This document is a supplement to the paper describing the smart skeleton project. Please see https://doi.org/10.1152/advan.00145.2019 to learn more about the smart skeleton.

Supplementary Data S1: Assembly of the Smart Skeleton

Preface

All supplementary tables and figures referenced below are appended to the end of this document. Item numbers refer to Supplementary Table S1.

Assembly of the main module

To begin assembly of the main module, a number of components are first added to the main board PCB. The power switch integrated circuit should first be soldered to its surface-mount pads (item 8; IC1 in Supplementary Fig. S1A). Surface-mount soldering is generally more difficult than through-hole soldering, but the power switch IC is a large component that is easily soldered. The power switch IC allows the sensor modules to be reset via software without disrupting the WiFi network. If this function is not desired, then the IC can be omitted and bypassed by soldering a short length of 26-gauge (or larger) wire between the points indicated by asterisks in Supplementary Fig. S1A. Four USB mini-B jacks (item 7) are then added to the top side of the main board PCB (dotted outlines in Supplementary Fig. S1A). USB jacks and cables are used in this project because they are reliable and readily available. However, the USB communication protocol is not used, and the assembled modules should not be connected to a USB network. A diode is then be added to protect the modules from reversed polarity if the power supply were ever to be plugged-in incorrectly (item 9; D1in Supplementary Fig, S1A). Finally, power filtering capacitors are added to reduce any voltage ripple produced by the power supply (items 10-11; C1, C2 in Supplementary Fig. S1A). The capacitors should first have their leads bent to 90 degrees so that they will lay flat against the PCB when soldered in place.

Once the main board PCB has been assembled, the microcontroller board (item 3) and one of the serial switch boards (item 2) can be added. These boards are provided with 2.54 mm (0.1”) snap-off headers that will be used to attach them to the main board PCB. The short ends of the headers should be soldered to the microcontroller board and serial switch board in the positions shown (Supplementary Fig. S1A, B). Once the header pins have been installed, the serial switch board assembly can be fully inserted into the bottom of the main board PCB in the positions shown (Supplementary Fig. S1B). The plastic bodies of the header pins should rest flush to the bottom of the main board PCB (Supplementary Fig. S1C). The serial switch board can then be soldered in place, and excess header pins trimmed. It is important to attach the serial switch board first, since the holes for soldering it will not be accessible once the microcontroller board is in place. Finally, microcontroller board can be attached. This board is inserted into the top of the main board PCB and soldered so that there is consistent 5.5 mm spacing between the microcontroller board and the main board PCB (Supplementary Fig. S1C). This spacing allows clearance for the small components, and also allows the assembled module to slide into its 3D-printed case. Precise spacing can be easily achieved by clipping the main board and microcontroller board into 3D-printed spacers before soldering. Files for printed the spacers are located in the project Github repository.

A power cable will be needed to connect the main module to a rechargeable USB power bank. A cable can be constructed by cutting soldering a 2-conductor JST cable (item 4) to the power conductors (red positive and black negative) of a cut USB type A cable. The soldered joints should then be reinforced with heat shrink tubing (item 6). The resulting cable should have a 2-pin JST plug on one end, and a USB type A plug on the other.

For the companion application to communicate with the microcontroller in the main module, it is necessary to install controller software on microcontroller using the Arduino integrated development environment (Arduino IDE, 4). Before this can be done, the Arduino IDE must first be configured to communicate with ESP8266 microcontroller board. Complete instructions for configuring the IDE are available online (1). In the process of configuring the IDE to communicate with the microcontroller, a number of code libraries will be installed, and these will be necessary for the skeleton controller software to compile properly. An additional set of libraries must be installed to support the orientation sensor (BNO055). Instructions for doing this are also found online (2, 5). Before compiling the skeleton controller software, one of the BNO055 library files must be slight modified to prevent a malfunction. The file “Adafruit_BNO055.cpp” should be edited to comment out or remove the line "Wire.begin();". Alternatively, the installed Adafruit_BNO55 library can simply be replaced with the already altered library found on the Github repository. The skeleton controller software (found in the Github repository) can then complied using the Arduino IDE and uploaded onto the microcontroller by connecting the host computer to the USB micro-B connector on the microcontroller board. It is also important to note that the 5V power supply should be disconnected from the main module while the driver software is uploaded.

Assembly of sensor modules

Assembly of the sensor modules follows the same basic procedure as the main module. USB jacks are needed on the arm, forearm, femur, and leg modules, and these should first be soldered to the sensor module custom PCBs (Supplementary Fig. S2A, S3A). A number of resistors of specific values are then added to each sensor module PCB. These "pull-up" resistors are needed for the serial bus to run stably at high speeds. The values of these resistors are based on the total length of the various segments of the serial bus network. For the arm and femur modules, R1 and R2 are 2.7 KΩ (item 12), while R3 and R4 are 6.8 KΩ (item 14). The pull-resistors for the torso, forearm, leg, hand, and foot modules differ based on the individual sensors (R1, R2 in Supplementary Fig. S3A). The resistors on the torso, forearm and leg boards are 2.7KΩ (item 12), while those on the hand and foot boards are 4.7KΩ (item 13).

