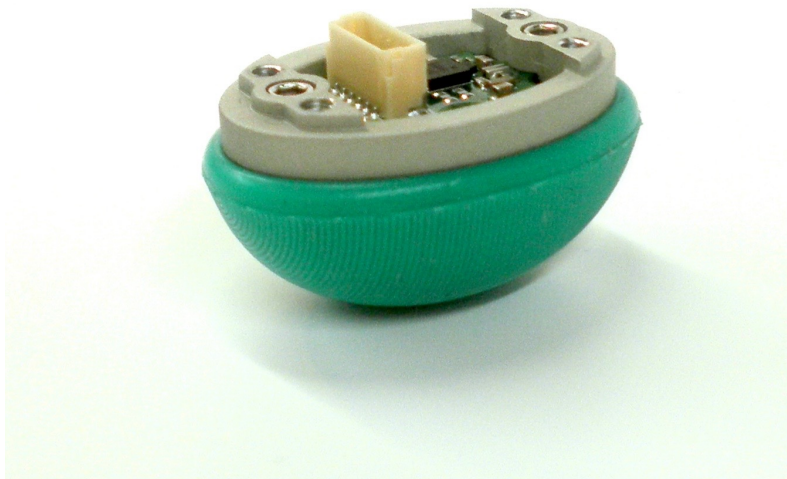


# syntouch<sup>®</sup> LLC



## BioTac<sup>®</sup> SP Product Manual

Updated: October 26, 2015, V2

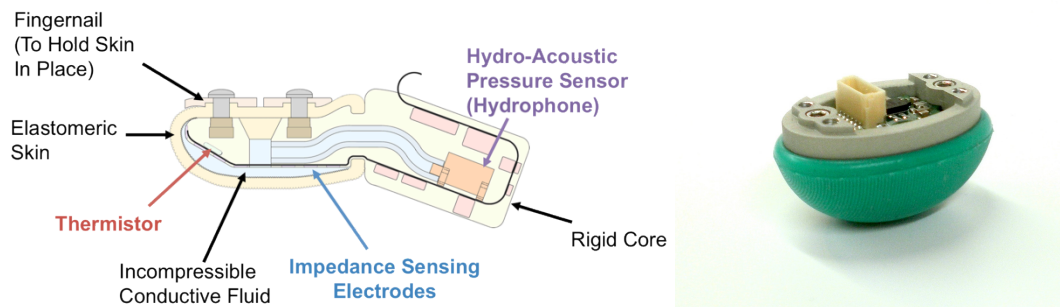
Authors: Blaine Matulevich, Jeremy Fishel, Gary Lin and Gerald Loeb

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# 1 Introduction to Technology

This manual describes the performance and function of SynTouch's BioTac® SP tactile sensor. The biomimetic design consists of a rigid core surrounded by an elastic skin filled with a liquid to give compliance similar to the human fingertip and the original BioTac design (Figure 1). The curved, deformable nature of both the BioTac SP and biological fingertips provides mechanical features that are desirable for the manipulation of objects. The skin of the BioTac SP possesses texture and tackiness similar to the properties of human skin.



**Figure 1 – Left: The Original BioTac Schematic, Right: BioTac SP Picture.**

The BioTac SP is the smallest tactile sensor capable of detecting the full range of cutaneous sensory information that human fingers can detect: forces, microvibrations, and temperature. Note that all of these sensory functions have been incorporated into the bone-like core of the device; there are no sensors in the skin itself. If the skin of the BioTac SP is damaged, SynTouch can replace it. The BioTac SP takes the functionality of the BioTac and incorporates it into a single phalanx design whereby the pressure sensor and electronics are inside the bone-like single-phalanx core.

The three sensory modalities of the BioTac SP are made possible by three separate sets of transducers:

- As forces are applied to the skin, the skin and fluid deform. Changes in impedance as the fluid deforms are detected by an array of electrodes on the surface of the BioTac SP core.
- As objects slide across the surface of the BioTac SP, they generate vibrations that are detected by a hydro-acoustic pressure transducer inside the core.
- As objects of different thermal conductivity come into contact with the core, the heat that flows from the BioTac SP into the object produces thermal gradients that are detected as a change in temperature of the thermistor in the BioTac SP.

Raw data collected from the BioTac SP include:

- Voltages on impedance sensing electrodes
- Absolute fluid pressure (DC Pressure)
- Dynamic fluid pressure = vibration (AC Pressure)
- Temperature (DC Temperature)
- Heat flow (AC Temperature)

Signal processing of these data enables the BioTac SP to do many things that humans can do by touch, such as:

- Determine point of contact
- Estimate tri-axial forces
- Estimate the radius of curvature of a contacted object
- Discriminate edges, corners, and flat surfaces
- Sense initial contact, with a remarkably high sensitivity
- Detect slip
- Discriminate objects based on their texture
- Discriminate object based on their compliance
- Discriminate objects based on their thermal properties

For tasks such as identifying objects or maintaining stable grasp, these sensory modalities tend to be synergistic. For example, information about texture and slip can be derived from vibrations of skin ridges sliding over a surface, but only if the forces on the skin are known and well-controlled. Similarly, information about the material composition of an object can be inferred from the rate of heat transfer from a heated finger to the object, but only if the location and force of contact are known and controlled.

## **2 Engineering Support**

SynTouch provides engineering support for troubleshooting and installation assistance with various platforms. Additional technical support can be purchased to aid with implementing new communication protocols, design and production of mechanical or electrical adapters, or generation of novel signal processing tools. Contact SynTouch at [support@syntouchllc.com](mailto:support@syntouchllc.com) for additional details.

### **3 Available Software**

SynTouch provides various software and programming libraries to help with the development of custom applications using the BioTac. These software are provided free of charge to all customers as a development tool. The latest versions of these software and their documentation are provided on our website at [www.syntouchllc.com](http://www.syntouchllc.com) under the products tab. SynTouch intends to update these software libraries to fully support the BioTac SP in the future.

Software provided by SynTouch includes various graphical user interfaces to visualize and record data (Windows) as well as software libraries for LabVIEW, and C-Libraries to support various hardware interfaces. As of the writing of this document, supported hardware includes the Cheetah SPI USB Host Adapter (LabVIEW: Windows, C-Libraries: Linux, Windows, OS X) and PEAK-System Technik's PCAN-PCI Card (C-Libraries: Real Time Linux). Software libraries for Willow Garage's Robotic Operating System (ROS) as well as other platforms and hardware are currently under development.

## 4 Care and Handling

Special care should be taken when using the BioTac SP to ensure its long life and stable performance.

- Skin Changes and Bracket Removal: Return the BioTac SP to SynTouch for skin changes or bracket removal.

---

➤ *The screws connecting the BioTac SP bracket to the sensor should NOT be removed by the customer. Doing so may cause BioTac fluid to leak into the core of the sensor, causing corrosion and potentially shorting electronics. Because of this the BioTac SP skin may NOT be changed by the customer.*

---

- Maximum Force: The BioTac SP is rated at forces up to 250N and should not be used in a robotic gripper using more force.
- Skin Leaks: Under normal usage the skin should not leak, if leaks are noticed disconnect the sensor, clean up any BioTac fluid and notify SynTouch. Do NOT attempt to run the sensor.
- Shock: The BioTac SP is not designed to be resistant to severe shock. Do not drop the BioTac SP on hard surfaces or swing a robotic hand with BioTac SPs installed into hard objects as fracture from this impact could occur.
- Storage: Store the BioTac SP in dry conditions and keep the electrical connectors coated with dielectric grease.

