Supplementary Materials

Experimental Study: Deep Learning-Based Fall Monitoring among Older Adults with Skin-Wearable Electronics

Yongkuk Lee [1,*], Suresh Pokharel [2], Asra Al Muslim [1], Dukka KC [2], Kyoung Hag Lee [3] and Woon-Hong Yeo [4,5]

[1] Department of Biomedical Engineering, Wichita State University, Wichita, KS 67260, USA; amalmuslim@shockers.wichita.edu
[2] Department of Computer Science, Michigan Technological University, Houghton, MI 49931, USA; sureshp@mtu.edu (S.P.); dbkc@mtu.edu (D.K.)
[3] School of Social Work, Wichita State University, Wichita, KS 67260, USA; kyoung.lee@wichita.edu
[4] George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA; whyeo@gatech.edu
[5] IEN Center for Human-Centric Interfaces and Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA

* Correspondence: yongkuk.lee@wichita.edu; Tel.: +1-316-978-7670

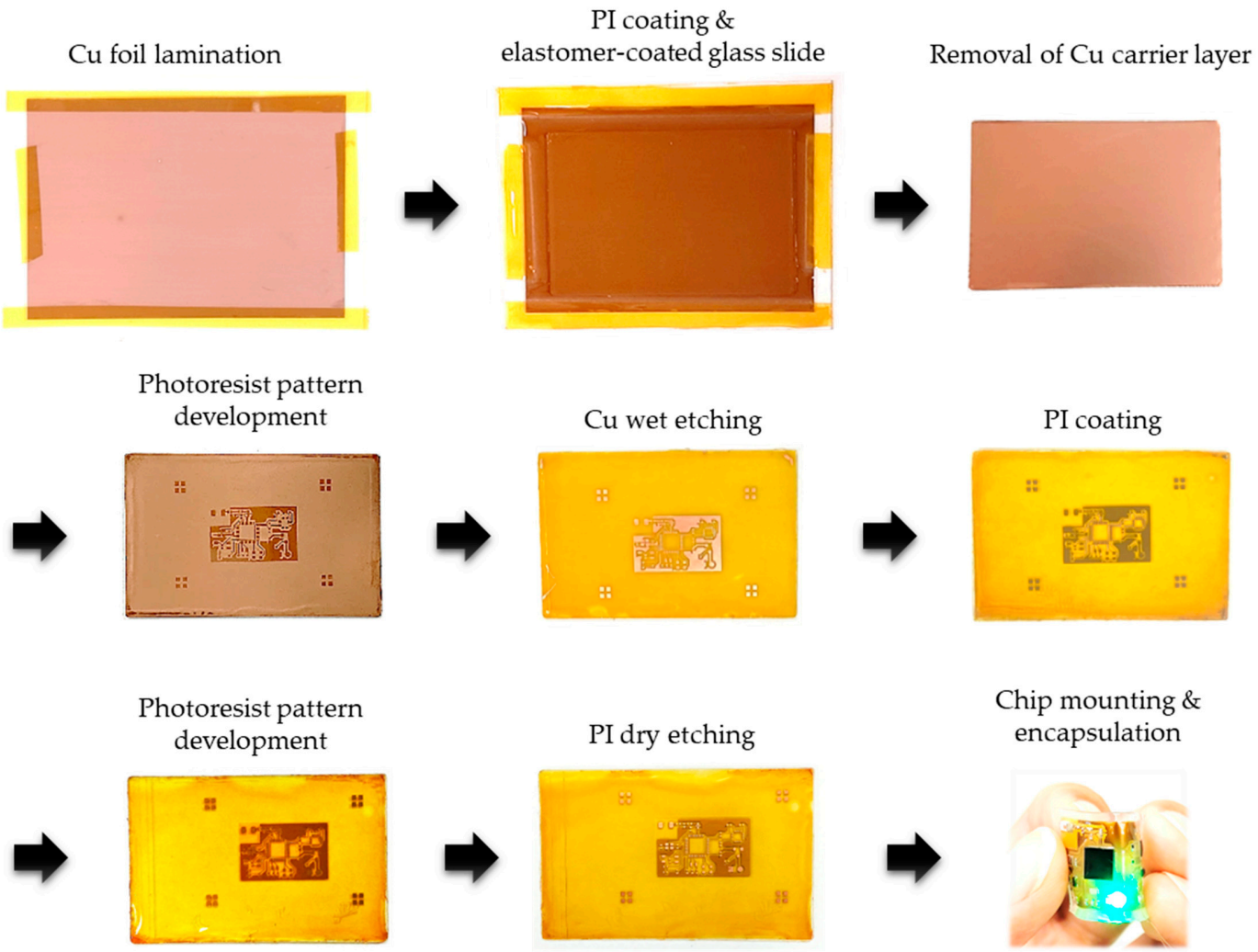
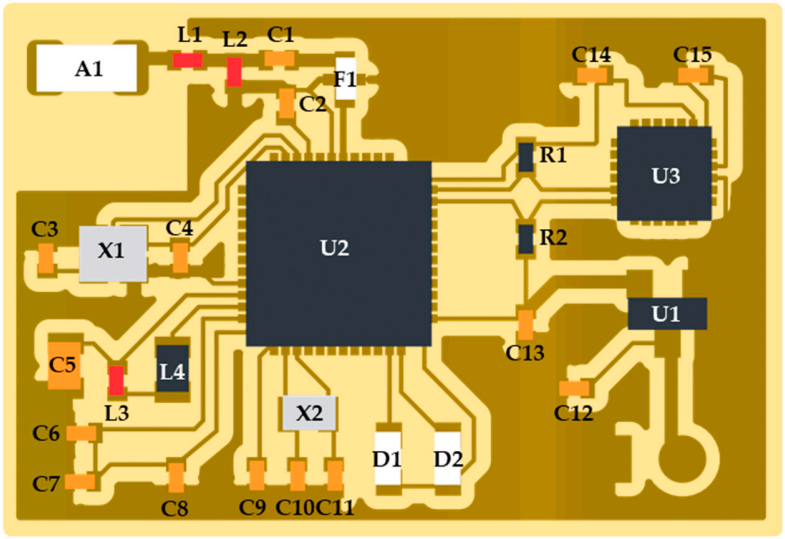