The next step is to attach a strip of four right-angle headers to the edge of each sensor module PCB (item 26; Fig. S4B). As described below, optional LED feedback modules can be added by soldering them to the right-angle headers. Even if the LED modules are not added right away, it will be easier to attach them in the future if the right-angle headers are added at this point. The straight sides of the right-angle headers should first be trimmed so that they do not pass completely through the PCB. This is easily accomplished by first passing the pins through the appropriate holes in the PCB and then cutting them with flush-cutting snips. Once the pins have been trimmed, the right-angle headers are soldered to the sensor module PCBs so that only small smooth domes of solder are visible from the bottom side of the PCB (Supplementary Fig. S4D). Attaching the headers in this way will make sure that no sharp surfaces will be near the wires from the USB cables.

Once the right-angle headers are in place, USB cables (item 19) can be attached to the sensor modules. The USB cables should be cut so that the length between the cut ends and the USB mini-B plugs are approximately the following dimensions: torso module, 67cm; hand and foot module, 25cm; forearm and leg modules, 42cm; arm module, 85cm; femur module, 100cm. The cut ends of the cables should then be stripped of a short length (approximately 20 mm) of their outer sheaths, and the shielding should be cut away (Supplementary Fig. S4C, D). The shielding braid includes a bare, stranded copper wire, and this must be carefully separated before the shielding is trimmed. The bare copper wire is soldered to a short length of insulated wire, which can in turn be soldered to the shield terminal on the sensor module PCBs (Supplementary Fig. S4D). Once the Smart Skeleton is fully assembled, all the shielding conductors will be connected to a common point on the main module PCB. Therefore, it is important that the shielding foil and braid be pared back so that no bare shield conductors will cause a short circuit. Once the shielding has been pared back, approximately three millimeters of insulation is stripped from the end of each of the insulated conductors in the USB cable. These are then be inserted into the appropriate terminal holes on the bottoms of the sensor module PCBs (Supplementary Fig. S4B, D). The black wire should be soldered to the "GND" terminal, and the red wire to the "Vin" terminal. The green wire is soldered to the "SDA" terminal, and the white wire to the "SCL" terminal. For the remainder of the assembly process, care should be taken to avoid straining the soldered wires until the completed sensor modules are enclosed in their cases.

To complete the assembly of the sensor modules, the serial switch boards and orientation sensor boards are first prepared by soldering the short ends of 2.54 mm header pins to the positions shown (Supplementary Fig. S2A, S2B, S3A). Before they are added to the arm and femur modules, labeled jumpers on the underside of the serial switch board must be cut in order to disable their built-in pull-up resistors (3). Once this modification has been made, the serial switch boards can be inserted and soldered flush to the bottom of the arm and femur PCBs (Supplementary Fig. S2C), and excess header pin length trimmed away. Finally, the orientation sensor boards can be mounted to the top side of the sensor module PCBs. As with the main module, these must be mounted so that there is a consistent 5.5 mm clearance between the orientation sensor board and the PCB (Supplementary S3C). Again, the correct spacing can be achieved using 3D-printed spacers. Before mounting the sensor boards in the hand and foot modules the i2c address of the orientations sensors in these two modules must be changed from 0x28 to 0x29. This is accomplished by using a small blob of solder to bridge a labeled jumper on the underside of the sensor boards (Supplementary Fig. S3B).

If LED feedback is desired, the LED modules can be assembled by soldering surface-mount components to each of seven LED module PCBs. For ease of assembly, it is useful to solder the LED driver chip first (item 22; IC 1 in Supplementary Fig. S4A, B), followed by the Red-Green-Blue LED (item 23; LED in Supplementary Fig. S4A, B), and the resistors. Position R1 is populated with a 130Ω resistor (item 25; Supplementary Fig. S4A, B), while positions R2 and R3 are populated with 82Ω resistors (item 24; Supplementary Fig. S4A, B). To set the i2c address of each LED board, the "a1" and "a0" solder jumpers on the reverse side of the boards must be closed by connecting the center pad to either the "1" or the "0" pad with a blob of solder (Supplementary Fig. S4A). For the arm and femur modules, "a1" is connected to "1" and "a0" is connected to "0." For the torso, leg, and forearm modules both "a1" and "a0" are connected to

"1". For the hand and foot modules, "a1" is connected to "0", and "a0" is connected to "1". Once the serial addresses have been set, the individual LED boards are soldered to the appropriate sensor modules using the right-angle headers (Supplementary Fig. S4C).

Final assembly and attachment to a laboratory skeleton

All modules are enclosed in individually labeled, 3D-printed cases. The cases for the limbs and the torso modules each consist of two halves. The bottom half includes grooves into which the assembled module can slide (Supplementary Fig. S5A). The top half includes two shallow holes into which two M2x0.4 brass threaded inserts are fixed (item 20). The threaded inserts can be placed by first threading them a short way onto a M2x0.4 screw (item 21). The insert can then be heated with a soldering iron or small torch while the screw is held with a pair of forceps. The hot inserts will then easily melt into the shallow holes in the top halves of the cases (Supplementary Fig. S5A, C). The screw should be kept perpendicular to the case while the brass insert is cooling (Supplementary Fig. S5C). Once the inserts have cooled, the sensor modules can slide into the bottom half, and the cases can be closed with two M2x0.4 screws. Notches designed into the top halves of the cases trap the cut ends of the USB cables to prevent strain on the wires soldered to the PCBs, and to prevent any shielding conductors from causing a short circuit (Supplementary Fig. S5A). Similarly, two threaded inserts are added to each of end of the main module case, and the main module is enclosed with two labeled, 3D-printed case ends (Supplementary Fig. S5B).