---

➤ *The BioTac SP is NOT water resistant and should not be rinsed in water.*

---

### 4.1 Skin Replacement and Fluid Filling Procedure

---

➤ *The BioTac SP skin may NOT be replaced or reinflated by the customer. If the skin becomes damaged, please contact SynTouch at [support@syntouchllc.com](mailto:support@syntouchllc.com). Skins may only be replaced or refilled by SynTouch. Attempting to remove the BioTac SP bracket, replace the skin, or refill the BioTac SP will void all warranties on the device and cause the sensor to fail.*

---

## 5 Sensor Electronics

The integrated electronics of the BioTac SP contains all sensory transducers, signal conditioning, and analog-to-digital conversion electronics to enable digital transmission of the sensor data (Figure 2).

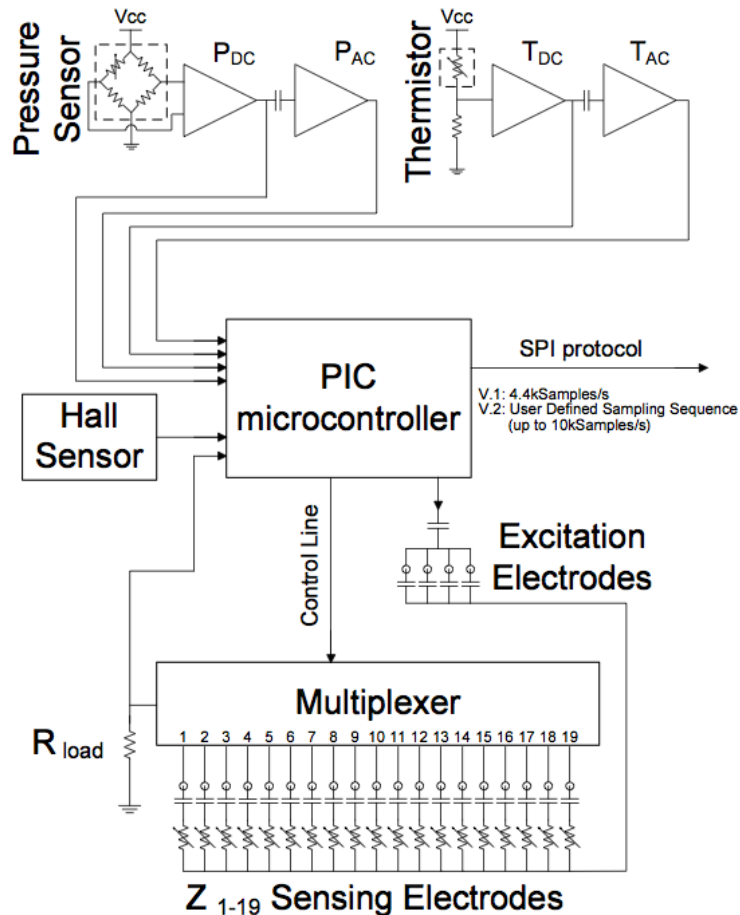


Figure 9 - Electrical schematic of the BioTac

### 5.1 Sensor Output

The BioTac SP contains three classes of sensors: impedance sensing electrodes, static and dynamic fluid pressure, and temperature and thermal flux. Details of the acquisition and summary of performance of the three main sensor types are provided below:



| Sensory Modality | Symbol   | Range       | Resolution | Frequency Response |
|------------------|----------|-------------|------------|--------------------|
| Impedance        | $E_n$    | 0 - 3.3V    | 3.2 mV     | 0 - 100 Hz         |
| Fluid Pressure   | $P_{DC}$ | 0 - 100 kPa | 36.5 Pa    | 0 - 1040 Hz        |
| Microvibration   | $P_{AC}$ | +/-0.76 kPa | 0.37 Pa    | 10 - 1040 Hz       |
| Temperature      | $T_{DC}$ | 0 - 75 C    | 0.1 C      | 0 - 22.6 Hz        |
| Thermal Flux     | $T_{AC}$ | 0 - 1 C/s   | 0.001 C/s  | 0.45 - 22.6 Hz     |

**Table 1 - BioTac Sensory Transducer Sampling Details**

- Impedance between each electrode and 4 common excitation electrodes is measured in a voltage divider with reference to a 10kΩ load resistor ( $R_{load}$ ). For each sampling, the electrode of interest is connected by the multiplexer and a short 3.3V pulse is sent from the excitation electrodes through the fluid to the sensing electrode. As the impedance over the sensing electrode increases, the measured voltage decreases. This voltage ( $V_n$ ) is digitized with 12-bit resolution ( $E_n$ : 0-4095). The exact impedance ( $Z_n$ ) can be determined from the voltage divider equation as:

$$impedance_n = \left( \frac{3.3V}{V_n} - 1 \right) 10 k\Omega = \left( \frac{4095 \text{ bits}}{E_n} - 1 \right) 10 k\Omega$$

- Fluid pressure is measured with a piezo-resistive pressure transducer with a range of 0-100kPa (15psi with reference to atmospheric pressure). The transducer output is biased in the positive direction to prevent negative saturation and amplified with a gain of 10 and a low-pass anti-aliasing filter at 1040Hz to produce the DC pressure signal ( $P_{DC}$ ). A second stage includes a band-pass filter of 10-1040Hz and an additional gain of 99.1 to produce the high-resolution AC pressure vibration signal ( $P_{AC}$ ). Both are sampled with 12-bit resolution for the range of 0-3.3V. Both AC and DC pressure can be estimated with the following equations (see Application Notes below):

$$fluid \ pressure = (P_{DC} - offset) 0.0365 \text{ kPa/bit}$$

$$dynamic \ pressure = (P_{AC} - offset) 0.37 \text{ Pa/bit}$$

- 
- **The pressure transducer used in the BioTac is not thermally compensated and can drift slightly in response to changes in temperature. Due to the fabrication of the BioTac, mechanical strains applied to the core are coupled to the pressure transducer and can cause small fluctuations in sensor output.**
-

- Temperature is measured with a thermistor voltage divider with reference to a 30kΩ resistor and a 10V supply. The resistance of the thermistor is given as:  $0.6444 \exp(4025^\circ\text{K}/T)$  in units of ohms. The absolute temperature ( $T_{DC}$ ) has a low-pass anti-aliasing filter at 22.6Hz and unity gain buffer. Dynamic temperature ( $T_{AC}$ ) is measured with a band-pass filter of 0.25-22.6Hz and an additional gain of 98. Both are sampled with 12-bit resolution for the range 0-3.3V. Both absolute temperature and dynamic temperature can be estimated with the following equations:

$$temperature = \frac{4025}{\ln\left(\frac{155183 - 46555 T_{DC}/4095bits}{T_{DC}/4095bits}\right)} ^\circ C - 273.15^\circ C$$

$$dynamic\ temperature = \frac{-41.07}{\ln\left(\frac{155183 - 46555 T_{AC}/4095bits}{T_{AC}/4095bits}\right)} ^\circ C$$

## 6 Sensor Performance Considerations

### 6.1 Maximum Loading and Saturation

The saturation force is the point at which the device output no longer varies with applied force. The saturation force for each electrode voltage is based on the skin properties, electrode configuration, fluid pressure and measurement circuitry. The saturation of the electrode impedance occurs above 250N, at which point the electrode voltage goes approximately to zero. Due to the non-linearity of the impedance circuit, higher-resolution is afforded at lower forces, while higher forces have a reduced resolution. The DC pressure also responds linearly to low forces before the skin comes into contact with the core; this measurement saturates at about 2N.

