

# From Human-to-Human Touch to Peripheral Nerve Responses

Steven C. Hauser, *Student Member, IEEE*, Saad S. Nagi, Sarah McIntyre, Ali Israr, Håkan Olausson, and Gregory J. Gerling, *Senior Member, IEEE*

**Abstract**—Human-to-human touch conveys rich, meaningful social and emotional sentiment. At present, however, we understand neither the physical attributes that underlie such touch, nor how the attributes evoke responses in unique types of peripheral afferents. Indeed, nearly all electrophysiological studies use well-controlled but non-ecological stimuli. Here, we develop motion tracking and algorithms to quantify physical attributes – indentation depth, shear velocity, contact area, and distance to the cutaneous sensory space (receptive field) of the afferent – underlying human-to-human touch. In particular, 2-D video of the scene is combined with 3-D stereo infrared video of the toucher’s hand to measure contact interactions local to the receptive field of the receiver’s afferent. The combined and algorithmically corrected measurements improve accuracy, especially of occluded and misidentified fingers. Human subjects experiments track a toucher performing four gestures – single finger tapping, multi-finger tapping, multi-finger stroking and whole hand holding – while action potentials are recorded from a first-order afferent of the receiver. A case study with one rapidly-adapting (Pacinian) and one C-tactile afferent examines temporal ties between gestures and elicited action potentials. The results indicate this method holds promise in determining the roles of unique afferent types in encoding social and emotional touch attributes in their naturalistic delivery.

## I. INTRODUCTION

People often touch one another to convey social thought and communicate emotion. For example, one might tap the shoulder of another to get their attention, or lightly grasp and stroke their arm to congratulate them. From prior work we know that many of these gestures can be readily understood [1], [2], suggesting the possibility that underlying neural codes, originating from the periphery, are elicited from the physical attributes delivered by another person. Various subtypes of neural afferents in the skin are thought to be involved, such as C-tactile afferents which respond to light stroking at particular velocities and at the temperature of human skin [3]. However, it is currently unknown how naturalistic human touch decomposes into low-level physical quantities that serve as direct input to neural afferents – indentation depth, shear velocity, contact area, distance to receptive field center – nor how they might be differentially parsed by the rich diversity of subtypes.

Nearly all prior efforts to characterize the response functions of human afferents to touch quantities have employed precisely-controlled mechanical stimuli, such as rigid indenters and rotating brushes [3]–[6]. Such stimuli vary only one attribute at a time. When stroked by a brush at a range of velocities, C-tactile afferents, for example, have been found to preferentially fire between 1 and 10 cm/s, which is perceived as being pleasant [7]. By contact with a rigid probe, rapidly-adapting (RA) and Pacinian corpuscle (PC) afferents have been found to detect small amounts of contact, and encode the onset and offset of held stimuli as well as periodic vibration frequencies [6], [8]. That said, a recent effort employed natural surface textures, e.g., velvet, fleece, drapery tape, mounted to wheels rotated against the stationary fingers of primates [9]. These textures indeed attempt naturalistic interactions, yet not to the point of one person touching another.

The response properties of tactile afferents may be further elucidated by considering naturalistic and human delivered inputs in other sensory systems. In human hearing, for example, the co-modulation property of auditory neurons was found to enhance their ability to pick out tones and vocalizations amidst background animal noises [10]. In the visual system, peripheral neurons perform specific decorrelations to reduce visual redundancy that is characteristic of natural scenes [11]. These sensory systems also contain human-specific components – distinct brain regions are dedicated to recognizing human faces [12] and human voices [13] as compared to other sights and sounds. For the tactile system as well, we must consider that the response properties of peripheral nerves in the skin may be particularly tuned to the touch of another human.

When trying to measure physical contact attributes underlying human touch, devices such as sensor mats, sleeves and pads have been used [14]–[16]. Although using such devices can allow for high-fidelity measurement of forces and contact areas, they inhibit direct human skin-to-human skin contact. This can change both how people deliver physical expressions and how neural afferents respond. For C-tactile fibers, which respond to light shearing of the skin as well as human body temperature, such a barrier may attenuate or confound their response. The extreme sensitivity of certain afferents, e.g., slowly adapting type I (SAI) afferents that fire at forces of less than 1 mN [17], may also preclude placing any external device on the skin. For this reason, measurement techniques which do not impede skin-to-skin contact are ideal.