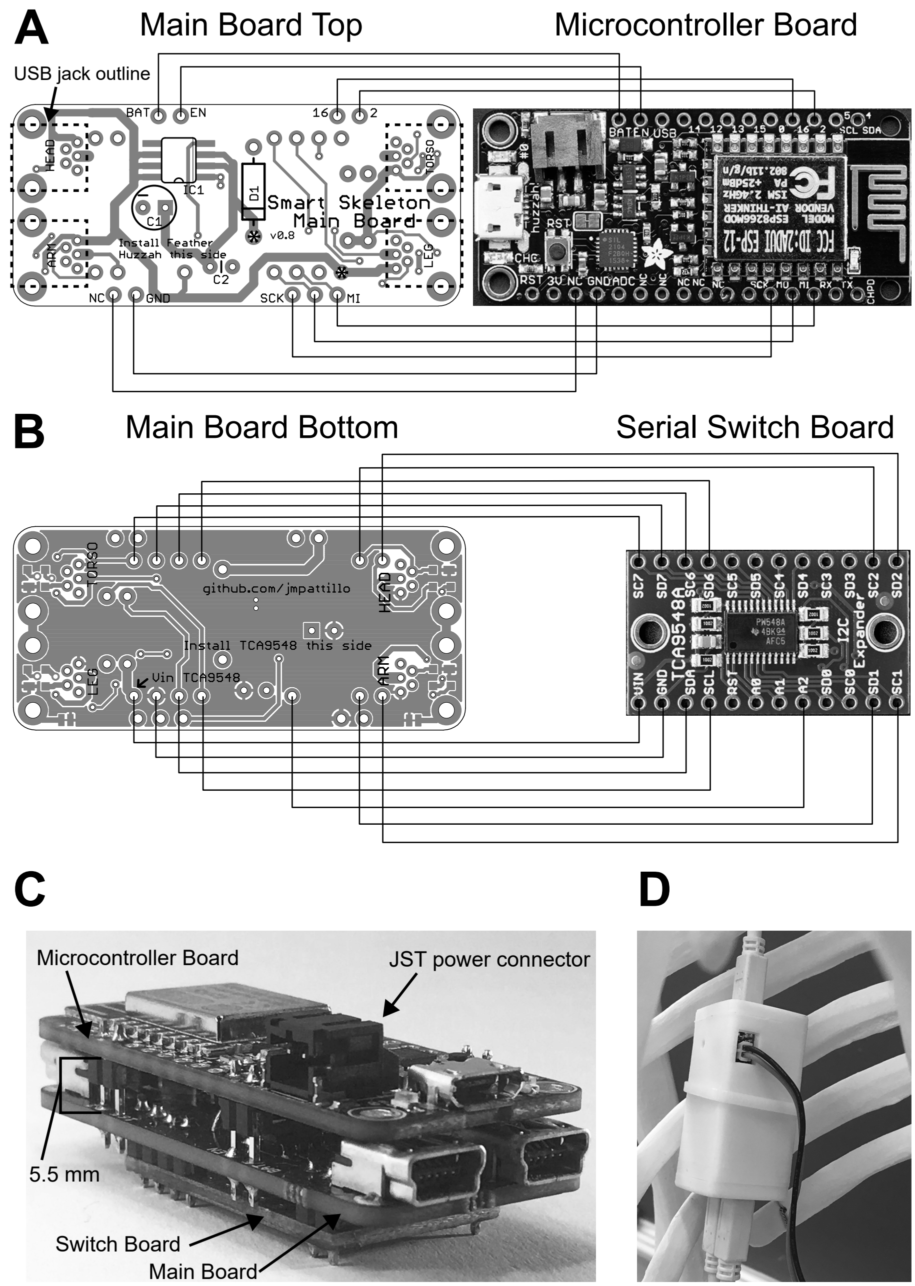
Completed sensors modules should be attached to the limbs with their USB cables pointed up. Grooves have been included in the 3D-printed cases so that it is easy to affix the modules using zip ties or similar fasteners (Supplementary Fig. S2D, S3E). It is important that the cases be mounted with grooved sides in the anterior direction, and that they are all roughly vertical when the skeleton is in anatomical position. The main module can be mounted inside the rib cage (Supplementary Fig. S3D). A wooden block can be attached to the lumbar vertebra with zip ties. The torso sensor module is then mounted to this block with Velcro (Supplementary Fig. S3D). A curve or notch should be cut into the back of the wooden block so that it rests firmly on two points along the anterior side of the lumbar curve. This allows the anterior face of the block to be vertical for mounting of the torso sensor module. Note that the case for the leg module includes a deep groove to help the module rest firmly over the anterior tibial crest. Mounting of the foot module in a vertical position is assisted by first mounting the module to an angled bracket, and then mounting the bracket to the metatarsals (Supplementary Fig. S6D). A file for printing the bracket is included in the Github repository.