---

➤ *The maximum recommended force applied to the BioTac SP should not exceed 250N.*

---

This assumes a 250N force applied to the tip while loading against a relatively large flat surface. Lower forces with sharper objects will result in higher local pressures that could result in skin puncture and should also be avoided.

As a general rule of thumb, the BioTac SP has a similar resistance to damage as the human finger. Large forces, heavy impacts, and sharp objects that would cause harm to the biological finger may also damage the skin or core of the BioTac SP. Common sense should be used to avoid these situations.

### 6.2 Skin Wear Rate

The skin's wear rate will depend upon usage and environmental conditions. In an effort to retain human-like compliance for grip, the hardness of the elastomer skin was kept low and near human skin (Shore A 26). However other properties of the elastomer have been maximized (tensile strength, elongation % at break) to minimize wear. In most applications the skin and fingerprints should last for more than 100 hours of use. Care should be taken to avoid intentionally sliding the BioTac SP over abrasive materials that could increase the wear rate of the skin and fingerprints. Wearing of fingerprints has a substantial impact on the loss of sensitivity to texture-related vibrations.

---

➤ *If a BioTac SP skin needs replacement, do not try to replace the skin. Instead contact SynTouch to arrange for the skin to be replaced.*

---

### 6.3 Calibration and Converting to Engineering Units

Calibration is the method by which the sensor's electrical output is related to an engineering unit, such Newtons or Pascals. The BioTac SP is a highly non-linear device susceptible to drift (like the human fingertip) so it is generally not

recommended to be used in this fashion, although these equations are provided for convenience and to give a sense of magnitude. The recommended use of the sensor output is to use the raw data output for various signal-processing algorithms. If it is still desired to convert to engineering units, direct values can be obtained through the equations in the previous section or through other analytical or machine learning methods. Frequent calibration is recommended if this approach is used.

#### **6.4 Accounting for Signal Drift**

Similar to human fingertips, the BioTac SP is better at providing information about changes than absolute values. The recommended use of the sensor output, is to use the raw data for various signal-processing algorithms. Further, absolute signal levels will drift slightly with changes in temperature, inflation volumes, and skin wear. The BioTac SP's fluid blend has been optimized to reduce the effects of fluid diffusion through the skin that might affect impedance sensed by the electrodes. In developing algorithms utilizing BioTac SP data, we suggest that users incorporate a function to account for signal drift that will occur in their particular application and/or conditions of use. In general, these effects are not dramatic, but it is important that users are aware of the potential for these changes to occur. When the BioTac SP is not in contact with external objects, it is recommended the sensor be tared to account for any offset.

## 7 Electrical Connections

The BioTac SP comes in two different versions for electrical connections and can be reconfigured by SynTouch if needed.

### 7.1 Flexible Circuit Model

The following pinout is used in the BioTac SP Flexible Circuit Model:

| Pin number | Function | Description                |
|------------|----------|----------------------------|
| 1          | N.C.     | Not Used                   |
| 2          | SCLK     | SPI, clock                 |
| 3          | SS       | SPI, Chip select           |
| 4          | MOSI     | SPI, Master out slave in   |
| 5          | GND      | Power (input)              |
| 6          | MISO     | SPI, Master in slave out   |
| 7          | 3.3-5V   | Power (do not exceed 5.5V) |
| 8          | N.C.     | Not Used                   |

**Table 2 - BioTac Flex Circuit Pinout**

---

➤ *BioTac fluid is electrically conductive by design and can damage electrical components and corrode electrical leads. Care should be taken to ensure the BioTac fluid does not come into contact with electrical connections!!!*

---

#### 7.1.1 Flexible Circuit Model Power Requirements

For optimal sensitivity, the noise of these power supplies should be less than 20mV.

---

➤ *Do not supply the BioTac SP with greater than 5.5V of voltage. This can cause damage to the electrical components, which could make the BioTac unusable.*

---

## 7.2 6 Pin Connector Model

The 6 pin connector model of the BioTac SP is designed to use the same cabling and electronics as the original BioTac and can be connected to with a 6-pin connector to supply 5V power and SPI communication.

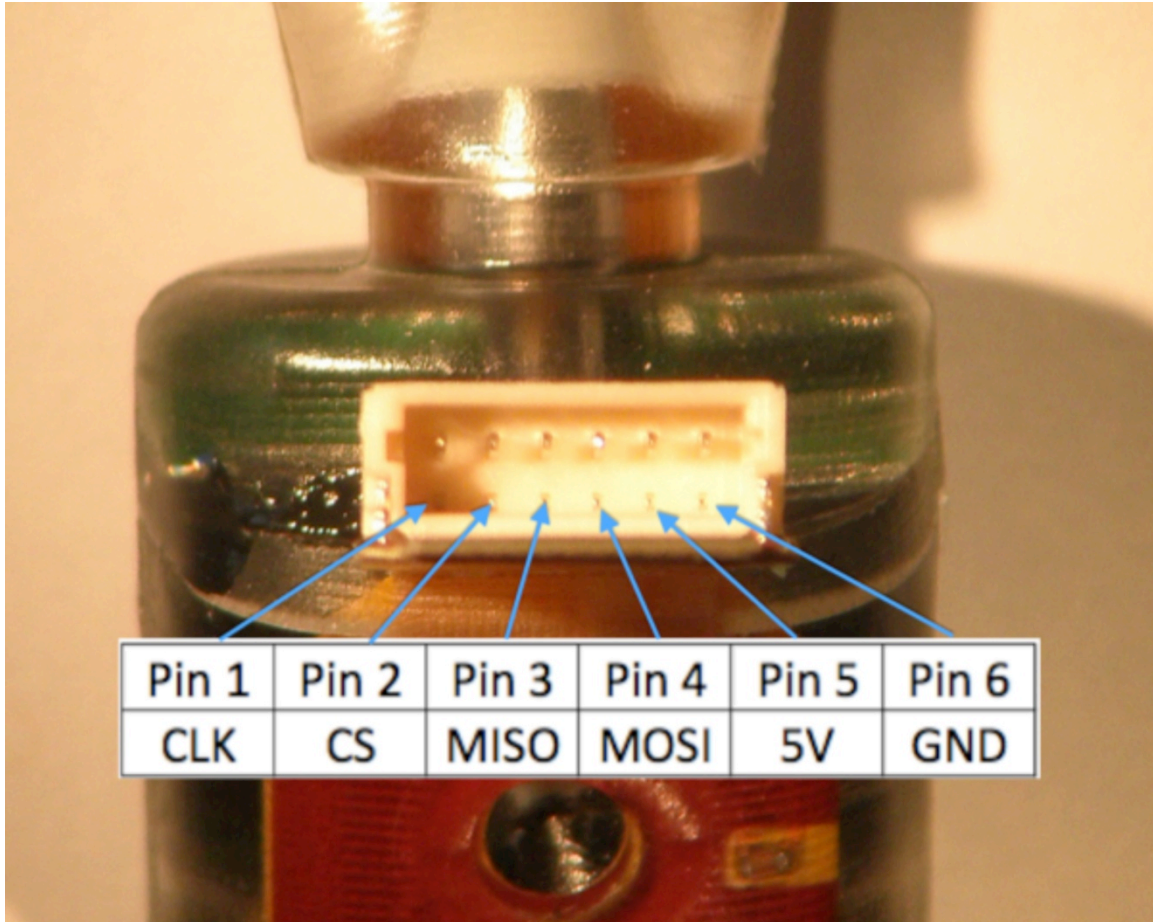


Figure 11 - BioTac 6-Pin Connections (Versions 2.4 and later)

