Analysis method for finger-machine non-smooth contact considering flexibility of skin

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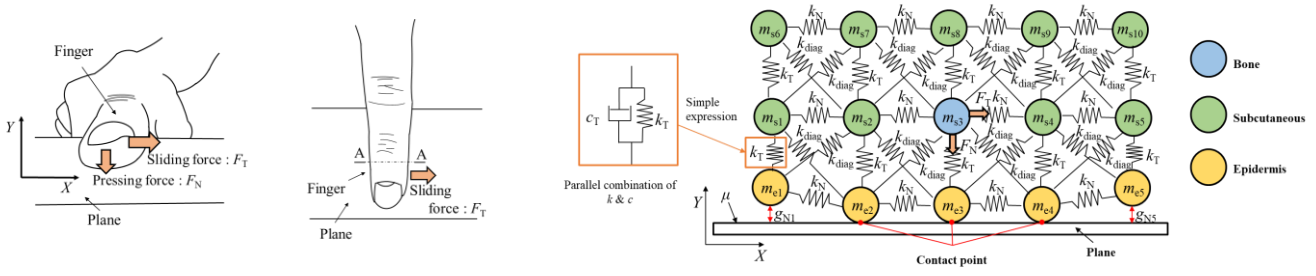
EXTENDED ABSTRACT

1 Introduction

In recent years, the opportunities for direct contact between humans and machines have been increasing in various fields, such as nursing, rehabilitation, and civil engineering. For example, RIKEN, Japan's largest comprehensive research institution, developed ROBEAR to assist with transfer tasks in the nursing field [1]. Additionally, Kobayashi et al. developed and commercialized a wearable exoskeleton suit called “Muscle Suit®” which provides physical support for human movement [2]. These machine behave with contact to human, so it’s called human-machine systems. For such systems, ensuring safety in human-machine contact is crucial for increasing social acceptance. To guarantee safety, it is neccesary to predict stress variation based on contact by simulation in advance is necessary. In e-sport tennis, for instance, contact between humans and objects occurs not only in real space but also in virtual space. Improving tactile sensation technology can lead to new communication possibilities in virtual space. To reproduce the tactile sensation touching an object in virtual space, it is necessary to model the contact phenomenon between a person and an object and generate an appropriate tasks that simulate a sense of touch, such as output from the actuator for a haptic glove. To determin the appropriate task for reproducing contact feeling, it is necessary to predict the deformation and stress of the skin around the contact area and the accompanying changes in stiffness and frictional force. However, current technology is inadequate due to the non-linear stiffness of the skin and the difficulty of formulating contact with friction. The purpose of this study is to analyze the motion of human-machine systems with contact phenomenon. This study focus on the contact between an object and a finger. Fingers are used in various contact conditions, such as power grasping and sliding. Analysis of deformation and sliding of the human finger realize to design machines and machine controls that can be operated intuitively and that can be used safety. This design aproach expected to increase the social acceptance of contact with machines and introduce machines that can actively interact people in various aspects of daily life. Additionally, improving haptic feedback through contact in virtual space can make it more realistic and effective.

2 Motion analysis

In this paper, finger sliding motion on a plane is used for basic motion analysis. Fig. 1(a) and (b) show a schematic diagram of the operation. A pressing force F_N and a force F_T for sliding in the direction of movement are applied to the bone of the finger placed on the plane. The forces applied to the bone are transmitted to the epidermis by deforming the subcutaneous tissue. On the other hand, friction occurs due to contact between the plane and the epidermal tissue. When the force applied to the epidermal tissue in the plane direction exceeds the friction force, the epidermal tissue slides on the plane. When all the epidermal tissue in contact with the plane slide, the whole finger slides on the plane. The Flores’s method [3] is attracting attention as a way of introducing non-smooth contact forces such as Coulomb friction assuming rigid body contact into motion analysis. In this method, numerical analysis is performed by Moreau’s time-stepping method [4] which is suitable for simulation of non-smooth systems. Non-smooth contact is formulated as an impulse in Linear Complementarity Problem (LCP). However, in this study, it is necessary to consider the non-smooth contact problem of flexible bodies. So, the spring mass model shown in Fig. 1(c) is introduced. In this report, for simplicity, the system is modeled in a two-dimensional vertical plane (A-A cross section in Fig. 1(b)) along the longitudinal direction of the finger. The epidermal tissue is modeled with 5 mass points (m_{e1}~m_{e5}), and the subcutaneous tissue is also modeled with 10 mass point (m_{s1}~m_{s10}, where m_{s3} is the bone). Virtual springs and dampers that express the viscoelasticity of the skin are placed between each mass point. The stiffness of skin tissue is nonlinear and depending