Modifying a skeleton to enhance motion

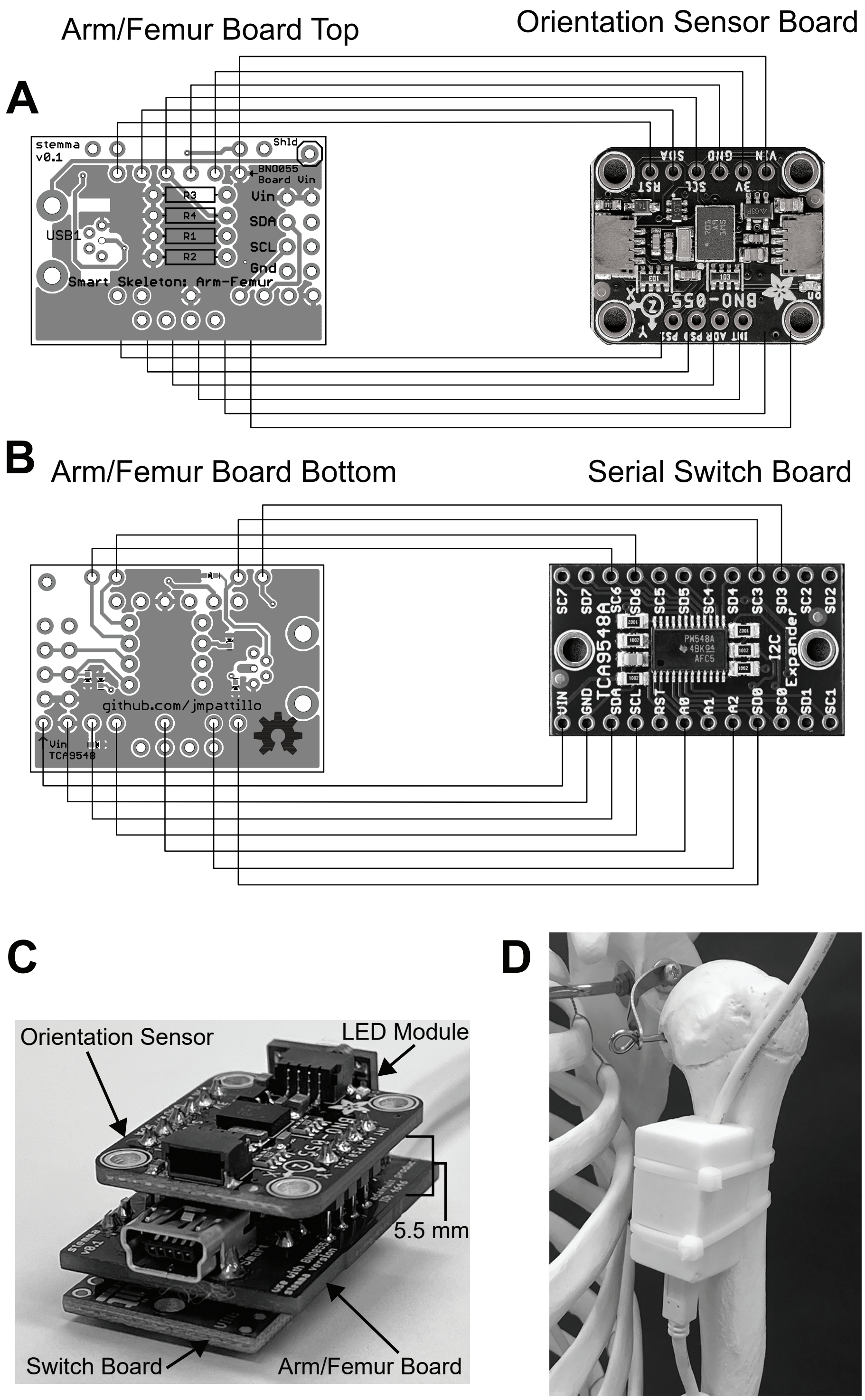
As described in the main text, some teaching skeletons lack the ability to rotate the shoulder or hip joints when in anatomical position. To solve this problem, the existing mounting hardware can be removed from these joints so that they can be mounted with a 3/16" (or similar) elastic cord. The cord can be passed through holes drilled in the head of the humerus and scapula and then tensioned with a spring-loaded cord lock (Supplementary Fig. S6A, B). Similarly, an elastic cord can be passed through the head of the femur and acetabulum to modify the hip for ease of rotation (Supplemental Fig. S6C). In some skeletons, the ankle hangs in a plantar flexed position. This is not ideal for use with the Smart Skeleton, as it is designed to test motions made from anatomical position. To solve this problem, a light elastic cord or rubber band can be fixed to the skeleton to hold the ankle in anatomical position (Supplementary Fig. S6D). Skeletons lacking the ability to plantar flex are also not ideal for use with Smart Skeleton. However, in this case, using a light elastic cord to hold the ankle slightly dorsiflexed may give the it enough motion for students to demonstrate plantar flexion. Alternatively, the ankle joint could be disassembled and remounted with elastic cords in a fashion similar to the ankle and hip.