- 
- *Do not supply the BioTac SP with greater than 5.5V of voltage. This can cause damage to the electrical components, which could make the BioTac unusable.*
- 

The 6-pin connector is designed to mate with the following connector:

|                          |                                                                                                             |
|--------------------------|-------------------------------------------------------------------------------------------------------------|
| Manufacturer             | JST Sales America Inc                                                                                       |
| Manufacturer Part Number | SHR-06V-S                                                                                                   |
| Digi-Key Part Number     | 455-1396-ND                                                                                                 |
| Datasheet                | <a href="http://www.jst-mfg.com/product/pdf/eng/eSR.pdf">http://www.jst-mfg.com/product/pdf/eng/eSR.pdf</a> |
| Family                   | Rectangular Connectors - Housings                                                                           |
| Connectors               | Interconnects                                                                                               |
| Series                   | SH                                                                                                          |
| Connector Type           | Receptacle                                                                                                  |
| Number of Positions      | 6                                                                                                           |
| Pitch                    | 0.039" (1.00mm)                                                                                             |
| Mounting Type            | Free Hanging (In-Line)                                                                                      |
| Termination              | Crimp                                                                                                       |

**Table 5 - 6-Pin Connector Information**

- 
- *BioTac fluid is electrically conductive by design and can damage electrical components and corrode electrical leads. Care should be taken to ensure the BioTac fluid does not come into contact with electrical connections!!!*
- 

#### **7.2.1 6-Pin Connector Power Requirements**

For optimal sensitivity, the noise of these power supplies should be less than 20mV.

- 
- *Do not supply the BioTac 5V power-supply with greater than 5.5V of voltage. This can cause damage to the electrical components, which could make the BioTac unusable.*
-

## 8 SPI Communication Protocol 2.3 and later

### 8.1 Overview

The BioTac SP uses identical communication protocol as the BioTac and NumaTac products.

During regular data acquisition the master sends a 2-byte request for a particular sensor channel measurement and then pauses the clock while each BioTac SP on the bus simultaneously acquires a 2-byte (12 bit) datum. The master then selects each BioTac SP in sequence and drives the SPI clock so that each slave transmits its datum to the master when its chip select is activated.

See Appendix A for SPI protocol V1.1 in which a single BioTac SP collects a preset sequence of data from its sensors for transmission as a buffer when queried by the host.

### 8.2 SPI Configuration

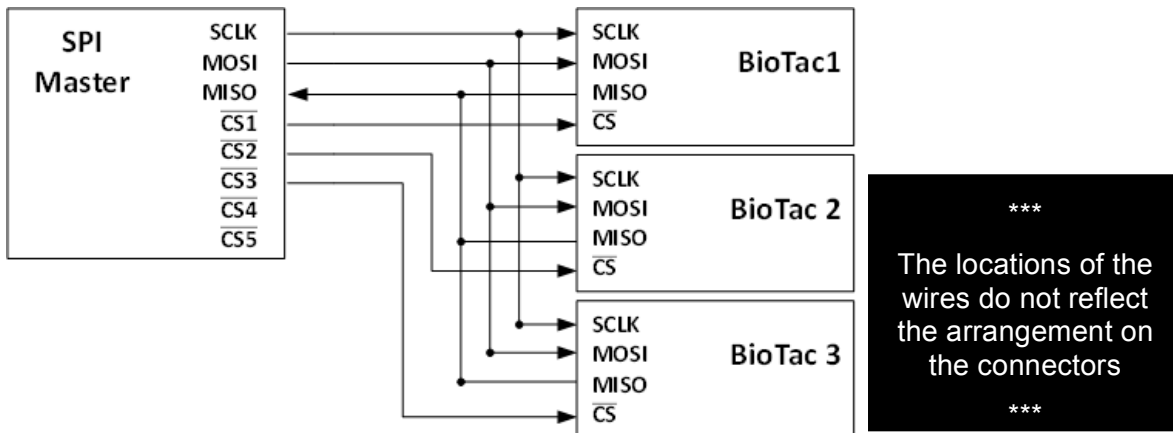


Figure 12 - SPI Connection Overview

#### SPI Communication Details

- Word Structure: 2-byte words (16 bits)
- Clock rate: 500kHz-10MHz
- Clock priority: idle low
- Clock phase: first edge
- MISO is changing at negative edge of SCLK; master should sample the signal from MISO line during positive edge and NOT sample the MISO line during negative edge of SCLK.



- BioTac SP samples MOSI line around positive edge; master should change the signal at negative edge and NOT change the signal at positive edge.

|               | MISO           | MOSI           |
|---------------|----------------|----------------|
| Signal update | -ve clock edge | -ve clock edge |
| Signal sample | +ve clock edge | +ve clock edge |

**Table 6 - Timing of SPI signal update and sample**

### **8.3 Command Types**

There are four types of basic commands between the host controller and individual BioTac SPs:

- Sampling command
- Resend command
- Parameter Set/Write command
- Parameter Read command

|           |    | First Byte |   |   |   |   |   |   |   | Second Byte |   |   |   |           |   |   |   |
|-----------|----|------------|---|---|---|---|---|---|---|-------------|---|---|---|-----------|---|---|---|
| bit#      |    | 7          | 6 | 5 | 4 | 3 | 2 | 1 | 0 | 7           | 6 | 5 | 4 | 3         | 2 | 1 | 0 |
| Sampling  | 0b | 1          | S | S | S | S | S | S | P | X           | X | X | X | X         | X | X | X |
| Resend    | 0b | 0          | 1 | 0 | 1 | 0 | 0 | 0 | 0 | X           | X | X | X | X         | X | X | X |
| Set/Write | 0b | 0          | 1 | 0 | 0 | 0 | 0 | 0 | 0 | N           | N | N | N | V         | V | V | P |
| Read      | 0b | 0          | 1 | 1 | 0 | 0 | 0 | 0 | 1 | N           | N | N | N | V         | V | V | P |
|           |    |            |   |   |   |   |   |   |   | Subset      |   |   |   | Variables |   |   |   |

**0b**: indicating the command is sent as binary code

**0/1** : command type

**SSSSSS**: sampling channels number (0~63)

**NNNN**: subset number (0~15)

**VVV**: variable number (0~7)

**P**: parity check (odd parity)

X: ignored

**Figure 13 – SPI Communication Protocol Command Types and Structure**

While SPI supports full duplex transmission, the current version of SPI protocol is designed to communicate in half duplex with two-byte commands being sent from the host and 2xn bytes of response from the BioTac SPs.

