Supplemental Material: Gait Cycle Validation and Segmentation using Inertial Sensors

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Appendix A

Algorithm 2 Gait Cycle Validation and Segmentation Algorithm

procedure GCVS($\boldsymbol{A}$, $\boldsymbol{C}$, λ, μ, γ_{D}, γ_{GCVS}, σ_{a}^2, σ_{ω}^2)
  $k \leftarrow 0, i \leftarrow 0$ ▷ Sample index and stride counters
  $\mathrm{MS} \leftarrow \{\}$, $\mathrm{TO} \leftarrow \{\}$, $\mathrm{HS} \leftarrow \{\}$ ▷ Initialized as empty vectors
  loop
    $k \leftarrow k+1$ ▷ Increment sample counter
    Compute $T_k(\boldsymbol{y}^{\mathrm{a}}, \boldsymbol{y}^{\omega})$ ▷ Compute test-statistic in (4)
    if $T_k(\boldsymbol{y}^{\mathrm{a}}, \boldsymbol{y}^{\omega}) < \gamma_{\mathrm{D}}$ **then**
      if $\boldsymbol{y}^{\omega_{\mathrm{s}}}$ is **not** empty **then** ▷ Batch-mode processing
        Scale and interpolate $\boldsymbol{y}^{\omega_{\mathrm{s}}}$ ▷ From (9) and (10)
        Extract DWT coefficients $\boldsymbol{k}_i$ using SAWD algorithm ▷ From (12) and Algorithm 1
        Compute RMSE_i using $\boldsymbol{k}_i$ and $\boldsymbol{k}_{\mathrm{T}}$ ▷ From (22)
        if $\mathrm{RMSE}_i < \gamma_{\mathrm{GCVS}}$ **then** ▷ Check if template matching is true
          $i \leftarrow i+1$ ▷ Increment stride counter
          Determine TO_i, and HS_i ▷ From (24) and (25)
          Reset $\boldsymbol{y}^{\omega_{\mathrm{s}}}$ ▷ An empty vector
        end if
      end if
      Store $T_k(\boldsymbol{y}^{\mathrm{a}}, \boldsymbol{y}^{\omega})$ in $\boldsymbol{z}^{\mathrm{a},\omega}$ ▷ To find midstance event
    else
      if $\boldsymbol{z}^{\mathrm{a},\omega}$ is **not** empty **and** $M_i > 0.1$ seconds **then**
        Determine MS_i ▷ From (5)
      end if
      Reset $\boldsymbol{z}^{\mathrm{a},\omega}$ ▷ An empty vector
      Store $[\boldsymbol{y}^{\omega}]_k$ in $\boldsymbol{y}^{\omega_{\mathrm{s}}}$ ▷ To find toe-off and heel-strike events
    end if
  end loop
  return MS, TO, HS
end procedure

Appendix B

In the treadmill experiment, as a reference system, we used a GoPro camera placed a few feet away from the treadmill (see Fig. 1). In addition, a digital clock was also placed next to the treadmill, so that the readings on the clock were clearly captured in the video data. The digital clock readings were used to manually synchronize the video data with the inertial sensor data. We used the following definition of a valid gait cycle to determine the ground truth:

"A gait cycle in the video data is defined as a valid gait cycle if it contains exactly one heel-strike and one toe-off event, in that order, between two consecutive midstance events."

Fig. 1: Snapshot of the video data collected in the treadmill experiment to determine the ground truth.

APPENDIX C

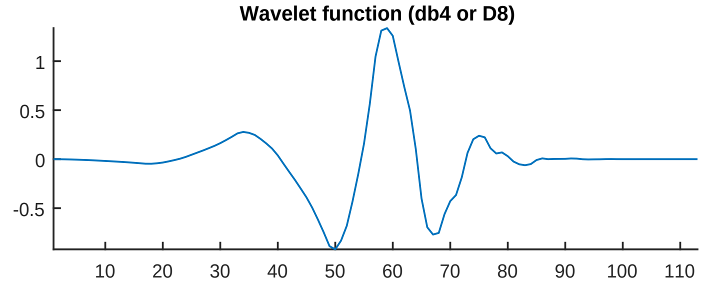


Fig. 2: Daubechies (`db4` or `D8`) wavelet function.

APPENDIX D

TABLE 1: Summary of the datasets validated in this work.

Table #	Sensor Type	Sampling Rate F_s	Sensor Location	# of Participants Healthy	PD	Geriatric	# of Strides Training Data	Total # of Strides
Table II	Opal APDM	128 Hz	Instep	1	0	0	31	180
Table III	Opal APDM	128 Hz	Instep	0	7	0	31	164
Table IV	Shimmer	102.4 Hz	Heel (Sagittal Plane)	10	10	10	31	1746
Table IV	Shimmer	102.4 Hz	Heel (Sagittal Plane	5	5	5	31	4154
Table VI	Openshoe	125 Hz	Heel (Frontal Plane	0	16	0	15	158

Remarks: When the sensor is attached to the instep region of the foot, with the help of FSR and inertial sensors, it was verified in [12], [13] that the local minima of the gyroscope signal in the sagittal plane represent the toe-off and heel-strike events. For the instep region, we validate the ON-GCVS in Table II and III. In Table II, we compute the number of valid gait cycles detected, and also the gait parameters, i.e., toe-off angle, heel-strike angle, and swing as % of gait cycle, and compare our implementation of the inertial navigation system with the results obtained using a proprietary software, MLBS (Mobility Labs Software). The MLBS software uses the algorithm proposed by Salarian *et al.* to detect gait events, such as heel-strike and toe-off events. In Table III, we validate the number of gait events detected by the proposed ON-GCVS method and the existing MLBS method.