Figure S1. Images of device fabrication process using an ultrathin Cu film. The fabrication process includes the lamination of an ultrathin Cu film, photolithography, wet/dry etching, chip mounting, and thin elastomeric encapsulation.



Annotation	Part description
A1	2.45 GHz ceramic antenna
F1	Impedance matched low pass filter
U1	3.3 V voltage regulator
U2	nRF52832
U3	MPU-9250
X1	32 MHz crystal
X2	32.768 kHz crystal
D1	Green LED
D2	Blue LED
L1	2.7 nH
L2	3.9 nH
L3	15 nH
L4	10 µH
R1, R2	10 kΩ
C1	5 pF
C2	100 pF
C3, C4, C10, C11	12 pF
C5, C7, C12	1 µF
C6, C9, C13, C14, C15	100 nF
C8	4.7 µF

Figure S2. Illustration of the flexible circuit for the SWM device and description of its electronic components.

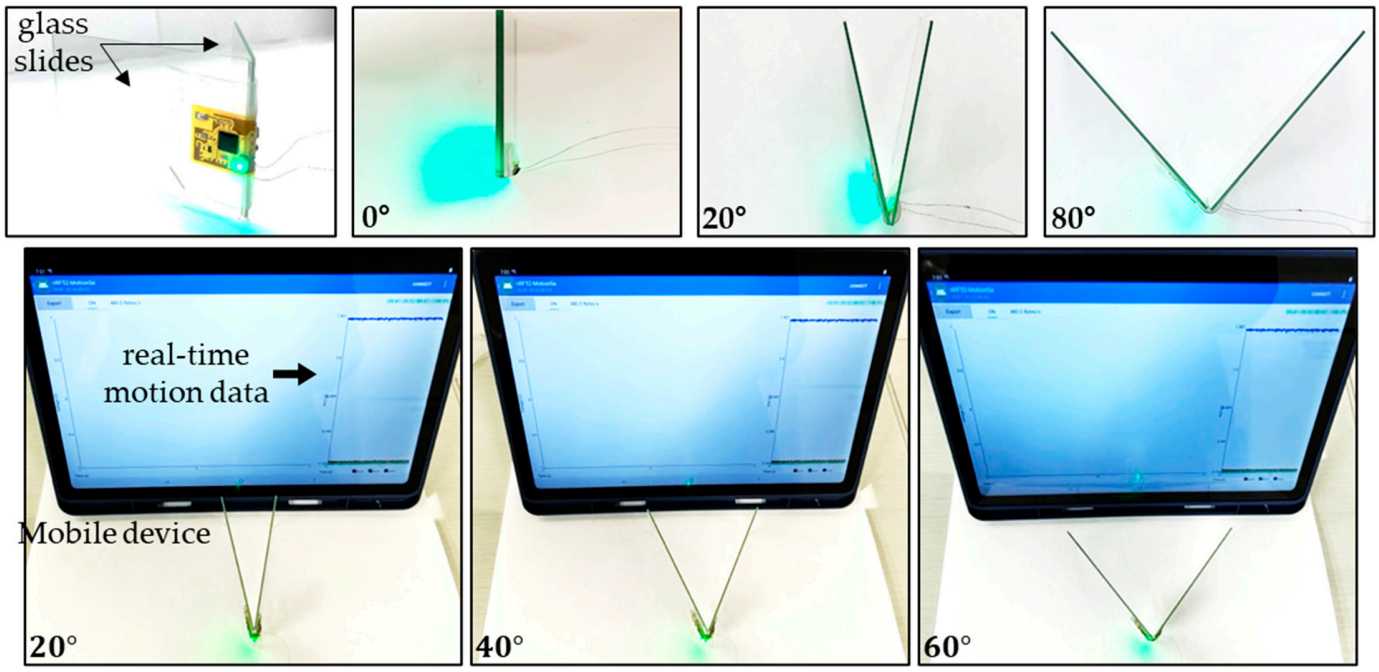


Figure S3. Mechanical bending tests of the SWM device using the hinge made by two glass slides. The minimum bending radius of the device was measured as approx. 1 mm. During the bending tests, the device was connected to a Tablet PC for wireless data transmission.