Item	Description	Vendor	Catalog No.	Qty	Total (USD)
1	BNO055 orientation sensor	Adafruit.com	2472	7	$139.65
2	TCA9548 i2c multiplexer	“	2717	3	$20.85
3	Feather Huzzah microcontroller	“	2821	1	$16.95
4	JST 2 pin cable	“	261	1	$0.75
5	5V USB rechargeable battery	“	1959	1*	$14.95
6	Heat shrink tube assortment	“	1649	1*	$4.95
7	USB mini-B jack	Digikey.com	WM17115-ND	10	$14.63
8	TPS2034DR load switch	“	296-26905-1-ND	1	$2.23
9	Schottky Diode	“	1655-1518-1-ND	1*	$0.31
10	10μF electrolytic capacitor	“	493-10275-1-ND	1*	$0.32
11	0.1μF ceramic capacitor	“	399-9870-1-ND	1*	$0.22
12	2.7KΩ 1/8W resistor	“	CF18JT2K70CT-ND	10*	$0.45
13	4.7 KΩ 1/8W resistor	“	CF18JT4K70CT-ND	4*	$0.40
14	6.8 KΩ 1/8W resistor	“	CF18JT6K80CT-ND	4*	$0.40
15	Main circuit board	Oshpark.com	See Ref. 12	3†	$9.00
16	Arm and Femur circuit board	“	“	3†	$4.85
17	Torso and forelimb board	“	“	6†	$9.70
18	3D Printed enclosures	N/A	N/A	7‡	$25.00§
19	Shielded USB A to mini-B cable	Monoprice.com	8634	7	$12.39
20	M2X0.4 brass inserts	Mcmaster.com	94180A307	100†	$14.69
21	M2X0.4 screws, 8mm length	“	92010A004	100†	$4.79
22	USB foot switch	Amazon.com	B00CK1BKZQ	1*	15.99
	Total				**$313.47**
	Optional LED Feedback				
22	PCA9632DP2 LED driver	Digikey.com	568-8254-2-ND	7	$9.31
23	RGB LED	“	516-3279-1-ND	7	$4.06
24	82Ω 1/8W 603 resistor	“	RK73H1JTTD82R0F	14*	$0.62
25	130Ω 1/8W 603 resistor	“	RK73B1JTTD131J	7*	$0.70
26	Right angle headers	“	S1111EC-40-ND	1*	$0.83
27	LED boards	Oshpark.com	See Ref. 12	9†	$2.40
	Total				**$17.92**
	Grand Total				**$331.39**

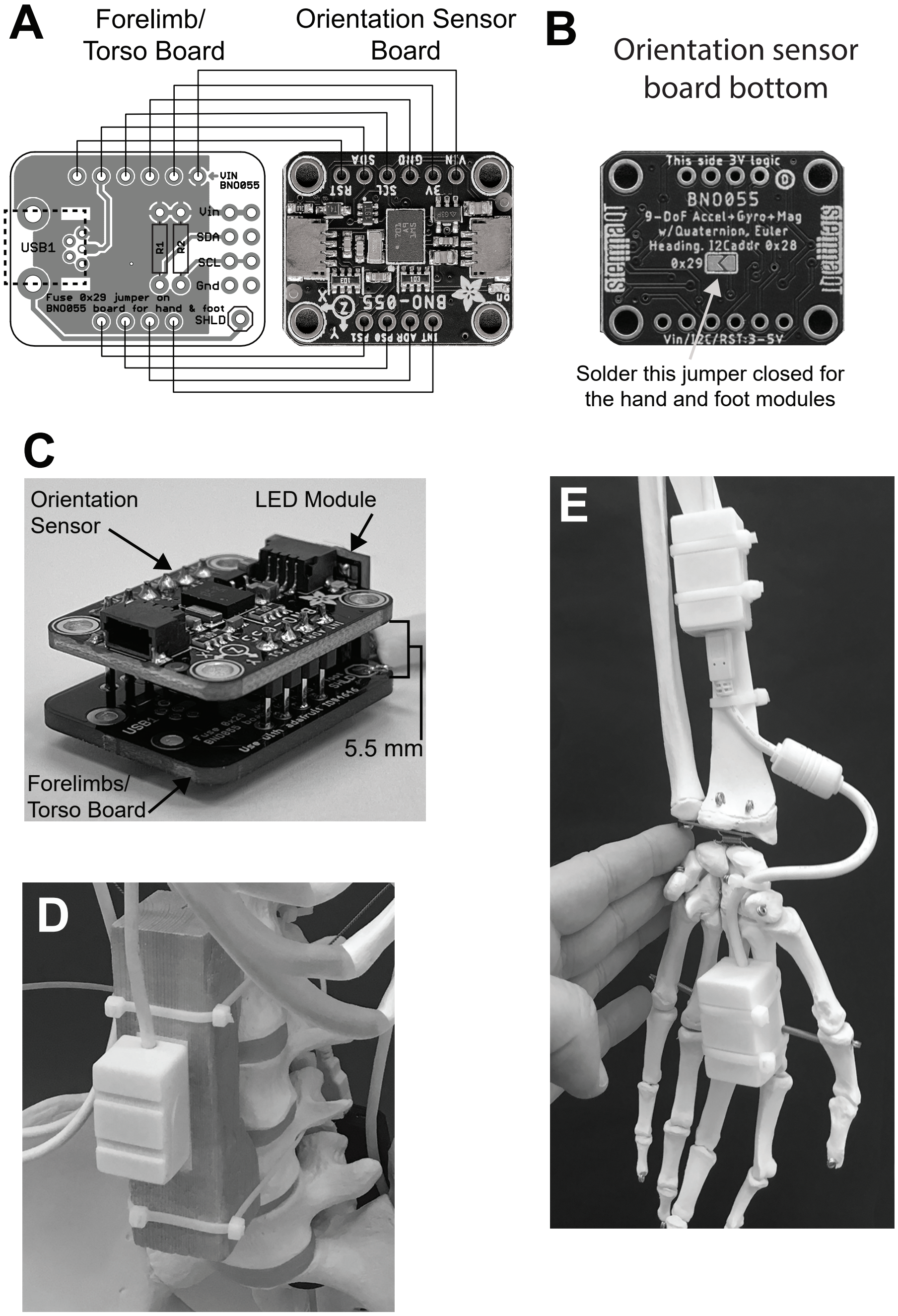
Supplementary Table 1: List of materials, suggested suppliers, part numbers and prices (as of February 2021). Unless noted, the listed quantities are the exact number of each component needed for construction. Parts out of stock at Adafruit.com may be in stock at Digikey, Amazon, or other distributor. *Similar part may be substituted. If a programmable foot switch is substituted, it must be programmed to enter ‘b’. †Fewer are required, but this is the minimum number that can be ordered. ‡One main board enclosure, and one each of the unique, labeled enclosures for the torso sensor and limb segment modules. §Estimated cost of having enclosures printed by a 3D printing service. Check the Github repository for any updates to the bill of materials or suggested suppliers