- 
- **While listening to the responses from the BioTac SP the host should write 0x0001 to the MOSI lines to avoid errors.**
- 

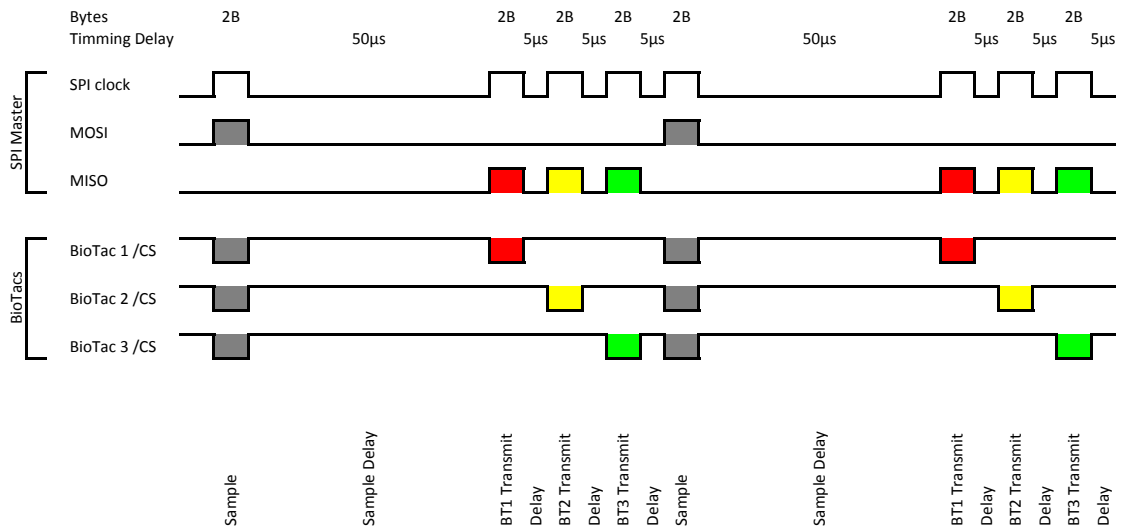
### 8.3.1 Sampling command

#### 8.3.1.1 Description

The sampling command is a 2-byte command from the host. Only the first byte is processed and the second byte is ignored. Upon receiving the 2-byte command from the host, all BioTac SPs with an active slave select during the command simultaneously and independently sample the requested channel specified by the 6-bit command SSSSSS (63 possible channels) and load the value into a 2-byte buffer.

➤ **NOTE: A minimum of 50µs delay is required between the sampling command and response from the BioTac SPs. During this time the CS lines should be disabled.**

After the minimum delay of 50µs individual BioTac SPs can be queried for this 2-byte buffer by enabling the CS and CLK line to each BioTac SP for two bytes. This buffer must be read before sending a new sampling request. A sample of the recommended communication structure is outlined below:



**Figure 14 - Recommended Sampling Sequence for 3 BioTac SPs**

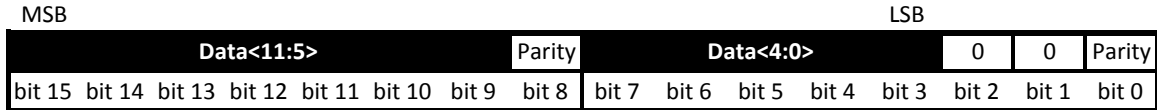
### 8.3.1.2 Detailed Sampling Commands

| Description                    | Index | 1 <sup>st</sup> Byte Command | Return (bytes) | Note                                          |
|--------------------------------|-------|------------------------------|----------------|-----------------------------------------------|
| Pac                            | 0     | 0b10000000                   | 2              |                                               |
| Pdc                            | 1     | 0b10000011                   | 2              |                                               |
| Tac                            | 2     | 0b10000101                   | 2              |                                               |
| Tdc                            | 3     | 0b10000110                   | 2              |                                               |
| Hall Sensor                    | 15    | 0b10011110                   | 2              | Only on specific models                       |
| Version 1.1 Streaming Protocol | 16    | 0b10100001                   | 92 x #Frames   | See Appendix for details of SPI V1.1 Protocol |
| Get Electrode #1 data          | 17    | 0b10100010                   | 2              |                                               |
| Get Electrode #2 data          | 18    | 0b10100100                   | 2              |                                               |
| Get Electrode #3 data          | 19    | 0b10100111                   | 2              |                                               |
| Get Electrode #4 data          | 20    | 0b10101000                   | 2              |                                               |
| Get Electrode #5 data          | 21    | 0b10101011                   | 2              |                                               |
| Get Electrode #6 data          | 22    | 0b10101101                   | 2              |                                               |
| Get Electrode #7 data          | 23    | 0b10101110                   | 2              |                                               |
| Get Electrode #8 data          | 24    | 0b10110000                   | 2              |                                               |
| Get Electrode #9 data          | 25    | 0b10110011                   | 2              |                                               |
| Get Electrode #10 data         | 26    | 0b10110101                   | 2              |                                               |
| Get Electrode #11 data         | 27    | 0b10110110                   | 2              |                                               |
| Get Electrode #12 data         | 28    | 0b10111001                   | 2              |                                               |
| Get Electrode #13 data         | 29    | 0b10111010                   | 2              |                                               |
| Get Electrode #14 data         | 30    | 0b10111100                   | 2              |                                               |
| Get Electrode #15 data         | 31    | 0b10111111                   | 2              |                                               |
| Get Electrode #16 data         | 32    | 0b11000001                   | 2              |                                               |
| Get Electrode #17 data         | 33    | 0b11000010                   | 2              |                                               |
| Get Electrode #18 data         | 34    | 0b11000100                   | 2              |                                               |
| Get Electrode #19 data         | 35    | 0b11000111                   | 2              |                                               |
| Get Electrode #20 data         | 36    | 0b11001000                   | 2              |                                               |
| Get Electrode #21 data         | 37    | 0b11001011                   | 2              |                                               |
| Get Electrode #22 data         | 38    | 0b11001101                   | 2              |                                               |
| Get Electrode #23 data         | 39    | 0b11001110                   | 2              |                                               |
| Get Electrode #24 data         | 40    | 0b11010000                   | 2              |                                               |

**Table 7 – Sampling Commands**

### 8.3.1.3 Response Format:

Signals from sensors are digitized as 12-14 bits of data; and split into two bytes (low byte and high byte) in the following format.



**Figure 15 - Sampling Command Response Format**

**8.3.1.4 SPI Version 1 Communication Note**

Sending a 0b10100001 command enters SPI Version 1.1 program loop, described in appendix A. To exit this loop, CLK must remain idle for 5 seconds.

**8.3.1.5 Error Handling**

| Sampling Errors                 | BioTac Response     | Description                                                                                              |
|---------------------------------|---------------------|----------------------------------------------------------------------------------------------------------|
| Insufficient Sampling Delay (-) | 0b10100101 00101101 | There has been insufficient delay between the sampling command and response time (minimum delay is 50µs) |
| Channel Not Recognized (X)      | 0b10100101 01011000 | The channel is not recognized by the BioTac firmware or unavailable                                      |

**Table 8 - Sampling Error Responses**

**8.3.2 Data Resend command**

The data resend command is a 2-byte command from the host. Only the first byte is processed and the second byte is ignored. Upon receipt of the data resend command, the BioTac SP responds with the previous 2 bytes of sampled data (this should be used in case of a parity error).

