber Chemistry and Technology 66(5):754–771. https://doi.org/10.5254/1.3538343

Yoshida H, Tada M, Mochimaru M (2011) A study of frictional property of the human fingertip using three-dimensional finite element analysis. Molecular & Cellular Biomechanics 8(1):61–71. https://doi.org/10.3970/mcb.2011.008.061

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