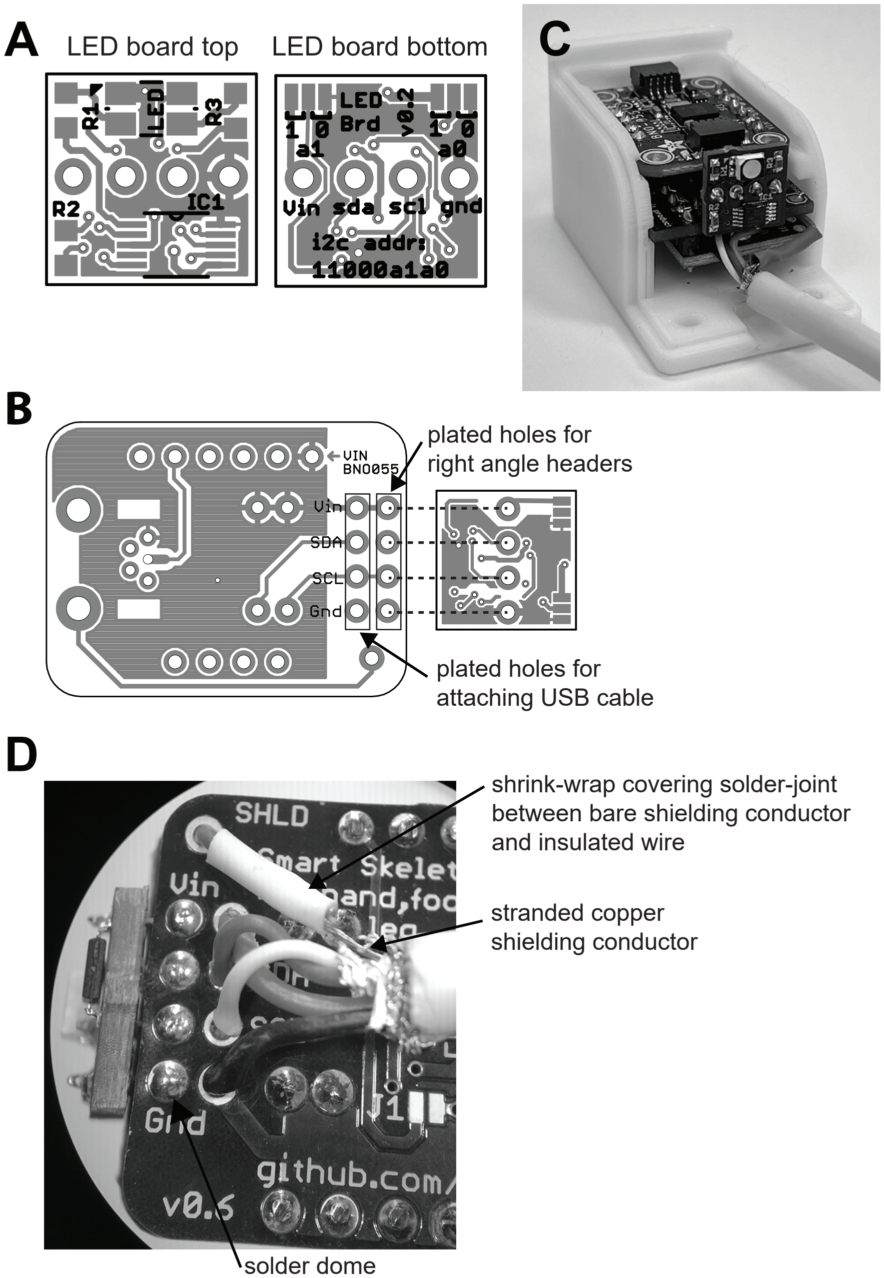
Supplementary Figure S1. Assembly of the main module. **A.** The Adafruit Feather Huzzah (microcontroller) board (right) is connected to the top of the main board custom PCB (left) making the connections shown. Asterisks indicate the wiring points for omitting and bypassing IC1, the power switch for the sensor serial network. **B.** A serial switch board (right) is connected to the bottom of the main board PCB (left), making the connections shown. **C.** The main module is assembled using standard 2.54 mm header pins. The microcontroller board is mounted with 5.5 mm of clearance. **D.** Main module mounted in 3D-printed enclosure and fixed to the ribs of a skeleton. A modified USB A cable with a 2-pin JST connector joins the main module to a rechargeable 5V battery (battery not shown).