Chip select can be used to request a data resend from an individual BioTac SP. If the data resend command is sent before the BioTac SP has been sent a sampling command the BioTac SP will ignore the resend request.

**8.3.3 Set/Write and read command**

The set/write and read commands are a 2-byte commands from the host (with additional bytes in the case of set/write). Upon receiving the command the BioTac SP responds with 2x bytes.

| Group index | Subset name | Function                                               |
|-------------|-------------|--------------------------------------------------------|
| 1           | NNNN=0001   | Information<br>BioTac SP general parameters            |
| 6           | NNNN=0110   | CPU<br>BioTac SP CPU parameters                        |
| 7           | NNNN=0111   | Internal sampling<br>Internal sampling mode parameters |

**Table 9 - Read/Write Function Subset Groups**

| Description                          | 2nd byte Command | Return Bytes | rw | Details                                                                                         |
|--------------------------------------|------------------|--------------|----|-------------------------------------------------------------------------------------------------|
| NNNN = 0001                          |                  |              |    |                                                                                                 |
| General information subset           | 0b0001VVVP       |              |    |                                                                                                 |
| Flex version                         | 0b00010000       | 2            | r- | Format: M.N - ASCII (no parity)                                                                 |
| Software version                     | 0b00010011       | 4            | r- | Format MMNN - ASCII (no parity)                                                                 |
| Serial number                        | 0b00010101       | 16           | r- | Format ASCII (no parity)                                                                        |
| NNNN = 0110                          |                  |              |    |                                                                                                 |
| CPU information subset               | 0b0110VVVP       |              |    |                                                                                                 |
| CPU speed                            | 0b01100001       | 2            | r- | 0-65535 kHz (no parity)                                                                         |
| NNNN = 0111                          |                  |              |    |                                                                                                 |
| Internal sampling information subset | 0b0111VVVP       |              |    |                                                                                                 |
| Sampling frequency                   | 0b01110000       | 2            | r- | 0-65535 Hz (no parity)                                                                          |
| Sampling pattern                     | 0b01110011       | 2 x n        | r- | 2 byte channel array:<br>0b 1SSSSSP 00000001 x n<br>Last Sample Ends in:<br>0b 1SSSSSP 11111110 |

**Table 10 - Read/Write Function Details**

### 8.3.3.1 Error Handling

| Set/Write Errors           | BioTac Response     | Description                              |
|----------------------------|---------------------|------------------------------------------|
| Parameter is read-only (R) | 0b10100101 01010010 | Trying to write to a read-only parameter |

**Table 11 - Read/Write Error Codes**

## 9 Sampling sequences

While the sampling sequence is configurable and controllable by the host by sending various sequences of sampling commands the following sequences are recommended by SynTouch to optimize the available bandwidth of sensory modalities and reduce the communication bandwidth.

### 9.1 Default Sampling Sequence

Vibrations signals are measured ( $P_{AC}$ ) and interleaved with the electrode impedances (Electrodes #n) and other sensor signals ( $P_{DC}$ ,  $T_{AC}$ , and  $T_{DC}$ ). It is recommended that this sampling sequence is run at a minimum 4.4kHz to take advantage of the full bandwidth of  $P_{AC}$  and electrodes.

#### Sequence (54 Samples/frame):

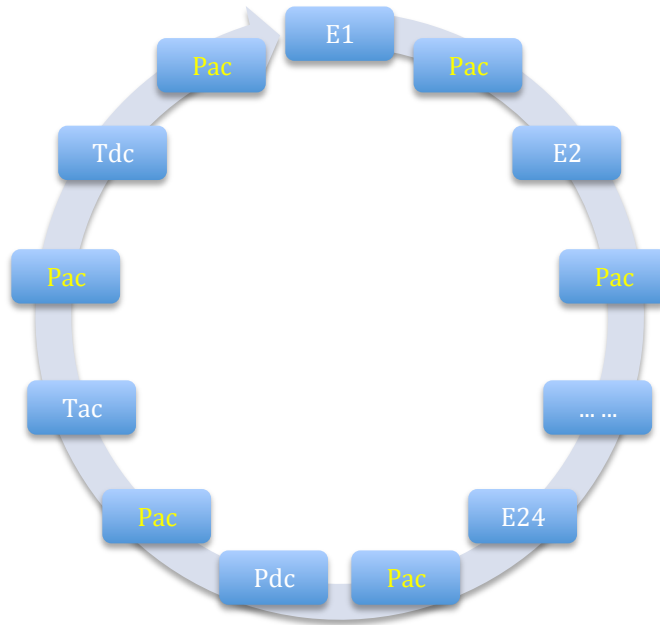
$P_{AC}$ ,  $E_1$ ,  $P_{AC}$ ,  $E_2$ ,  $P_{AC}$ ,  $E_3$ ,  $P_{AC}$ ,  $E_4$ ,  $P_{AC}$ ,  $E_5$ ,  $P_{AC}$ ,  $E_6$ ,  $P_{AC}$ ,  $E_7$ ,  $P_{AC}$ ,  $E_8$ ,  $P_{AC}$ ,  $E_9$ ,  $P_{AC}$ ,  $E_{10}$ ,  $P_{AC}$ ,  $E_{11}$ ,  $P_{AC}$ ,  $E_{12}$ ,  $P_{AC}$ ,  $E_{13}$ ,  $P_{AC}$ ,  $E_{14}$ ,  $P_{AC}$ ,  $E_{15}$ ,  $P_{AC}$ ,  $E_{16}$ ,  $P_{AC}$ ,  $E_{17}$ ,  $P_{AC}$ ,  $E_{18}$ ,  $P_{AC}$ ,  $E_{19}$ ,  $P_{AC}$ ,  $E_{20}$ ,  $P_{AC}$ ,  $E_{21}$ ,  $P_{AC}$ ,  $E_{22}$ ,  $P_{AC}$ ,  $E_{23}$ ,  $P_{AC}$ ,  $E_{24}$ ,  $P_{AC}$ ,  $P_{DC}$ ,  $P_{AC}$ ,  $T_{AC}$ ,  $P_{AC}$ ,  $T_{DC}$

#### Bandwidth:

Data: 16 bits/ch/BioTac SP, 864 bits/frame/BioTac SP

Communication Overhead: 864 bits/frame

3 BioTac SPs sampled at 4.4kHz: 281.6 kB/s



**Figure 16 - Recommended Default Sampling Sequence**

Using the recommended sampling rate of 4.4kHz, this permits for the following bandwidth:

| Sensor type                 | Numbers of sensor | Sampling rate      | Signal bandwidth |
|-----------------------------|-------------------|--------------------|------------------|
| Electrode                   | 24                | 73Hz per electrode | 36.5Hz           |
| AC Pressure ( $P_{AC}$ )    | 1                 | 2200Hz             | 1100Hz           |
| DC Pressure ( $P_{DC}$ )    | 1                 | 73Hz               | 36.5Hz           |
| AC Temperature ( $T_{AC}$ ) | 1                 | 73Hz               | 36.5Hz           |
| DC Temperature ( $T_{DC}$ ) | 1                 | 73Hz               | 36.5Hz           |

