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Mimicking the End Organ Architecture of Slowly Adapting Type I Afferents May Increase the Durability of Artificial Touch Sensors

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Abstract

In effort to mimic the sensitivity and efficient information transfer of natural tactile afferents, recent work has combined force transducers and computational models of mechanosensitive afferents. Sensor durability, another feature important to sensor design, might similarly capitalize upon biological rules. In particular, gains in sensor durability might leverage insight from the compound end organ of the slowly adapting type I afferent, especially its multiple sites of spike initiation that reset each other. This work develops models of compound spiking sensors using a computational network of transduction functions and leaky integrate and fire models (together a spike encoder, the software element of a compound spiking sensor), informed by the output of an existing force transducer (hardware sensing elements of a compound spiking sensor). Individual force transducer failures are simulated with and without resetting between spike encoders to test the importance of both resetting and configuration on system durability. The results indicate that the resetting of adjacent spike encoders, upon the firing of a spike by any one, is an essential mechanism to maintain a stable overall response in the midst of transducer failure. Furthermore, results suggest that when resetting is enabled, the durability of a compound sensor is maximized when individual transducers are paired with spike encoders and multiple, paired units are employed. To explore these ideas more fully, use cases examine the design of a compound sensor to either reach a target lifetime with a set probability or determine how often to schedule maintenance to control the probability of failure.

Keywords

Tactile; touch; neurophysiology; mechanoreceptor; somatosensory afferent; slowly adapting type I afferent; biomechanics; biomimetic; sensor

1 Introduction

Through the application of biomimetic design, our understanding of biological sensing may help inform newly engineered systems. Recent examples in this growing field include understanding how insects use optic flow to inform navigation of unmanned aerial vehicles [1], understanding how rats move their whisker arrays to design shape extraction algorithms [2], and understanding how skin ridges interact with tactile afferents to design robotic grip control [3] and texture sensing [4]. Similarly, neural spike-based output and processing has

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been investigated in the rapid processing of sparse signals for image classification [5] and interfacing advanced prosthetics [6].

Other recent works have developed spike-based sensor systems that mimic tactile afferents with force transducers embedded in artificial skin, coupled to virtual spike encoders composed of transduction and neural dynamics models [6], [7]. Despite their success in mimicking the force-spike transformations for slowly adapting type I (SAI) afferents, in addition to rapidly adapting (RA), and Pacinian corpuscle (PC) afferents, such systems couple a single transducer to a single spike encoder. In contrast, the SAI end organ couples multiple transducer elements (Merkel cell-neurite complexes) with multiple spike encoders (spike initiation zones) [8]. These multiple spike encoders are thought to reset each other, i.e., a spike generated at any spike encoder antidromically propagates to all other spike encoders, initiating absolute refractory periods and restarting the process of spike initiation [8]. A likely benefit of the SAI end organ's compound nature has been suggested as increasing the durability of the natural mechanosensory unit [9].

In the case of man-made sensors, durability can be defined as the ability to perform the same input-output transformation despite some level of damage to the sensor. In terms of a compound spiking sensor, where physical force transducers are tied to an analog to digital (A/D) converter to provide input to virtual spike encoders, durability can be defined as the ability to produce the same output for a given stimulus, even though a number of the physical force transducers have failed. The mechanical and materials capabilities in the manufacturing of sensors can extend durability to some extent, though not perfectly. Thus, the network structure and interactions of a compound sensor might handle the consequences of nearly inevitable degradation.

Herein, we computationally model and simulate compound spiking sensors, based upon the SAI end organ, seeking to obtain design patterns for increased durability. We hypothesize that a) resetting between spike encoders will be an essential mechanism to durability, and that b) of the repeated elements in the compound spiking sensor, the number of spike encoders will be of greatest importance, compared to the number of transducers grouped to each spike encoder. To explore these ideas more fully, we examine the design of a compound sensor to either reach a target lifetime with a set probability or determine how often to schedule maintenance to control the probability of failure.

2 Methods

The compound spiking sensors developed herein employ a computational network of transduction functions and leaky integrate and fire models (together a spike encoder, the software element of a compound spiking sensor), driven by existing force transducers (hardware sensing elements of a compound spiking sensor). To test our hypothesis that resetting and the number of spike encoders are essential to compound sensor durability, we use this model to simulate random transducer failures with and without resetting. Then, we examine the simulation results to derive rules governing compound sensor failure, and analyze these rules with fault trees to gain a probabilistic understanding of how a compound sensor's configuration, i.e., the number of spike encoders and number of transducers linked

to each, can influence its durability. Finally, we use discrete event simulation derived from the fault tree to illustrate example cases of compound spiking sensor design and use.