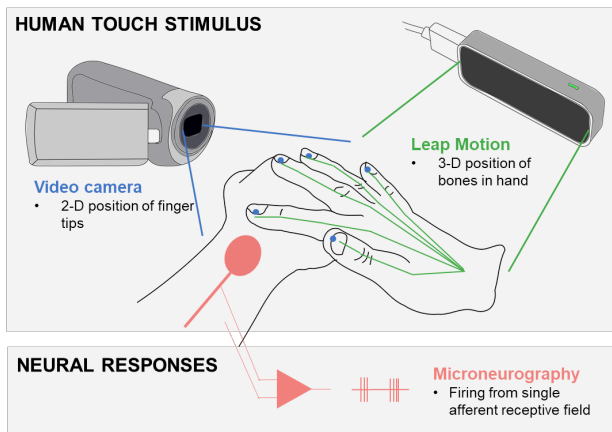
In order to understand how distinct populations of neural afferents in the skin might encode the complex and

\*Research supported by Facebook, Inc.

S.C. Hauser and G. J. Gerling are with Systems Engineering, Mechanical Engineering and Biomedical Engineering at the University of Virginia, Charlottesville, VA, USA (e-mail: {sch5zc, gg7h}@virginia.edu).

S. S. Nagi, S. McIntyre, and H. Olausson are with the Center for Social and Affective Neuroscience (CSAN), Linköping University, Sweden.

A. Israr is with Facebook Reality Labs, Redmond, WA, USA.



**Fig 1. Experimental setup.** The two major components for tracking human touch attributes are a video camera and a Leap Motion controller, used in tandem to track contact between the toucher’s hand and the receiver’s receptive field. Neural responses are measured simultaneously via microneurography.

interdependent physical quantities that underlie natural human touch, a first step is to conduct synchronous measurement of physical contact and neural firing outputs. Towards this end, we developed a methodology to track and measure contact between a toucher’s hand and the receptive field of a single peripheral afferent via a motion tracking system, while simultaneously recording trains of action potentials via *in vivo* microneurography [18].

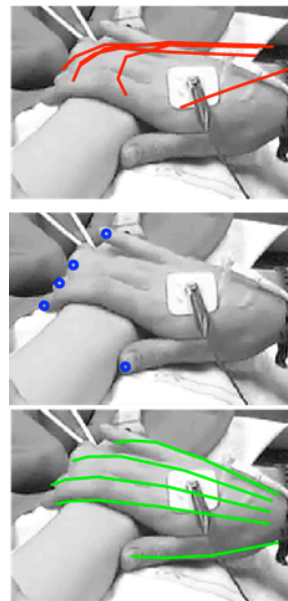
## II. METHODS

Human-to-human contact, between a toucher’s hand and the receiver’s arm or hand, was measured using a motion tracking system consisting of both a 2-D high definition video camera and a 3-D stereo infrared device (Figure 1). The latter device produces highly accurate measurements of the positions of the bones of each of the joints in the hand, when it is properly recognized and stable; however, it is prone to errors in mid-identifying the hand position, especially during dynamic motion or when fingers are occluded by the hand [19]. To address these shortcomings, an additional 2-D video camera, positioned at a different viewing angle, was used along with algorithms to track the fingertips and determine proper orientations of the hand (Figure 2).

Simultaneous to the visual observations, action potentials from single, peripheral neural afferents were recorded using microneurography. In particular, in a study with touchers and receivers, recordings were done from one C-tactile fiber and one Pacinian corpuscle fiber, in separate participants. Temporal correlations were examined afterward between the contact characteristics (as determined via motion tracking) and the neural firing.

### A. Motion Tracking Components

The motion tracking consisted of two main components: a 2-D high definition video camera (HDR-CX625, 9.2 megapixel, Sony Corp., Tokyo, Japan) and a 3-D infrared stereo camera system (Leap Motion, San Francisco, CA). During experiments, while the “toucher” was contacting a participant, the positions of the bones in the toucher’s hand