For the datasets in Table IV and V, i.e., when the sensor is attached to the heel region (in the sagittal plane), we only validate the number of gait cycles. We cannot validate the gait parameters observed at gait events, such as heel-strike and toe-off events because the ground truth information for these parameters is not available in database [16]. The database only consists of time instances of valid gait cycles and not the gait parameters observed during these valid gait cycles. Furthermore, the datasets used in Table III and IV are also not compatible with the Mobility Labs Software (MLBS) because the MLBS is a proprietary software that works only when the inertial sensor data is collected using the APDM Opal sensor.

Similarly, for the datasets in Table VI, i.e., when the sensor is attached to the heel region (in the frontal plane), we only validate the number of gait cycles. The ground truth in this case was obtained using video data, which captures the validity of a gait cycle and does not determine the gait parameters observed at these valid gait cycles. Furthermore, the datasets used in Table VI are also not compatible with the Mobility Labs Software (MLBS).

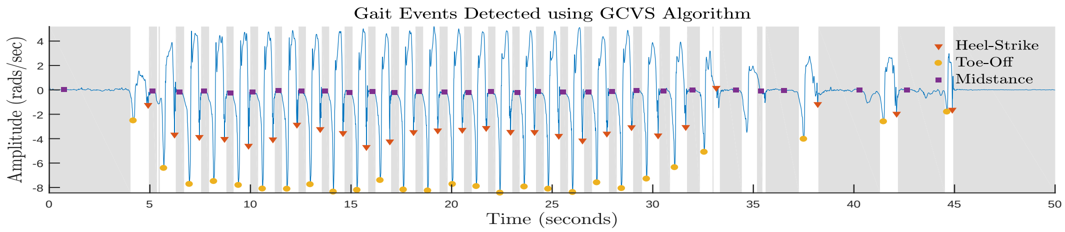
Our main contribution in this work is the gait cycle validation algorithm presented in Section III, i.e., given any non-stationary segment of the gyroscope measurement in the sagittal plane, our proposed method determines if it is a valid gait cycle or not. The validation of the gait parameters observed at gait events, such as heel-strike and toe-off, depends on the implementation of the inertial navigation system (INS). An INS can be implemented in many different ways depending on the sensors and the pseudo measurements used to correct the states of the Kalman filter. In our work, we used the sensor measurements from the accelerometer and gyroscope, and zero-velocity event intervals as pseudo measurements, to estimate the position, velocity, and orientation estimates of the foot. In Table II, we validated the implementation of our INS by computing gait parameters observed at gait events, such as toe-off and heel-strike events, and compare our implementation of the INS with the results obtained using the MLBS.

Appendix E

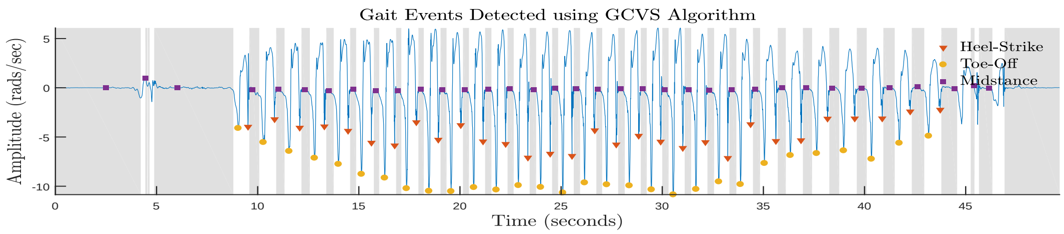
TABLE 2: Performance of the existing and proposed methods for the 12 meter walk task.