2.1 Compound Spiking Sensors

Single spiking sensors can be contrasted with compound spiking sensors, as in Fig. 1. In the case of a single spiking sensor, a single force transducer is connected to a single spike encoder, which produces one train of spikes. As in natural tactile afferents, the frequency of the spikes embeds information about both the magnitude of stimulus compression and magnitude changes over time. In the case of a compound spiking sensor, multiple force transducers are tied to multiple spike encoders, and then these spike encoders are connected so as to output one train of spikes for the compound sensor as a whole.

Each spike encoder is composed of a transduction function (Eqn. 1) and leaky integrate and fire model (Eqn. 2). In the transduction function, force, f serves as input and is transformed to output current, I , as defined by the offset β , and the gains α and λ for force and the first derivative of force, respectively. M reflects the number of force transducers associated with each spike encoder. Note that in practice this term would not be included because one would utilize actual, unique force transducers, but here it was used to simulate multiple identical force transducers. Force is sampled and converted to current at a frequency of 1000 Hz, resulting in one sample per millisecond. As the modeled transduction function is linear, saturation would be a function of the force transducer specification. However, if matching the saturation of a particular afferent was desired, a sigmoidal transduction function could be employed, similar to that expected in natural tactile afferents, and as observed for nociceptors and hair cells [10][11].

$$I(t) = \beta + M \left(\alpha f(t) + \lambda \frac{df}{dt} \right) \quad (1)$$

The current originating from each transduction function serves as input to a leaky integrate and fire model, representing a spike initiation zone. Neural dynamics are abstracted to a single differential equation (Eqn. 2), where R is resistance, C is capacitance, u is membrane potential, and I is current. The term $\tau = RC$ is the time constant of the leaky membrane of the neuron. In general, when current drives the membrane potential to a spike initiation threshold, v , a spike time is recorded and a 1 ms absolute refractory period is entered. Numeric evaluation of the leaky integrate and fire model is performed with the fourth order Runge-Kutta method [12].

$$RC \frac{du}{dt} = -u(t) + RI(t) \quad (2)$$

In the case of the biology, it is expected *in vivo* that a spike generated at one spike initiation zone would antidromically invade the other spike initiation zones, resetting them and initiating an absolute refractory period [8]. Thus, in the case of a compound spiking sensor, when resetting is enabled and a spike is generated by a given leaky integrate and fire model, that spike resets the accumulated membrane potential in all other leaky integrate and fire

models in the modeled end organ, and causes them to enter a 1 ms refractory period. In contrast, when resetting is disabled, the output of the compound spiking sensor is the superposition of spiking from all associated spike encoders.

Parameters of the leaky integrate and fire models were set to $\tau = 71.409$ ms, $C = 9.7e^{-7}$ mF, and $v = 47.3$ mV, matching those of prior work in creating a single spiking sensor [7]. Parameters of the transduction functions were set such that the summed current from multiple force transducers would produce identical spiking. For example, transduction parameters for a configuration with one transducer per spike encoder would have α and λ values that were twice that of a configuration with two transducers per spike encoder. Therefore, all simulated sensor configurations, when undamaged, perform identical input-output transformations. The resulting parameters for the transduction function for the four compound spiking sensor configurations are given in Table 1.

In the simulations that follow, force input (f) is attained by use of a piezo-resistive transducer (Flexiforce A201; Tekscan Inc., South Boston, MA) embedded in a silicone-elastomer substrate, described in [7], indented by the blunt end of a 20 mm diameter cylindrical probe. Ramp-and-hold stimuli were delivered at 1.1, 1.2, and 1.3 mm depths at the same velocity, with six trials per depth. In Fig. 2, force measured at the load cell at the probe relaxes over the indentation due to the silicone-elastomer. Force at the piezo-resistive transducer in Fig. 2B ties to spikes produced in Fig 2.C. Spikes produced by this single force transducer to spike encoder case increase in frequency with indentation.

Before introducing transducer failure, spike timings were produced for the compound sensors for the same force input. To compare the output of compound sensor configurations as transducers failed, the percent undamaged response was examined. This measure was obtained by dividing the summed difference in static firing frequencies (calculated during a 2.5 sec window 2 sec after stimulus onset) for the 18 stimulations of the undamaged and damaged cases by the summed static firing frequencies for the undamaged case.