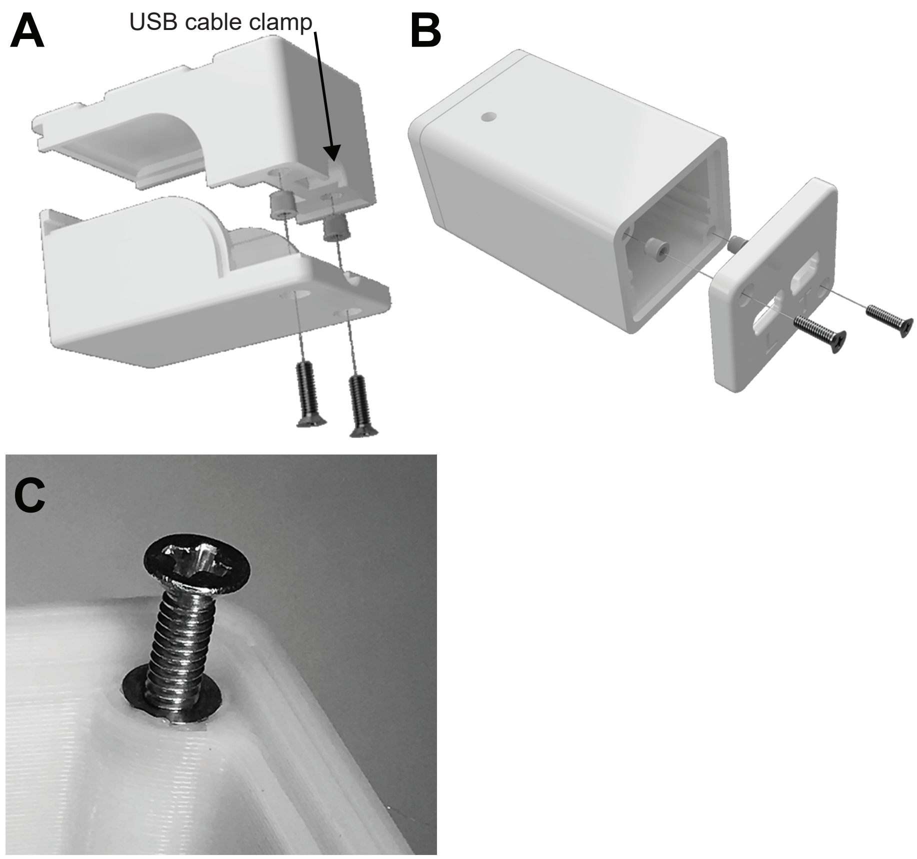
Supplementary Figure S2. Assembly of the arm and femur modules. **A.** An orientation sensor board is (right) is mounted to the top of the arm and femur custom PCB (left). **B.** A serial switch board (right) is mounted to the bottom of the arm and femur PCB (left). **C.** The assembled arm and femur module joined with 2.54 mm header pins. The orientation sensor board is with 5.5 mm clearance. An LED feedback module can also be seen. **D.** Arm module mounted in 3D-printed enclosure and fixed near the head of the humerus.