1. 3-D hand misaligned

2. 2-D fingertips identified in video recording

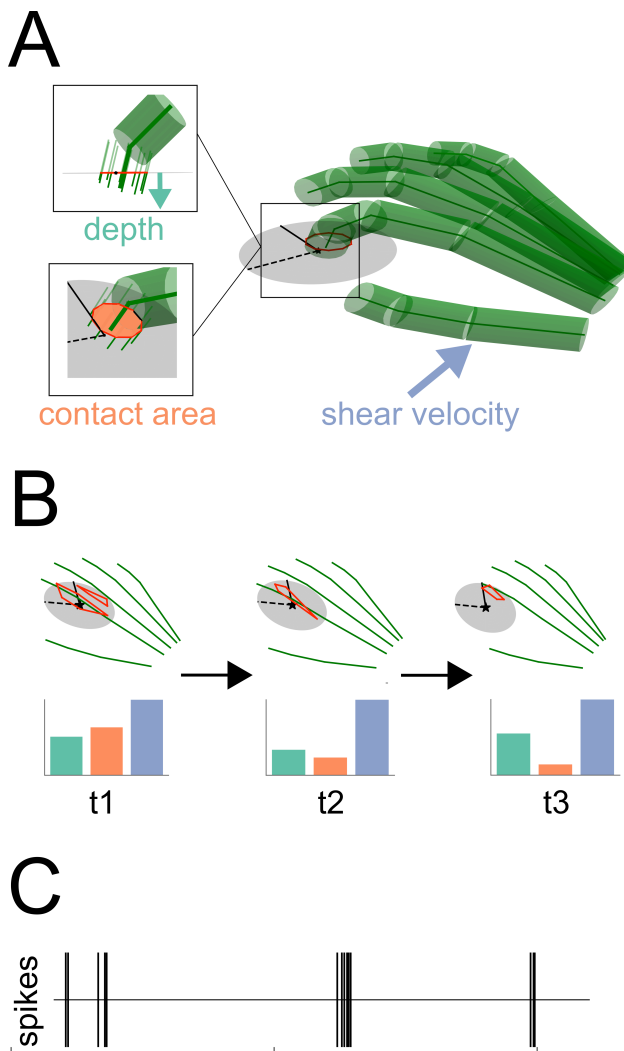
3. 3-D hand found and rotated to match video fingertips

**Fig 2. Combining 2-D video and 3-D stereo infrared data to improve overall accuracy.** A series of three steps is shown beginning the 3-D stereo data which yield the positions of the bones in the hand, in this case misaligned relative to the video data. Next, the fingertips are identified in the 2-D video data. Finally, the 3-D hand in the top frame is rotated given the fingertip positions.

were measured in 3-D by the Leap Motion controller at approximately 40-60 Hz, as well as recorded in 2-D high definition video (1280 x 720 pixels) at 30 Hz. The use of both systems together afforded much better results than using either alone, as will be explained.

The first step of this process was to perform post-processing of the video data. The fingertips and palm were hand-identified in the 2-D video by a research assistant at one-second intervals. This process took approximately 5-10 minutes per minute of video. Between these hand-coded frames, a simple linear least-squares correlation filter was used to track the position of the palm and fingertips from frame to frame. Afterwards, the tracked palm and fingertips were reviewed by the research assistant along with the video data, and any notable discrepancies were fixed manually. The result was a list of 2-D locations in the video coordinates for the fingertips and palm per each frame of video (6 locations by 30 frames per second = 180 points per second of video).

The next step was to align 3-D measurements of the hand to fit the 2-D video data (Figure 2). Utilizing the palm locations, which were reliably measured in both the 2-D video coordinates and the 3-D Leap Motion coordinates, an affine camera matrix was fit to transform the Leap Motion coordinates to the video coordinates. In a processing program written in MATLAB, for each frame of video, fingertip locations were compared in the 2-D video coordinates (as identified in post-processing) versus the transformed Leap Motion measurements at that time. If the discrepancy between the transformed Leap Motion fingertips and video fingertips was above a certain threshold, the program would search for alternate hand configurations from prior measurements in the Leap Motion recording. For each



**Fig 3. Measuring contact near the afferent's receptive field along with elicited neural spikes.** A) Three physical quantities are shown as measured by the tracking system: mean indentation depth, contact area, and shear velocity. Note that the fingers are represented as cylinders, formed by multiple line segments, as shown in the “depth” panel. Their intersection with the plane forms contact points which are connected to estimate contact area. B) Three distinct time points are shown for contact made by a stroking gesture, with relative levels of each physical quantities, associated by hue from panel A). C) Neural spike times as measured via microneurography for a multi-finger stroking gesture.

alternate hand configuration, the program would place the alternate hand at the original palm position, and perform several 3-D rotations to it. The best hand configuration was chosen as the pair (hand configuration, rotation) that best fit the 2-D video fingertip data. The result of this process was a set of “toucher” hand measurements in 3-D space that matched the video much more closely than the original Leap Motion recording.