2.2 Simulating Transducer Failures with and without Resetting

To test the importance of resetting the adjacent spike encoders of a compound sensor, and to gain insight into how the grouping of force transducers to spike encoders influences compound sensor durability, simulations were run for four spiking sensor configurations: {12}, {6, 6}, {4, 4, 4}, and {3, 3, 3, 3}, where the notation represents compound spiking sensors with 1, 2, 3, and 4 spike encoders, each of which is linked to 12, 6, 4, and 3 force transducers, respectively. Therefore, in the case of configuration {4, 4, 4}, term M in Eqn. 1 is 4. Even numbered distributions of transducers to spike encoders, as compared to the uneven distribution of Merkel cells to spike initiation zones as observed for the SAI end organ, are assumed for the purposes here.

For each of the four configurations, models with and without resetting were examined. Note that the model configured {12} is identical with or without resetting, as there is a single spike encoder. Transducers were simulated as randomly failing one at a time, up to 6 failures in total, where a failure is defined as a transducer no longer outputting analog voltage to the A/D converter. The random failure of transducers was repeated five times for each

configuration of compound spiking sensor, with a different random set. A compound spiking sensor failure was defined as any change in its input-output relationship of force to spike frequency. If resetting is an essential mechanism in the durability of a compound spiking sensor, then a single transducer failure with resetting disabled would result in a changed input-output transformation (a compound sensor failure). Similarly, if the configuration of the compound sensor influences its durability, then some spiking sensor configurations should be able to tolerate more transducer failures than others before failing.

2.3 Analyzing the Impact of Compound Spiking Sensor Configuration on Durability

To determine how the durability of compound spiking sensors is influenced by its configuration, the simulation results were further examined to determine rules governing the maximum and minimum number of transducers that can fail before the compound spiking sensor fails entirely. These rules were then visualized through fault trees to give a probabilistic understanding of how the number of spike encoders and transducers associated with each influences compound spiking sensor durability.

2.4 Discrete Event Simulation of Use Cases

The understanding obtained through the fault tree analysis was used in discrete event simulations of two potential use cases. These use cases illustrate how understanding the impact of transducer failure on system durability can inform 1) the number of transducers a compound spiking sensor requires to reach a target lifetime, and 2) how often to schedule maintenance to control the probability of failure. These use cases illustrate the temporal aspects of system durability. Use case simulations were coded in Python, and each transducer in the simulated compound spiking sensor drew its time to failure from an exponential distribution using the built in random library. In essence, for each transducer a Poisson process was simulated where the event was transducer failure and only the first event was of interest. Based on the fault tree analysis, the lifetime of the compound spiking sensor was defined as the maximum life of the associated transducers. Probabilities of reaching target lifetimes were obtained by observing the outcome of 100,000 trials.

3 Results

3.1 Simulations of Transducer Failures with and without Resetting

Overall, the results suggest that resetting between spike encoders is an essential mechanism for compound spiking sensors to be robust to transducer failure.

In particular, when resetting between spike encoders is disabled, a single transducer failure changes the input-output transformation of the compound sensor, regardless of configuration. This can be observed in Fig. 3 in terms of the percent undamaged response. Note that the response actually increases for the initial transducer failures. This is due to spikes that would have been masked in the undamaged case becoming discernible in the output when one or more spike encoders are firing at different frequencies (Fig. 4).

In contrast, resetting allows more than one transducer to fail before the compound spiking sensor fails for configurations of {6, 6}, {4, 4, 4}, and {3, 3, 3, 3} Specifically, 1, 2, and 3

transducers could fail, respectively, before the compound sensor's input-output transformation changed (Fig. 5). Note the configuration of {12}, with one spike encoder, exhibited changes in its input-output relationship with a single transducer failure.

Examining the configurations before and after the overall failure for the five random orders of transducer failure indicates that a compound sensor with resetting does not fail until each spike encoder has had its functioning number of transducers reduced. For example, one random order of transducer failures for a starting configuration of {4, 4, 4} yielded a configuration of {2, 4, 2} after four transducer failures, and this configuration exhibited the same input-output relationship as the undamaged one. It was not until the 5th transducer failure resulted in a configuration of {2, 3, 2} that the input-output transformation changed. In other words, when each spike encoder starts with the same number of transducers, as long as there is one spike encoder with an undamaged complement of transducers, the compound spiking sensor's input-output relationship remains unchanged.