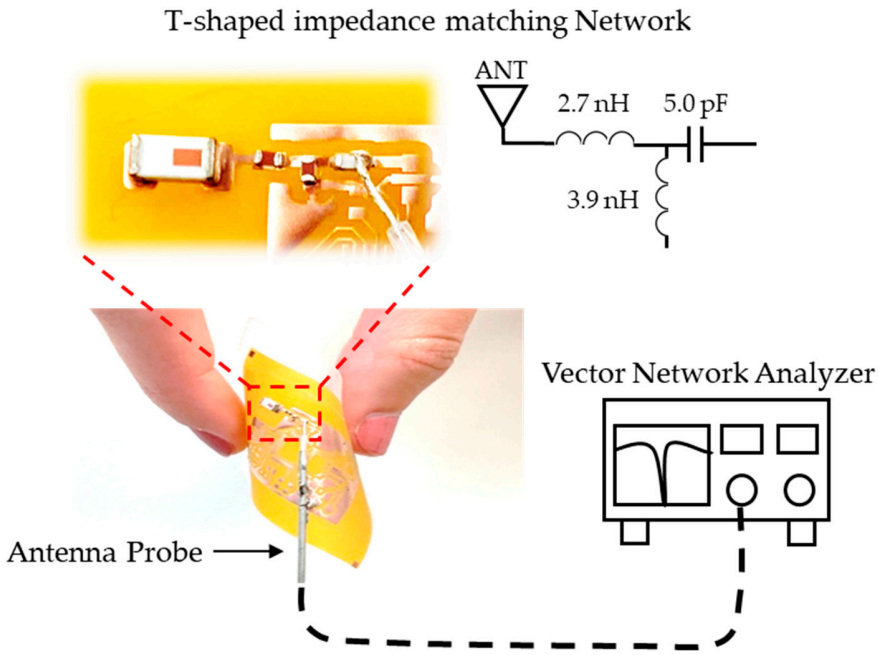


Figure S4. Experimental setup for the measurement of reflection coefficients of the SWM device. The T-shaped impedance matching network was incorporated on the middle of the transmission line. The network was experimentally tunned such that the resonant frequency formed at the Bluetooth operating frequency range, 2.40 – 2.48 GHz.

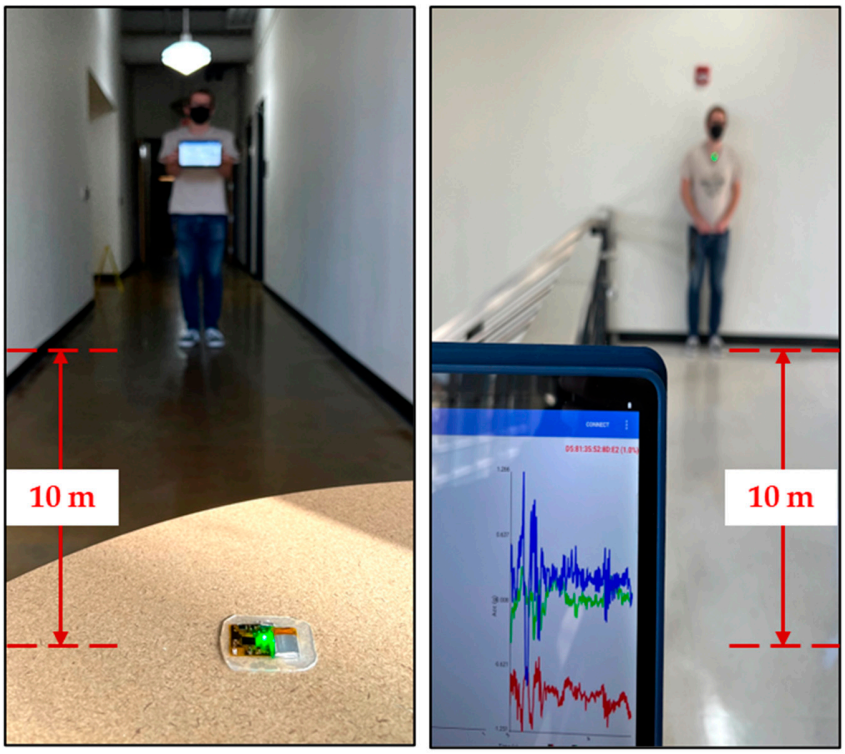


Figure S5. Demonstration of the wireless connection of the SWM device. The T-shaped impedance matching network was separately optimized, but the SWM device enabled seamless wireless data transmission up to 10 meters for both when the device was operated on the air and skin.