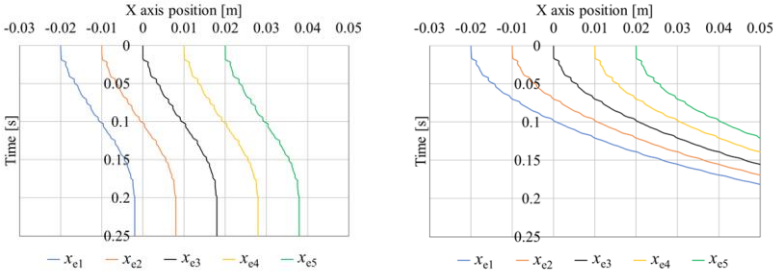
(a) Front view (b) Plan view (c) Modelling result of A-A cross section in (b)

Figure 1: Analysis target finger sliding motion on the plane

on internal stress. However, in this report, the virtual springs are assumed to be linear springs for fundamental study purposes. For the same reason, the coefficient of friction μ between the plane and the epidermal tissue is also assumed to be constant. The Moreau's time-stepping method is applied to the motion analysis of the mass points with contact (epidermal tissue) because this method is suitable for analyzing non-smooth phenomena. On the other hand, the Runge-Kutta method is applied to the motion analysis of the mass points without contact (subcutaneous tissue). Such a combination of different integration scheme has great potential for implementing various skin nonlinearities that require special treatment in numerical integration. Each motion analysis affects each other via virtual springs and dampers. By using this combined method, the motion analysis of nonlinear flexible systems with contact can be performed efficiently. The analysis is performed under the conditions shown in Table 1. In this report. Fig. 2(a) and (b) show the analysis result of the time history of each epidermis mass point's X direction position. In the high pressing force F_N condition shown in (a), the mass points move with stick-slip-like motion and then stop. On the other hand, in the low F_N condition shown in (b), the mass points move with stick-slip-like motion and then converge to uniform motion. These phenomena are qualitatively consistent with empirical observations. Therefore, the proposed analytical method is considered physically interpretable.

Table 1: Analysis parameters

Item		Symbol	Unit	Value
Mass of each element		m	kg	$4.0*10^{-3}$
Coefficient of friction		μ	-	1.5
Virtual spring rate	Slipping direction	k_T	N/m	31900
	Normal direction	k_N	N/m	26600
	Diagonal direction	k_{diag}	N/m	5000
Rayleigh damping **$\mathbf{C}=\alpha\mathbf{M}+\beta\mathbf{K}$**	Mass factor	α	N/m/s	$1.0*10^{-7}$
	Stiffness factor	β	N/m/s	$0.5*10^{-3}$
Input force from skeleton	X axis	F_T	N	6.9
	Y axis (Weight)	F_N	gf	280, 340
Step time		dt	s	0.0001



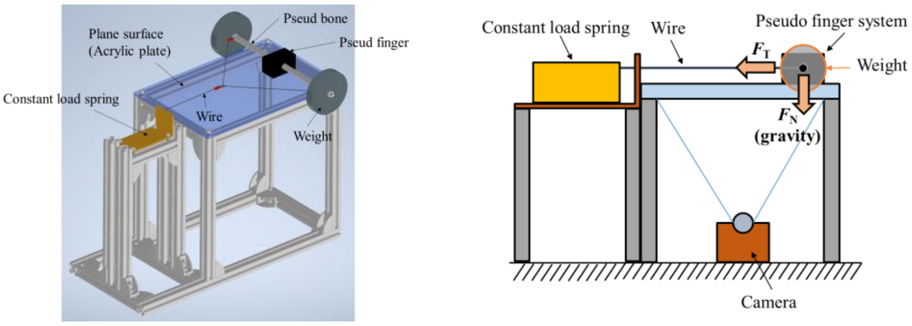
(a) High pressing force condition (F_N=340 [gf])

(b) Low pressing force condition (F_N=280 [gf])

Figure 2: Analysis result (X axis position time history)

3 Experimental verifications

The suggested analysis method should be validated by an experiment. Fig. 3 shows the experimental equipment used for validating the analysis. With this equipment, it is possible to reproduce the fingertip sliding motion on a plane. The pseudo finger system consists of a pseudo finger (low elastic rubber) and a pseudo bone (SUS304 rod). The pressing force F_N is applied by the gravity of the brass disk weight. The force F_T for sliding in the direction of movement is applied by a constant load spring. By using this type of spring, the pseudo bone can be pulled with a constant force. The motion of the pseudo finger is measured by motion capture and displacement measurement. The experimental results are compared with the analytical ones.



(a) Equipmental equipment.

(b) Working diagram.

Figure 3: Equipment for analysis validation.

Acknowledgments

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