**Table 12 - Bandwidth and Sampling rate for Default Sampling Sequence at 4.4kHz**

## 9.2 Alternate Sampling Sequences

### 9.2.1 All Channels (28 Samples/frame):

This sampling sequence is advised when high bandwidth vibration is not necessary. It reduces the sampling rate of  $P_{AC}$  to conserve bandwidth. Recommended sampling rate is 3.1kHz, however lower sampling rates can be used if desired. This is a preferred sampling pattern for a low-bandwidth standby mode when not interacting with objects. *NOTE: when using this sampling sequence  $P_{AC}$  is subject to aliasing.*

**Sequence:**



$P_{AC}$ ,  $P_{DC}$ ,  $T_{AC}$ ,  $T_{DC}$ ,  $E_1$ ,  $E_2$ ,  $E_3$ ,  $E_4$ ,  $E_5$ ,  $E_6$ ,  $E_7$ ,  $E_8$ ,  $E_9$ ,  $E_{10}$ ,  $E_{11}$ ,  $E_{12}$ ,  $E_{13}$ ,  $E_{14}$ ,  $E_{15}$ ,  $E_{16}$ ,  $E_{17}$ ,  $E_{18}$ ,  $E_{19}$ ,  $E_{20}$ ,  $E_{21}$ ,  $E_{22}$ ,  $E_{23}$ ,  $E_{24}$

**Bandwidth:**

Data: 16 bits/ch/BioTac, 448 bits/frame/BioTac

Communication Overhead: 448 bits/frame

3 BioTacs sampled at 3.1kHz: 198.4 kB/s

3 BioTacs sampled at 310Hz: 19.8 kB/s

**9.2.2 Electrodes Only**

This sampling sequence is preferred for force extraction algorithms that make use of the BioTac electrodes, preferably for lighter forces. The recommended sampling rate is 1.9kHz.

**Sequence (24 Samples/frame):**

$E_1$ ,  $E_2$ ,  $E_3$ ,  $E_4$ ,  $E_5$ ,  $E_6$ ,  $E_7$ ,  $E_8$ ,  $E_9$ ,  $E_{10}$ ,  $E_{11}$ ,  $E_{12}$ ,  $E_{13}$ ,  $E_{14}$ ,  $E_{15}$ ,  $E_{16}$ ,  $E_{17}$ ,  $E_{18}$ ,  $E_{19}$ ,  $E_{20}$ ,  $E_{21}$ ,  $E_{22}$ ,  $E_{23}$ ,  $E_{24}$

**Bandwidth:**

Data: 16 bits/ch/BioTac, 384 bits/frame/BioTac

Communication Overhead: 384 bits/frame

3 BioTacs sampled at 2.4kHz: 153.6 kB/s

**Sequence:**

**9.2.3 AC/DC Pressure**

This sampling sequence is preferred for high-resolution sampling of vibration signals and alternates between the  $P_{AC}$  and  $P_{DC}$  channels. The recommended sampling rate is 4.4kHz.

**Sequence (2 Samples/frame):**

$P_{AC}$ ,  $P_{DC}$

**Bandwidth:**

Data: 16 bits/ch/BioTac, 32 bits/frame/BioTac

Communication Overhead: 32 bits/frame

3 BioTacs sampled at 4.4kHz: 281.6 kb/s

**9.2.4 Single Channel and Other Sampling Sequences**

The provided sampling sequences above are merely guidelines and users are able to customize their own sampling sequences or configure software to sample a single channel at any rate they prefer.

## Appendix A. Materials

| Part        | Material                                             | Weight      | Remarks              |
|-------------|------------------------------------------------------|-------------|----------------------|
| Core        | Vectra® Thermoplastic                                | 7 g         | Durable              |
| Skin        | Silicone Elastomer                                   | 2 g         | Good Wear Properties |
| Bracket     | Aluminum                                             | 0.5 g       | Anodized             |
| Electrodes  | Stainless Steel                                      | -           |                      |
| Screws      | Stainless Steel                                      | -           |                      |
| Cover Plate | Stainless Steel                                      | -           |                      |
| Fluid       | 1M Sodium Bromide dissolved in PEG-200/Water mixture | 0.3 - 0.5 g | Nontoxic             |

## **Appendix B. Legal**

### **BioTac® SP Warranty**

1. The customer should check goods immediately after receipt for possible problems. Defective, damaged, or missing goods (hereafter: Defective Goods) are to be reported to SynTouch in writing within 5 working days. If a customer elects to not notify SynTouch about Defective Goods, or if a customer uses Defective Goods they waive all rights under this warranty.
2. Repairs or replacements of Defective Goods occur at the discretion of SynTouch. Discretion is not waived under any circumstances, including prior attempts to repair or replace Defective Goods.
3. Upon SynTouch acknowledging notice from a customer about Defective Goods, SynTouch has 90 days in which they may elect to resolve the issue by either: A) repairing or replacing the Defective Goods, or B) crediting the customer for the value of the Defective Goods.
4. The customer must provide access by shipping Defective Goods and all documentation about them to SynTouch. SynTouch may elect to send a representative to the customer, in which case the customer must provide access by enabling the representative to perform testing, repairs and replacements to Defective Goods. If a customer refuses to provide access they waive all rights under this warranty.
5. After receiving an acknowledgement about Defective Goods from SynTouch, if 90 days elapse without resolution of the issue, a customer has the right to a credit for the Defective Goods. To receive their credit a customer must return the Defective Goods along with a written description of the issues encountered, and a written description of efforts to resolve the issue.
6. No warranty claims will be accepted if it is determined that the cause was due to normal wear and tear, or damage caused by faulty or negligent maintenance, shipping with packaging other than the original packaging, modification, or use outside the specifications listed. Nor will warranty claims be accepted if it is determined that Damaged Goods have insignificantly reduced value or utility.
7. No warranty claims will be accepted if the customer removes the screws holding the skin in place.
8. SynTouch is not liable for consequential or incidental damages during customer attempted repairs or any cost or expense of providing substitute equipment during periods of malfunction or pending repairs.
9. If any part of this warranty is deemed unenforceable, all remaining parts remain in full effect.

## **Customer Service and Health and Safety Acknowledgements**

### **9.2.5 PURPOSE**

This document is intended as a written confirmation of the terms and conditions under which SynTouch LLC will provide Customer Service for our products to our customers. This agreement defines the services SynTouch LLC will provide to customer in conjunction with license of or purchase of SynTouch LLC products as well as Customer's notice and acknowledgement of any potential hazards, restrictions or limitations with regards to SynTouch LLC's products.

### **9.2.6 CUSTOMER SUPPORT AND SERVICE**

Under this agreement, Customer seeks to receive, and SynTouch LLC agrees to provide customer service, in some cases for a fee, for Customer's purchased SynTouch LLC products.

Customer agrees and understands that some service options may be limited to normal business hours and days of the week. Customer agrees and understands that this agreement only covers their SynTouch LLC products and not any third-party product or modification. Customer understands that if it is determined that support and service are being used to support a third-party product or any modification or alteration to a SynTouch LLC product not authorized or approved in SynTouch LLC documentation, Customer may be charged and Customer agrees to pay for such service, at SynTouch LLC's sole discretion .