*Fitting the local region of the receptive field.* After the 3-D finger and hand measurements had been properly matched to the 2-D video recordings, the location of the receptive field was identified in 3-D. Based on the hand marking on the receiver's arm that corresponded to the receptive field center, frames of video in which the index finger crossed over the receptive field were selected. A plane was fit to the 3-D positions of the index finger for these frames, with the center at the mean coordinates. A local region of skin surrounding

the receptive field was modeled as a circular region of this plane with a radius of 3 cm. In subsequent measurements, contact was only considered if it lied within this local region.

#### B. Measuring Contact with the Receptive Field

Hand position data from the Leap Motion resulted in 3-D poses, widths, and lengths for each bone in the hand (Figure 3). In custom software, written in Python 2.7, these were translated into cylinders made up of 3-D line segments. Each intersection between these lines segments and the plane representing the receptive field was treated as a contact point.

We examined four quantified touch attributes, which had been considered in prior work [20], [21]. The attributes of 1) *contact* was determined as a binary value representing whether any bones from the toucher's hand intersected with the receptive field plane. 2) *Depth* was measured as the mean of the normal distance from the plane to the end of each contacting line segment per bone of the hand. 3) *Contact area* was measured as the area of the convex hull enveloping the contact points for each bone in the hands. 4) *Shear velocity* was measured as the mean velocity of each contacting fingertip (or palm) tangent to the local receptive field plane.