Table S1. Hyperparameters of deep learning Models

Name of Model	Hyperparameters
LSTM	No. of LSTM layers: 2 No. of units in layer 1: 256 No. of units in layer 2: 256 No of dense layer: 1 No. of neurons in hidden layer: 64 Optimizer: Adam (Initial learning rate: 0.0001) Loss function: sparse_categorical_crossentropy Intermediate layer's activation function: ReLU Final layer's activation function: Softmax Regularization Method: Dropout No. of trainable parameters: 475,013
CNN-1D	No. of Conv1D layers: 2 Conv1D (filters=128, kernel_size=2) MaxPool1D(pool_size=2)) Conv1D (filters=128, kernel_size=2) No. of Maxpooling layer: 1 MaxPool1D (pool_size=2)) No. of LSTM layer: 1 LSTM (units=256, input_shape= X_train[0].shape, return_sequences=True) No of dense layer: 1 No. of neurons in hidden layer: 128 Optimizer: Adam (Initial learning rate: 0.0001) Loss function: sparse_categorical_crossentropy Intermediate layer's activation function: ReLU Final layer's activation function: Softmax Regularization Method: Dropout No. of trainable parameters: 126,837
CNN-LSTM	No. of Conv1D layers: 1 Conv1D (filters=256, kernel_size=2) No. of Maxpooling layer: 1 MaxPool1D (pool_size=2) No. of LSTM layer: 1 LSTM (units=256, input_shape= X_train[0].shape, return_sequences=True) No of dense layer: 1 No. of neurons in hidden layer: 128 Optimizer: Adam (Initial learning rate: 0.0001) Loss function: sparse_categorical_crossentropy Intermediate layer's activation function: ReLU Final layer's activation function: Softmax Regularization Method: Dropout No. of trainable parameters: 562,181

ConvLSTM-1D	No. of ConvLSTM layers: 2 No. of intermediate dense layer: 1 No of Neurons in hidden dense layer 1: 64 Optimizer: Adam (Initial learning rate: 0.0001) Loss function: sparse_categorical_crossentropy Intermediate layer's activation function: ReLU Final layer's activation function: Softmax Regularization Method: Dropout No. of trainable parameters: 828,101
Bi-LSTM	No. of Bi-LSTM layers: 2 No. of units Bi-LSTM layer 1: 256 No. of units Bi-LSTM layer 2: 256 No of dense layer: 1 No. of neurons in hidden layer: 64 Optimizer: Adam (Initial learning rate: 0.0001) Loss function: sparse_categorical_crossentropy Intermediate layer's activation function: ReLU Final layer's activation function: Softmax Regularization Method: Dropout No. of trainable parameters: 2,136,443

* Other hypermeters not mentioned above are taken default from Keras API. The number of layers and filter size were adjusted for fewer features (1 and 3). No. of parameters are based on 6 input configurations. The approximate training time for these models varied between 15 to 20 minutes for our dataset on a Dell Precision 7920 Workstation with Intel® Xeon(R) Silver 4216 CPU @ 2.10GHz x 32 processor and Quadro RTX 4000 graphics card.

Table S2. Number of samples and weights associated with each class for cost-sensitive learning based on motion data from young adults.

Class	Walking	Stairs	Running	Sitting	Falling
Number of Samples	1389	672	454	239	140
Class Weight	0.4167	0.8613	1.2748	2.4210	4.1342

Table S3. 10-fold cross-validation results of different models and input datasets.