### **9.2.7 CUSTOMER FEEDBACK**

Under this agreement, SynTouch LLC seeks to receive, and Customer agrees to provide, certain levels of customer feedback regarding Customer's purchased SynTouch LLC products.

### **9.2.8 TAXES AND TARIFFS**

Customer shall be responsible for payment and satisfaction of all taxes applicable and/or tariffs, costs of import or costs of export related to purchasing, shipping or transporting materials for providing services under this agreement.

### **9.2.9 SAFETY AND HEALTH ACKNOWLEDGEMENTS**

SynTouch LLC is concerned for your safety has communicated to Customer, and Customer understands, the following potential safety and health issues associated with SynTouch LLC Products:

1. **SHARPS WARNING** Many SynTouch LLC products use a standard insulin syringe with a 25 gauge needle in the operation of said products. Customer acknowledges

- a. that he or she has consulted with a SynTouch sales, marketing or development professional regarding whether his or her purchase uses such needles and therefore whether proper operation of that product involves a sharps hazard;
  - b. that Customer is wholly responsible for communicating such a hazard to any parties using his or her SynTouch LLC product, whether or not such use is under his or her supervision; and
  - c. that Customer is wholly responsible for proper storage and disposal of sharps and biomedical waste in conjunction with operation of his or her SynTouch LLC product and in compliance with applicable law.
2. **CHEMICAL WARNING** Many SynTouch LLC products use certain chemicals in their operations. Customer acknowledges:
- a. that Customer has been provided with the Material Safety Data Sheets (MSDS) for all SynTouch LLC products he or she has purchased, either with said purchase or through a request to a SynTouch LLC sales, marketing or development professional;
  - b. that Customer has read all MSDS for chemicals used in the appropriate SynTouch LLC products and understands the potential safety and health risks associated with such chemicals;
  - c. that Customer is wholly responsible for communicating such a safety and health risks to any parties using his or her SynTouch LLC product, whether or not such use is under his or her supervision;
  - d. that Customer will provide copies of the MSDS for chemicals used in the appropriate SynTouch LLC products to any parties who request them in conjunction with the Customer's SynTouch LLC products; and
  - e. that Customer is wholly responsible for proper storage and disposal of chemicals in conjunction with operation of his or her SynTouch LLC product and in compliance with applicable law.

## **Indemnification**

Customer shall indemnify and hold harmless SynTouch LLC for all legal claims resulting from Customer's failure to reasonably communicate information in this agreement to parties using Customer's SynTouch LLC products, reasonably communicate information listed under above section Health & Safety Acknowledgements to parties using Customer's SynTouch LLC products or failure to take steps to account for responsibilities listed under above section Health & Safety Acknowledgements. SynTouch LLC shall indemnify and hold harmless Customer for all legal claims resulting from failure to respond in a reasonable time to requests made by Customer under above section Health & Safety Acknowledgements or for failure to provide full information requested in response to requests made by Customer under above section Health & Safety Acknowledgements. Procedure. In case any Claim is at any time brought against Syntouch LLC or Customer, the party obligated to provide such indemnification (the "*Indemnifying Party*") will defend such Claim, at the sole expense of the Indemnifying Party, using counsel selected by the Indemnifying Party but subject to the Indemnified Party's reasonable approval. If the Indemnifying Party fails to take timely action to defend such a Claim after having received written notice from the Indemnified Party of such failure, the Indemnified Party may defend such a Claim at the Indemnifying Party's expense. The Indemnifying Party will keep the Indemnified Party fully advised with respect to such Claims and the progress of any suits, and the Indemnified Party shall have the right to participate, at the Indemnified Party's expense, in any suit instituted against it and to select attorneys to defend it, which attorneys will be independent of any attorneys chosen by the Indemnifying Party relating to such Claim or related claim. The Indemnifying Party will not settle, compromise or otherwise enter into any agreement regarding the disposition of any Claim against the Indemnified Party without the prior written consent and approval of the Indemnified Party which shall not be unreasonable withheld.

## **GOVERNING LAW**

This Agreement and the performance hereunder shall be governed by the laws of the State of California without regard to conflicts of law rules. The Parties agree on behalf of themselves and any person claiming by or through them that the sole and exclusive jurisdiction and venue for any litigation which may arise hereunder shall be an appropriate federal or state court located in the County of Los Angeles and the Parties hereby consent to the personal jurisdiction of such courts.

## **DISCLAIMERS AND LIMITATIONS**

DISCLAIMER OF WARRANTIES. EXCEPT AS OTHERWISE PROVIDED IN THIS AGREEMENT, NEITHER PARTY MAKES, AND EACH PARTY HEREBY WAIVES AND DISCLAIMS, ANY REPRESENTATIONS OR WARRANTIES

REGARDING THIS AGREEMENT OR THE TRANSACTIONS CONTEMPLATED HEREBY, INCLUDING ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE OR NON-INFRINGEMENT OR IMPLIED WARRANTIES ARISING OUT OF COURSE OF DEALING, COURSE OF PERFORMANCE OR USAGE OF TRADE.

LIMITATION OF DAMAGES. NEITHER PARTY SHALL HAVE ANY LIABILITY TO THE OTHER PARTY FOR ANY LOST PROFITS OR SPECIAL, INCIDENTAL, PUNITIVE, EXEMPLARY, INDIRECT OR CONSEQUENTIAL DAMAGES, EVEN IF SUCH PARTY HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES, NOR SHALL ANY OF THE TERMS OF THIS AGREEMENT BENEFIT OR CREATE ANY RIGHT OR CAUSE OF ACTION IN OR ON BEHALF OF ANY PERSON OR ENTITY OTHER THAN THE PARTIES HERETO REGARDLESS OF THE FORM OF THE ACTION, DAMAGE, CLAIM, LIABILITY, COST, EXPENSE, OR LOSS, WHETHER IN CONTRACT, STATUTE, TORT (INCLUDING WITHOUT LIMITATION, NEGLIGENCE), OR OTHERWISE, PROVIDED THAT THIS LIMITATION SHALL NOT APPLY TO ANY AMOUNTS PAYABLE TO THIRD PARTIES UNDER THE INDEMNIFICATION PROVISIONS OF THIS AGREEMENT OR TO BREACH BY A PARTY OF THE CONFIDENTIALITY OBLIGATIONS APPLICABLE HEREUNDER.

**Severability and Conflict of Prevailing Law:** The provisions of this Agreement are severable and if any provision shall be rendered invalid, void or otherwise unenforceable by statute, court order or any other legal action, it shall not affect the validity or enforceability of any other provision and all remaining provisions shall remain in full force and effect. Should any applicable federal law of the United States or applicable international treaty of which the United States is a signatory conflict with any part of this agreement, that part of the agreement shall be read and construed as broadly as possible within the limits of that law or treaty, and all other provisions of this agreement shall be unchanged and retain full force and meaning.

## **CONTACT**

SynTouch LLC  
2222 S.Figueroa St, PH2  
Los Angeles, CA 90007

213.493.4400  
info@syntouchllc.com

[www.syntouchllc.com](http://www.syntouchllc.com)