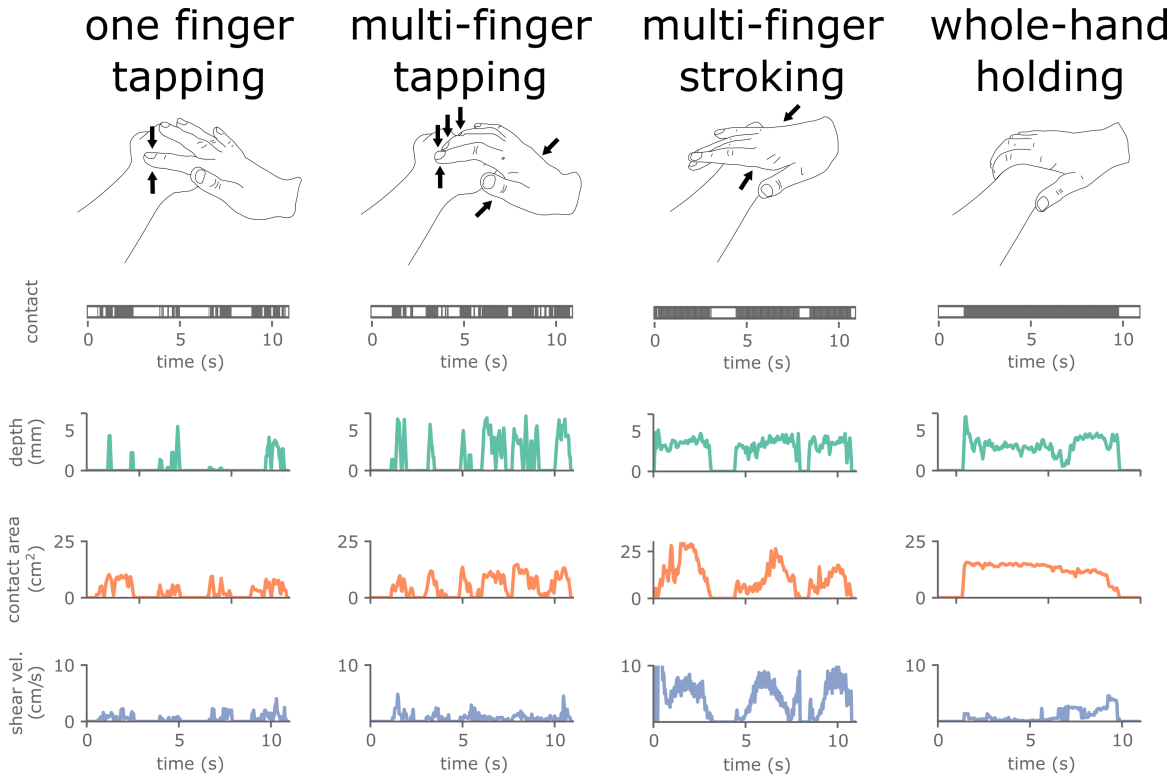
#### C. Human-subjects experiments

*Participants.* Two participants took part in this study (ages 34 and 27, both female). Informed consent, in writing, was obtained before the start of the experiment. The study was approved by the ethics committee of Linköping University (Dnr 2017/485-31) and complied with the revised Declaration of Helsinki.

*Experimental design.* In each experiment, a trial-set of four gestures were performed to the receptive field of a single-unit neural afferent. 1) Single-finger tapping: the toucher delivered three sets of 3-6 taps, directly on top of the receptive field. 2) Multi-finger tapping: the toucher tapped continuously with 3-4 fingers, while moving the entire hand back and forth across the receptive field. 3) Multi-finger stroking: the toucher performed 3 broad strokes in succession across the receptive field of the afferent using 3-4 fingers lying flat against the skin. 4) Whole-hand holding: the toucher laid the hand down flat onto the receptive field, mostly contacting with the fingers with slight contact of the palm, and a very light squeezing. These standardized gestures were applied by trained experimenters. The experimenter received spoken cues via headphones, first the cue-word, then a countdown (3, 2, 1, go). They were instructed to perform the touch starting from the “go” signal until they heard a stop signal (3, 2, 1, stop), creating a continuous time window of touch for 10 seconds. The toucher was familiarized with the neuron's receptive field and required to touch an area of skin including but not limited to the receptive field. Gesture data for 2 trial-sets for the C-tactile fiber and 1 trial-set for the Pacinian corpuscle were obtained. Each gesture lasted a total of 10 seconds. The exact execution of each gesture was kept somewhat vague, in an attempt to deliver a more natural and volitional stimulus.

#### D. Microneurography

Microneurography is a long-standing, safe, and painless procedure for recording from single peripheral afferents in



**Fig 4. Example physical contact data for each of the four gestures.** Physical contact measurements are shown for each of the four gestures over 10-second time windows. Short bursts of depth along with low contact area and shear velocities are characteristic of the one-finger tapping gesture. The multi-finger tapping gesture resembles the one-finger tapping except with greater contact and contact area and a small shear velocity component as the toucher moved across the arm. The multi-finger stroking gesture generally contained three strokes of about 3 seconds each, with consistent depth as well as high amounts of contact area and shear velocity. The whole hand holding gesture consisted of long, continuous contact with large contact area and low shear velocity.

awake, unanesthetized participants [22]. The participants were seated in a comfortable chair and pillows were provided to ensure minimal discomfort. All recordings were made from the right radial nerve. As a first step, the radial nerve was visualized using the ultrasound technique (LOGIQ e, GE Healthcare, Chicago, IL, USA). Then, a recording electrode (FHC, Inc. Bowdoin, ME, USA) was inserted percutaneously followed by localization of the nerve by electrical stimulation through the recording electrode. Minute movements were made to the recording electrode, manually or with a pair of forceps, until single-unit activity could be recorded. In addition to the recording electrode, an indifferent (uninsulated) electrode was inserted subdermally, approximately 5 cm away from the nerve.

After the recording electrode reached a stable position for single-unit recording, each neuron was classified by its physiological characteristics, as per the criteria used in [23]. Neural recordings were performed with equipment purpose-built for human microneurography studies from AD Instruments (Oxford, UK) or the Department of Integrative Medical Biology, Umeå University (Sweden).

All neural data were recorded and processed using LabChart Pro (v8.1.5 and PowerLab 16/35 hardware PL3516/P; AD Instruments, Oxford, UK) or SC/ZOOM (Department of Integrative Medical Biology, Umeå University). Action potentials were distinguished from background noise with a signal-to-noise ratio of at least 2:1, and were confirmed to have originated from the recorded