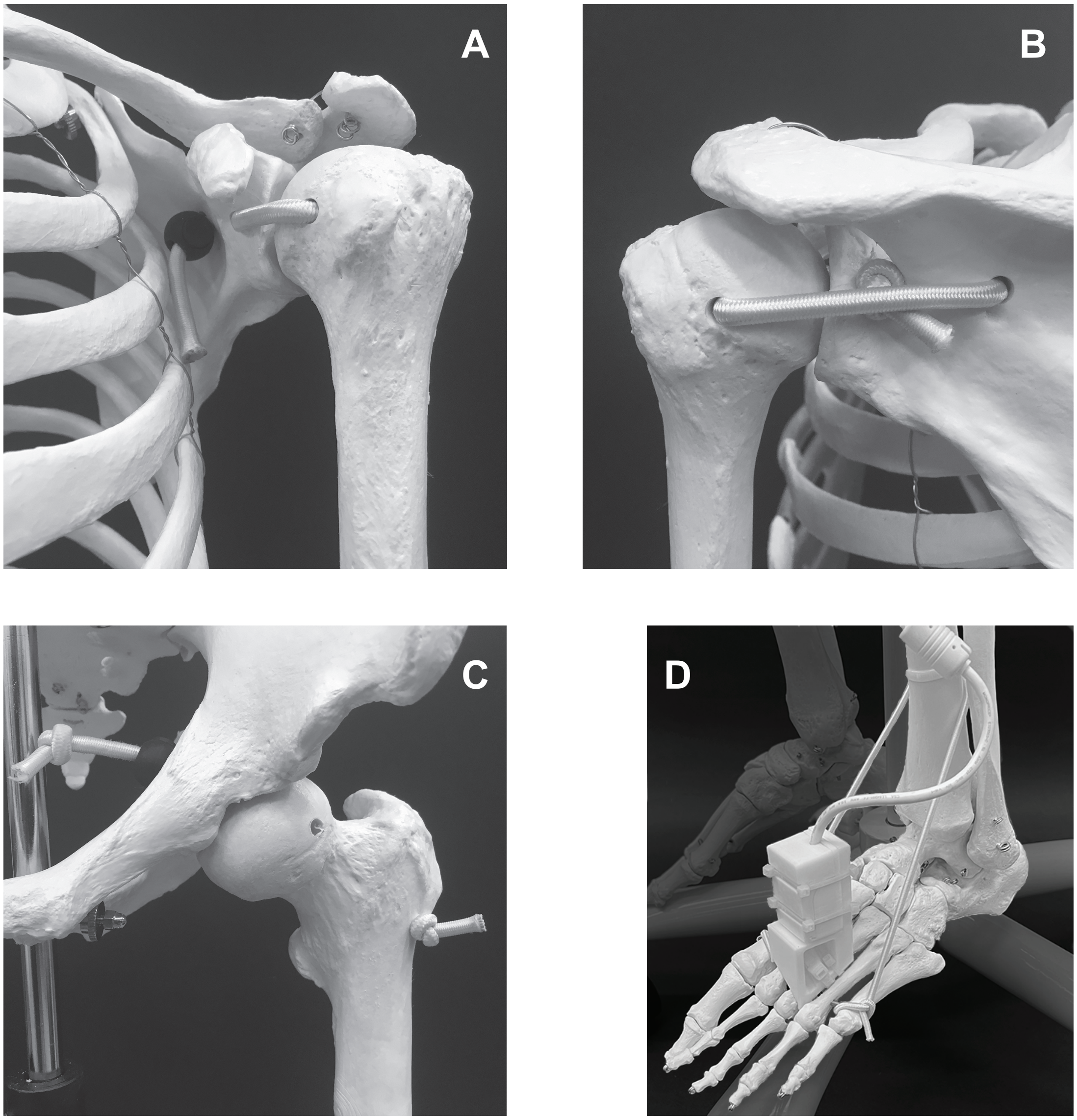
Supplementary Figure S3. Assembly of the forelimb and torso modules. **A.** An orientation sensor board (right) is mounted to the top of the forelimbs and torso custom PCB (left) with the connections shown. **B.** Bottom of the orientation sensor board, illustrating the solder bridge needed to change the i2c address for the hand and foot modules. **C.** The assembled forearm or leg module (the hand, foot, and torso modules omit the USB jack). The orientation sensor board is mounted with 5.5 mm clearance. **D.** Torso module Velcro-mounted to a wooden block affixed to anterior side of the lumbar curve. **E.** Forearm and hand modules mounted in 3D-printed enclosures and fixed to the radius and metacarpals.



Supplementary Figure S4. Optional LED feedback boards and attachment of USB cables. **A.** Top and bottom of the LED board. **B.** The led module board is soldered to sensor module boards using a 2.54 mm right-angle header. The forelimbs and torso board is shown as an example, but the pattern of connection is the same on the arm and femur board. **C.** An LED feedback module mounted to the femur sensor. **D.** Closeup image showing how the leads of the LED board are soldered with a smooth dome of solder exposed to the underside of the sensor module PCB. Note that the USB cable has been folded back 180 degrees from its normal position in this image. The attachment of the bare copper shielding conductor can also be seen in this image.



Supplementary Figure S5. Assembly of the 3D-printed cases. **A.** Exploded view of the main module case showing placement of threaded inserts. **B.** Exploded view of case for sensor module. The case for the hand module is shown as an example. The placement of threaded inserts is consistent in all sensor module cases. **C.** A heated insert has been allowed to melt into a pre-prepared hole in the main module case. Note that the screw used to hold the heated insert remains perpendicular the face of the case.



Supplemental Figure S6: Modifications of a plastic teaching skeleton to enhance motion. **A.** Anterior view of the modified shoulder joint held with 3/16" elastic cord. A spring-loaded cord stop can be seen holding the elastic cord taught in the subscapular fossa. The cord can be seen passing from behind the glenoid cavity and into the head of the humerus **B.** Posterior view of the shoulder. One end of the cord has been tied and passed behind the glenoid cavity. The cord can be seen emerging from the head of the humerus and passing through a hole drilled between the infraspinous fossa and subscapular fossa. **C**. A cord has been passed through a drilled hole passing from the lateral greater trochanter of the femur, through the anatomical neck, and out of the fermoral head. The cord then passes through a hole drilled in the acetabulum. A cord stop can be seen holding the cord from inside the pelvis. D. An elastic band can be used to hold the ankle in anatomical position, rather than hanging slightly plantar flexed. This image also shows how the foot module is held vertically on the metatarsals with a 3D-printed wedge.