3.2 Analyzing the Impact of Compound Sensor Configuration on Durability

Recall, in the case of enabled resetting, that simulations indicate that a compound spiking sensor fails after each spike encoder has had at least one associated transducer fail.

Therefore, in the case of a compound spiking sensor with N spike encoders, each of which receives input from M transducers: 1) a minimum of N transducers must fail before the compound sensor fails, and 2) a maximum of $M(N-1)$ transducers can fail before the compound sensor fails. This can be visualized as a fault tree for a compound sensor with N spike encoders each with M transducers (Fig. 6, Upper). If a single transducer is associated with each spike encoder, a simplified fault tree is obtained (Fig. 6, Lower).

Inspection therefore suggests that the more spike encoders the more durable the compound sensor, but the more transducers associated with each spike encoder the less durable the compound sensor. For example, if the probability of a transducer failing is 0.01, then the probability of failure for a compound spiking sensor with two spike encoders, each with two transducers, is given by Eqn. 3, where $P(x,y)$ denotes the probability of failure for transducer y of spike encoder x . This results in a 0.000396 probability of failure for the compound spiking sensor.

$$P(\text{compound fail}) = (P(1.1) + P(1.2) - P(1.1 \text{ and } 1.2)) * (P(2.1) + P(2.2) - P(2.1 \text{ and } 2.2)) \quad (3)$$

Alternatively, if one transducer is associated with each spike encoder, the overall probability of failure is 0.0001, by Eqn. 4.

$$P(\text{compound fail}) = P(1.1) * P(2.1) \quad (4)$$

In this case, doubling the number of transducers grouped to each spike encoder increased the overall probability of failure almost fourfold. Therefore, it is recommended a single transducer be linked to each spike encoder in practice. Note that when this is the case, the life of a compound sensor is the maximum life of the transducers comprising it. This result can inform the design of compound sensors, as demonstrated in the following use cases.

3.3 Use Case Simulation 1: Designing for a Target Lifetime

Consider a mars rover being designed using spike-based sensing that will have a mission of three years. A robotic arm for sample collection will be instrumented with a compound spiking sensor providing feedback on grip force. If the force transducers available have exponentially distributed lives with expectations of 2, 3, and 4 years, how many transducers of each type would be required for a compound spiking sensor to achieve a 3 year lifetime with 99% confidence?

Discrete event simulation reveals that for transducers with expected lives of 2, 3, and 4 years, 8, 11, and 19 transducer-encoder pairs, respectively, are required for the compound sensor to last the three year mission with a 0.99 percent certainty (Fig. 7).

3.4 Use Case Simulation 2: Scheduling Maintenance

Consider an upper limb neural prosthesis that provides tactile feedback using a compound spiking sensor on the thumb. Due to size constraints, only 4 force transducers can be used. If force transducer lives are exponentially distributed with an expected lifetime of 2 years, how often should maintenance be scheduled? Maintenance must be scheduled often enough that there is a low probability that artificial touch will fail at a critical time, such as while holding a child, but not so often as to be an inconvenience or unnecessary expense to the prosthetic user.

Discrete event simulation can illicit options for the prosthetic user to consider. For example, to have no unexpected failures between scheduled maintenance with probabilities of 0.99, 0.95, and 0.90, maintenance should be scheduled for every 9, 15, and 19 months, respectively (Fig 8).

4 Discussion

Inspired by the compound nature of the end organ of the SAI afferent, this work simulates compound spiking sensors as a more durable alternative to single spiking sensors. Overall, the results indicate that the resetting of adjacent spike encoders, upon the firing of a spike by any one, is an essential mechanism to maintain a stable overall response in the midst of transducer failure. In particular, when resetting between spike encoders is disabled, a single transducer failure changes the input-output transformation of the compound sensor, regardless of its number of spike encoders or transducers grouped to each. Alternatively, when resetting is enabled, more than one transducer can fail before the compound sensor fails. In terms of the configuration of a compound sensor influencing its durability, fault tree analysis revealed that the while the probability of a compound spiking sensor failing decreases with the number of spike encoders, it increases with the number of transducers grouped to each spike encoder. In practice therefore, to maximize overall durability, it is recommended that single transducers be linked to spike encoders and multiple spike encoders employ adjacent resetting.