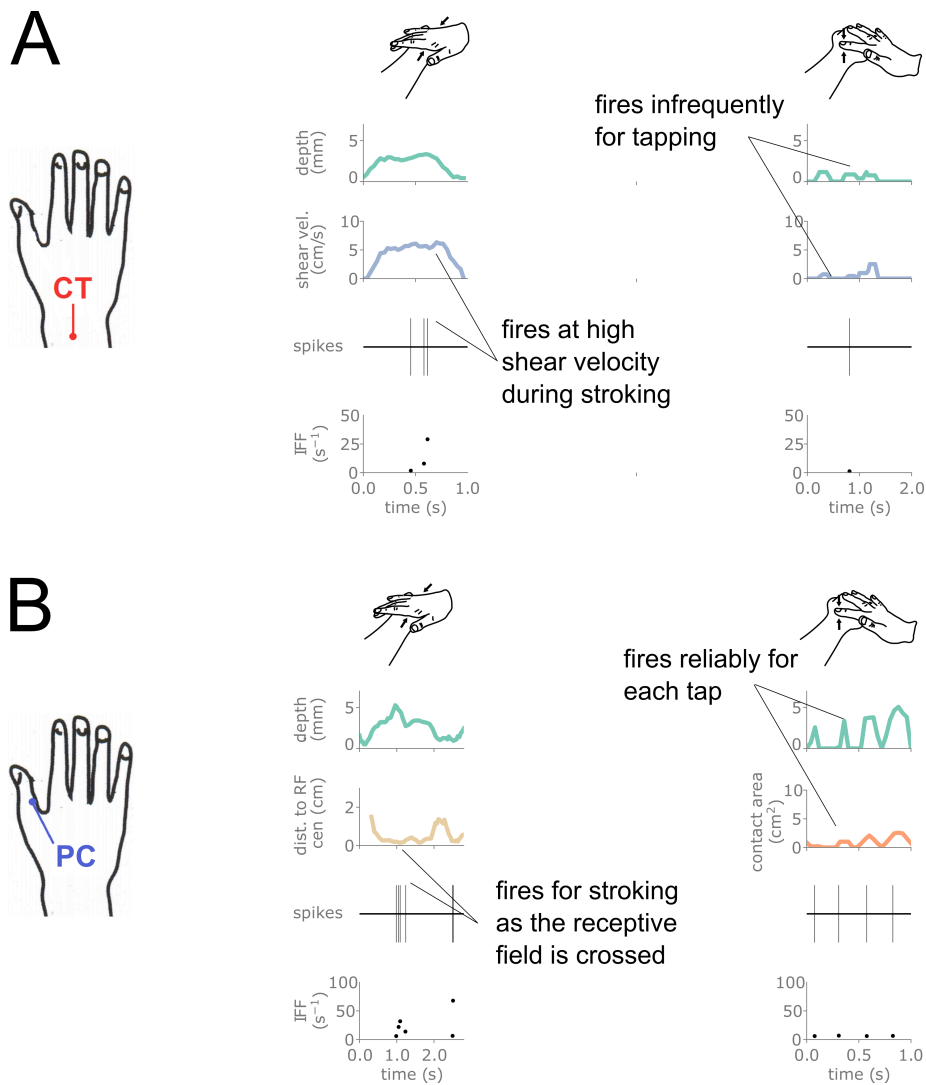
afferent by a semi-automatic inspection of their morphology [22].

### III. RESULTS

Example physical attributes identified from one set of each of the four gestures are shown in Figure 4. For one finger tapping, there were relatively small amounts of contact area and shear velocity, with changes in depth in concert with each tap. For multi-finger tapping, contact area was slightly greater with multiple fingers contacting at once, with a greater frequency of taps compared to the one-finger tapping. In the multi-finger stroking gesture, depth remained consistent, as both shear velocity and area increased the fingers swept across the receptive field. Finally, in the whole-hand holding gesture, depth and area remained constant, with minimal shear velocity.

Example neural responses for the C-tactile afferent are shown in Figure 5A. The C-tactile afferent fires mostly during the long stroking from the multi-finger stroke gesture, when both shear velocity and contact area are large. The ranges of velocities employed by the toucher matched the peak response range of C-tactile afferents from brushing experiments, 1-10 cm/s [7]. During tapping, the C-tactile afferent fired rarely if at all. Peak firing rates for the C-tactile afferent over all gestures were during the multi-finger stroking, at a maximum frequency of 44 Hz (Figure 6).

