INTRODUCTION
Age-related physiological changes and functional deficits within the neuromotor system include reduction of muscle mass, impairment of tactile sensitivity, slowing down of muscle contractions, etc. In particular, healthy aging is known to be associated with higher grip forces and safety margins. The changes with advanced age in the manipulation strategies of hand/digit actions are partially due to the changes in mechanical properties of peripheral structures [1, 2]. In this study, we examined age-related differences in mechanical properties of the human hand digits by estimating the apparent stiffness [3, 5] and the friction coefficients between digit tips and contacting surfaces with the newly developed measurement devices.

METHODS
Subject: Twelve healthy elderly subjects and twelve healthy young subjects (age: 76.1 ± 5.6 for the elderly; 26.9 ± 4.9 years for the young; 6 females for each group) were recruited. All subjects were right-hand dominant. The elderly subjects were recruited from a local retirement community, and they passed a series of screening tests (e.g., cognition, depression, quantitative sensory tests, and general examination).

Equipment
Apparent stiffness estimation: Four hand digits (the thumb, and three fingers) grasped the handle, which was fixed to the table, and four miniature force sensors were used to measure the forces applied by the digits. The force sensors were connected to a rod, which was connected to an electromagnet. A compression spring was placed between the force sensor and the base. With this setup, when the electromagnet was turned on, the finger support was effectively rigid, when the electromagnet was off, the force sensor yielded under the corresponding digit resulting in a quick, low-amplitude motion. The electromagnets were controlled by the experimenter.

Friction coefficient estimation: A multi-axis force sensor was attached to the frame to measure normal and tangential forces, and a linear motor applied force that moved the sensor with respect to the digit [4]. The top of the sensor was covered with sandpaper (300-grit).

Experimental Procedure
Apparent stiffness estimation: There were fifteen experimental conditions: 5 digits (Thumb, Index, Middle, Ring, and Little fingers) × 3 force levels (15, 30, 45% of maximal voluntary contraction force, MVC). For each condition, the subjects were required to grasp the handle naturally and then to produce a steady-state level of force with a task-digit while keeping all non-task digits on the sensors for about 5 s. The normal force was displayed on the computer screen in %MVC of the task-digit. At a random time (uniformly distributed between 5 and 8 s), the electromagnet holding the task-digit was turned off, causing the task-digit to move into flexion. The displacement of the digit tip was approximately 5–10 mm. When the perturbation was applied, the task-digit force decreased immediately. The subjects were instructed to recover the dropped digit force to the original force level as quickly as possible. The sampling frequency was set at 500 Hz.

Friction coefficient estimation: There were fifteen experimental conditions: 5 digits (Thumb, Index, Middle, Ring, and Little fingers) × 3 normal force levels (15, 30, 45% of MVC). The subjects were instructed to exert a steady-state level of normal force by pressing with one of digits on the sensor while the sensor was moved horizontally. The subjects were instructed to keep the task-digit in the same position and configuration against sensor movement. The produced normal force was displayed on the computer screen. The subject
performed three consecutive trials for each digit and condition.

Data analysis
Apparent stiffness estimation: We used a simple linear damped mass-spring model (one degree-of-freedom) for the hand digits [5]:

\[ m \ddot{x}(t) + r \dot{x}(t) + kx(t) = f(t) \]

\( x, \dot{x}, \ddot{x} \): digit tip position and its time derivatives; \( f \): digit normal force; \( m \): mass coefficient; \( r \): damping coefficient; \( k \): apparent stiffness coefficient. The apparent stiffness was estimated using the time window of 25 ms after the initiation of perturbation (0 ms) to avoid the influence of reflexes and voluntary reactions.

Friction coefficient estimation: the ratio between the tangential force during the sensor motion and the subject’s normal force was computed as the dynamic coefficient of friction [3, 4].

RESULTS AND DISCUSSION
Apparent stiffness: In general, the elderly group showed larger values of \( k \) as compared to the young group (Young: 425.9 ± 23.1 N/m; Elderly: 548.6 ± 23.1 N/m, mean ± standard error, \( p < 0.01 \)). The stiffness increased with the magnitude of baseline force (15% < 30% < 45% of MVC) in both groups (Fig. 1). Also, both groups showed significant differences across digits (thumb > index > middle > ring, little) confirmed by post-hoc comparisons (\( p < 0.05 \)).

Friction coefficient: Overall, the elderly group showed smaller friction coefficients as compared to the young group (Young: 0.81 ± 0.03; Elderly: 0.59 ± 0.03, mean ± standard error, \( p < 0.001 \)). The friction coefficients decreased with the force level in the young group (15% > 30% > 45% of MVC) while there was no significant change between the force levels in the elderly group (Fig. 2). No significant differences were seen among digits.

CONCLUSIONS
1. Healthy aging is associated with higher apparent stiffness of the digits. Generally, the apparent stiffness increases with the magnitudes of digit-tip force.
2. Healthy aging is associated with smaller coefficients of dynamic friction between the skin and hand-held objects.