Mag. of Acc. (n=1)					
Fold	CNN-1D	LSTM	BI-LSTM	ConvLSTM-1D	CNN-LSTM
1	0.9181034483	0.9094827586	0.875	0.9051724138	0.9137931034
2	0.9125862069	0.9310344828	0.900862069	0.8922413793	0.9051724138
3	0.9267241379	0.8879310345	0.875	0.9094827586	0.8793103448
4	0.9267241379	0.9094827586	0.9181034483	0.8706896552	0.8965517241
5	0.9153448276	0.9120689655	0.849137931	0.8577586207	0.8577586207
6	0.9264069264	0.9047619048	0.9004329004	0.8961038961	0.9220779221
7	0.9004329004	0.8831168831	0.8744588745	0.9177489177	0.9437229437
8	0.9004329004	0.8961038961	0.8787878788	0.8614718615	0.8744588745
9	0.9123809524	0.9134199134	0.8917748918	0.8787878788	0.9220779221
10	0.9107359307	0.9004329004	0.8917748918	0.8787878788	0.9177489177
Mean	0.9149872369	0.9047835498	0.8855332886	0.886824526	0.9032672787
SD	0.00983218260	0.01377863641	0.01917859355	0.02054507621	0.02622229183
XYZ Acc. (n=3)					
Fold	CNN-1D	LSTM	BILSTM	ConvLSTM-1D	CNN-LSTM
1	0.8793103448	0.9137931034	0.9051724138	0.9267241379	0.9353448276
2	0.8836206897	0.9396551724	0.9353448276	0.9396551724	0.9482758621
3	0.8879310345	0.9310344828	0.9353448276	0.9353448276	0.9267241379
4	0.875	0.9353448276	0.9525862069	0.9310344828	0.8706896552
5	0.8405172414	0.9525862069	0.9224137931	0.9120396552	0.9267241379
6	0.8831168831	0.9393939394	0.9350649351	0.9393939394	0.9393939394
7	0.8787878788	0.9090909091	0.9090909091	0.9267241379	0.9220779221
8	0.8961038961	0.9177489177	0.8571428571	0.9047619048	0.9264069264
9	0.8874458874	0.9350649351	0.9134199134	0.9350649351	0.9047619048
10	0.8787878788	0.9090909091	0.8701298701	0.9090909091	0.9090909091
Mean	0.8790621735	0.9282803403	0.9135710554	0.9259834102	0.9209490222
SD	0.01482868659	0.01492371894	0.03013389952	0.01288244924	0.0219104719
XYZ Acc. & Gyro. (n=6)					
Fold	CNN-1D	LSTM	BILSTM	ConvLSTM-1D	CNN-LSTM
1	0.9396551724	0.9396551724	0.9137931034	0.9267241379	0.9094827586
2	0.9439655172	0.9439655172	0.9181034483	0.9137931034	0.9525862069
3	0.9382758621	0.9324137931	0.9094827586	0.8879310345	0.9396551724
4	0.9396551724	0.9396551724	0.9267241379	0.9051724138	0.9482758621

5	0.9224137931	0.9396551724	0.9094827586	0.8448275862	0.9051724138
6	0.9264069264	0.9437229437	0.9220779221	0.9177489177	0.9393939394
7	0.9177489177	0.9480519481	0.9220779221	0.9047619048	0.9090909091
8	0.9307359307	0.9177489177	0.8701298701	0.8917748918	0.8831168831
9	0.9223809524	0.9177489177	0.9264069264	0.8874458874	0.9264069264
10	0.9264069264	0.9393939394	0.9047619048	0.7705627706	0.9350649351
Mean	0.9307645171	**0.9362011149**4	0.9123040752	0.8850742648	0.9248246007
SD	0.00904419271	0.01053355872	0.01661726774	0.04620006843	0.0222833058
Combined features (n=7)					
Fold	CNN-1D	LSTM	BILSTM	ConvLSTM-1D	CNN-LSTM
1	0.9224137931	0.9482758621	0.9310344828	0.8793103448	0.9267241379
2	0.9310344828	0.9396551724	0.9224137931	0.8405172414	0.9439655172
3	0.9353448276	0.9267241379	0.9137931034	0.8879310345	0.9353448276
4	0.9439655172	0.9396551724	0.875	0.9439655172	0.9267241379
5	0.9181034483	0.9224137931	0.9224137931	0.8318965517	0.9224137931
6	0.9264069264	0.9264069264	0.9090909091	0.8701298701	0.9437229437
7	0.9177489177	0.9393939394	0.9264069264	0.8268398268	0.9090909091
8	0.9220779221	0.9104329004	0.8614718615	0.8961038961	0.9004329004
9	0.9264069264	0.9350649351	0.9264069264	0.8605172496	0.8961038961
10	0.9264069264	0.9264069264	0.9004329004	0.8225108225	0.9047619048
Mean	0.9269909688	0.9314429766	0.9088464696	0.8659722355	0.9209284968
SD	0.00806079446	0.01100758952	0.02348154318	0.03789950829	0.01752878326