Example neural responses for the PC afferent are shown in Figure 5B. For one-finger and multi-finger tapping, the PC



**Fig 5. Responses of neural afferents to the physical quantities of human touch.** A) Depicts the firing of the C-tactile afferent under a few example conditions during the experiments. During a stroking gesture, the afferent responded to the high shear velocity (left); when being tapped, the afferent fired infrequently (right). B) Depicts the firing of the PC fiber to similar example conditions during the gestures. During a stroking gesture, the PC afferent fired in short bursts as the receptive field was crossed (left); during tapping, the PC fired synchronously with each tap (right). For both afferents, the position of the receptive field on the touch receiver’s arm/hand is illustrated.

afferent fires synchronously with each tap. For stroking, however, the PC afferent fires only as the stimulus crosses the center of its receptive field. Peak firing rates for the PC afferent over all gestures were during multi-finger tapping, at a maximum frequency of 362 Hz (Figure 6).

#### IV. DISCUSSION

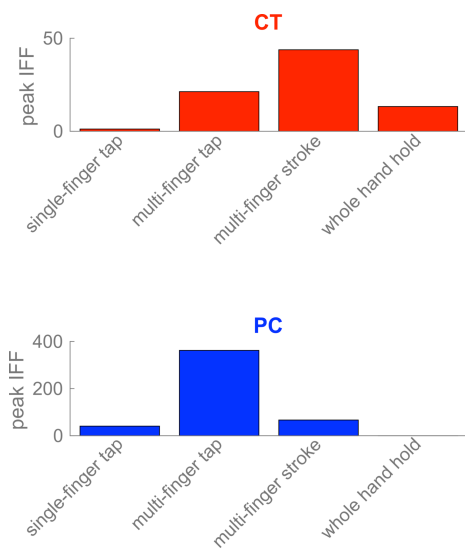
To our knowledge, this effort is the first to report methods that allow natural human-to-human gestures to be delivered and tracked as stimulus input simultaneous with single afferent microneurography. Nearly all prior microneurography studies have employed a classical stimulus-response paradigm [3], [4], [6]–[8], [23]. The use of non-contact stimulus tracking is a paradigm shift where we allow natural movements and contact interactions as desired by the human toucher, and seek only to track what occurs, for post experiment correlation with the neural response. Our preliminary examination of C-tactile and PC responses align

well with prior literature and suggest that each afferent type may encode unique aspects of human touch.

To quantify human touch during the neural recordings, we decided to use an optical, camera-based motion tracking system. Sensor mats, sleeves, and other physical components create barriers between skin-to-skin contact and thereby alter the delivery of gestures as well as the neural responses. We found a combination of the Leap Motion IR camera system along with 2-D video recordings to offer the best accuracy given the constraints of other devices and those of the microneurography environment. In the future, using pressure-sensitive devices in separate experiments may allow us to better inform the “depth” metric in our contact modeling to represent real pressure distributions from human touch.

In our preliminary neural recording data, we observe trends in the response properties for both the C-tactile and PC afferents that align well with the literature. In terms of encoding human touch, we observe that the C-tactile afferent





**Fig 6. Peak firing rates per gesture.** The C-tactile afferent (Top) fired at the greatest frequency (43.8 Hz) during the multi-finger stroke, while the PC afferent (Bottom) fired at the greatest frequency (362.3 Hz) during the multi-finger tapping.

responds most to light stroking, while the PC afferent responds synchronously with tapping gestures, as well as the onset of contact with the receptive field during stroking. Of course, with a sample size of two, these findings are preliminary and require further studies with a greater number of afferents and subtypes.

Unlike traditional methods of controlling stimuli, in which a single factor is varied at a time, the naturalistic touch inputs simultaneously include several factors. Some of the covariance between these factors may be inherent to human touch and help elucidate neural encoding patterns—as neurons in the visual system decorrelate redundancy that is characteristic of natural scenes. Likewise, it is possible that tactile neurons are tuned to inherent dependencies in the physical primitives that underlie human touch. In particular, metrics such as contact area and indentation depth may be intimately related—a finger pressing more deeply into the arm will contact with a greater area. Multivariate statistical analyses or machine learning techniques may prove useful in examining these types of complicated, multi-factor relationships. Constructing such relationships is key to further understanding our innate ability to decipher the touches from another human.

#### ACKNOWLEDGMENT

We would like to thank Dr. Ewa Jarocka at the Department of Integrative Medical Biology (IMB) at Umeå University for her assistance in performing the microneurography experiments.

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