Note that compound spiking sensors are distinct from using a population of single spiking sensors. While compound spiking sensors, as discussed here, provide a single force reading in terms of spike frequency, a population of single spiking sensors provides multiple

spatially distributed readings which require more extensive processing to interpret. Also, while populations of single spiking sensors could be arranged so to provide multiple readings at the same location, such populations are more likely to be leveraged to obtain spatial information on shape or texture, similar to populations of tactile afferents [13], [14].

This biomimetic work is inspired by the compound nature of the SAI end organ. Guclu speculated that SAI afferents innervate multiple Merkel cells so SAI afferents can continue responding to stimuli despite the loss of one or more of these biological [9]. While focused on artificial sensors, the work presented here suggests that a compound sensor such as the SAI end organ would gain the most durability from its multiple transducers if they were matched to spike encoders in a one-to-one relationship. However, recent work has demonstrated multiple Merkel cells grouped to spike encoders (heminodes) in the SAI end organ, and shown this grouping to be highly asymmetric [15]. Further simulations linked the specifics of an end organ's structure (grouping of Merkel cells to heminodes) to the sensitivity of the end organ's input-output transformation. In the case of artificial sensors explored here, it is possible to arbitrarily change the parameters of the transduction function to obtain the desired input-output relationship, regardless of how many transducers are grouped to a spike encoder. This may not be the case biologically, and there may be a trade-off where multiple Merkel cells increase sensitivity, but at the cost of reduced robustness.

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Fig. 1.

Diagram of Kim and Gerling's spiking sensor (A) where a force transducer embedded in artificial skin connected to an analog to digital converter drove a spike encoder running in software that was composed of a transduction function and leaky integrate and fire model. A comparable compound sensor is shown in (B), where N spike encoders receiving input from M transducers each. In the simulations run here, duplicates of the force readings from the hardware portion of (A) served as inputs to the software portion of (B). A/D represents the analog to digital converter.

Fig. 2.

Example indentations of a force transducer at two depths of ramp-and-hold indentation. In A, the force at the tip of the probe, in B, the force at the transducer embedded in the silicone elastomer, and in C, the spike times produced as the transducer's force is transformed by the spike encoder.

Fig. 3.

Percent undamaged response vs. number of transducer failures for 4 compound spiking sensor configurations when resetting between spike encoders is disabled. Results are averaged over 5 random orders of transducer failure. Note that the output changes with a single transducer failure regardless of configuration.

Fig. 4.

Example of how simultaneous spikes mask each other when resetting is disabled, underlying an increase in firing rate when transducers are damaged as the spike encoder with one fewer functioning transducer fires out of sync with the spike encoders with undamaged complements of transducers.

Fig. 5.

Percent undamaged response vs. number of transducer failures for 4 compound spiking sensor configurations. Results are averaged over 5 random orders of transducer failure. Note that 100% indicates no change in output while 0% indicates no output. Note that configurations of {12}, {6, 6}, {4, 4, 4} and {3, 3, 3, 3} do not have altered output until 1, 2, 3, and 4 transducers are damaged, respectively, and that this matches the associated number of spike encoders.

Fig. 6.

(Upper) Fault tree for compound spiking sensor with N spike encoders receiving input from M transducers each. (Lower) Fault tree for a compound sensor with N spike encoders receiving input from one transducer each.

Fig. 7.

Probability of a compound spiking sensor lasting through the three year mission as a function of the number of transducers (and therefore spike encoders) used. Results are shown for transducers with expected lives of 2, 3, and 4 years. The horizontal dashed line denotes a probability of 0.99.

Fig. 8.

Probability of the prosthetic's compound spiking sensor surviving the interval between scheduled maintenance as a function of months between maintenance. The horizontal dashed lines denote probabilities of 0.99, 0.95, and 0.90.

Table 1

Transduction parameters for each of four configurations of a compound spiking sensor.

Configuration	β (mA)	α (mA/N)	λ (mA·S/N)
{12}	2.72×10^{-8}	0.5167×10^{-7}	0.22583×10^{-4}
{6, 6}	2.72×10^{-8}	1.0333×10^{-7}	0.45167×10^{-4}
{4, 4, 4}	2.72×10^{-8}	1.5500×10^{-7}	0.67750×10^{-4}
{3, 3, 3, 3}	2.72×10^{-8}	2.0667×10^{-7}	0.90333×10^{-4}