Method	Dataset	Free WALK											
		$F_{\mathrm{s}} = 125$ Hz				$F_{\mathrm{s}} = 250$ Hz				$F_{\mathrm{s}} = 500$ Hz			
		Precision	Recall	F1-Score	Time	Precision	Recall	F1-Score	Time	Precision	Recall	F1-Score	Time
	TT003	91.66%	100.0%	95.65%	0.101	91.66%	100.0%	95.65%	0.103	91.66%	100.0%	95.65%	0.193
	TT004	81.81%	100.0%	90.00%	0.168	81.81%	100.0%	90.00%	0.096	81.81%	100.0%	90.00%	0.195
	TT005	92.85%	100.0%	96.29%	0.122	92.85%	100.0%	96.29%	0.100	86.66%	100.0%	92.28%	0.198
	TT006	90.00%	100.0%	94.73%	0.123	90.00%	100.0%	94.73%	0.116	90.00%	100.0%	94.73%	0.194
	TT010	81.81%	100.0%	90.00%	0.100	81.81%	100.0%	90.00%	0.098	81.81%	100.0%	90.00%	0.197
	TT013	85.71%	100.0%	92.30%	0.102	85.71%	100.0%	92.30%	0.097	85.71%	100.0%	92.30%	0.197
OFF-PDT	TT014	85.71%	100.0%	92.30%	0.100	85.71%	100.0%	92.30%	0.104	85.71%	100.0%	92.30%	0.201
	TT015	90.00%	90.00%	90.00%	0.101	90.90%	100.0%	95.23%	0.105	90.90%	100.0%	95.23%	0.197
	TT017	85.71%	100.0%	92.30%	0.100	85.71%	100.0%	92.30%	0.105	85.71%	100.0%	92.30%	0.211
	TT021	81.25%	100.0%	88.00%	0.122	81.25%	100.0%	89.65%	0.153	76.47%	100.0%	86.66%	0.197
	TT022	88.23%	100.0%	93.75%	0.103	88.23%	100.0%	93.75%	0.103	88.23%	100.0%	93.75%	0.107
	TT024	81.81%	100.0%	90.00%	0.099	81.81%	100.0%	90.00%	0.100	81.81%	100.0%	90.00%	0.195
	TT026	92.30%	100.0%	96.00%	0.139	92.30%	100.0%	96.00%	0.131	92.30%	100.0%	96.00%	0.197
	TT027	87.50%	93.33%	90.32%	0.100	87.50%	93.33%	90.32%	0.100	87.50%	93.33%	90.32%	0.265
		86.88%	98.80%	92.26%	0.112	86.94%	99.52%	92.75%	0.107	86.16%	99.52%	92.25%	0.196
	TT003	91.66%	100.0%	95.65%	1.030	91.66%	100.0%	95.65%	2.104	91.66%	100.0%	95.65%	4.119
	TT004	81.81%	100.0%	90.00%	0.589	81.81%	100.0%	90.00%	1.317	90.00%	100.0%	94.73%	2.461
	TT005	100.0%	92.37%	96.00%	0.904	92.30%	92.30%	92.30%	1.339	85.71%	92.30%	88.88%	3.018
	TT006	81.81%	100.0%	90.00%	0.325	63.63%	77.77%	70.00%	0.622	18.18%	22.22%	20.00%	1.853
	TT010	80.00%	88.88%	84.21%	0.474	72.72%	88.88%	80.00%	0.862	63.63%	77.77%	70.00%	1.644
	TT013	90.90%	83.33%	86.95%	0.426	83.33%	83.33%	83.33%	0.843	83.33%	83.33%	83.33%	1.705
OFF-SDTW	TT014	91.66%	91.66%	91.66%	1.652	76.92%	83.33%	80.00%	3.381	76.92%	83.33%	80.00%	7.124
	TT015	100.0%	90.00%	94.73%	0.491	100.0%	90.00%	94.73%	0.990	80.00%	80.00%	80.00%	2.193
	TT017	83.33%	93.33%	93.33%	0.789	83.33%	83.33%	83.33%	1.580	76.92%	83.33%	80.00%	3.422
	TT021	91.66%	84.61%	88.00%	0.977	91.66%	84.61%	88.00%	1.104	91.66%	84.61%	88.00%	2.231
	TT022	86.67%	86.67%	86.67%	0.719	86.67%	86.67%	86.67%	1.342	88.66%	88.66%	88.66%	2.731
	TT024	88.88%	88.88%	88.88%	0.641	88.88%	88.88%	88.88%	1.364	80.00%	88.88%	84.21%	2.824
	TT026	83.33%	83.33%	83.33%	0.694	84.61%	91.66%	88.00%	1.287	69.23%	75.00%	72.00%	2.823
	TT027	92.85%	86.66%	89.65%	0.856	86.66%	86.66%	86.66%	1.761	86.66%	86.66%	86.66%	3.611
		88.89%	90.69%	89.93%	0.754	84.58%	88.38%	86.25%	1.421	77.32%	81.86%	79.43%	2.982
	TT003	90.90%	90.90%	90.90%	0.001	00.00%	00.00%	00.00%	0.001	00.00%	00.00%	00.00%	0.001
	TT004	88.88%	88.88%	88.88%	0.001	100.0%	11.11%	20.00%	0.001	00.00%	00.00%	00.00%	0.001
	TT005	92.28%	100.0%	96.29%	0.001	00.00%	00.00%	00.00%	0.001	00.00%	00.00%	00.00%	0.001
	TT006	88.88%	88.88%	88.88%	0.001	100.0%	11.11%	20.00%	0.001	00.00%	00.00%	00.00%	0.001
	TT010	90.00%	100.0%	94.73%	0.001	75.00%	33.33%	46.15%	0.001	00.00%	00.00%	00.00%	0.001
	TT013	100.0%	100.0%	100.0%	0.001	00.00%	00.00%	00.00%	0.001	00.00%	00.00%	00.00%	0.001
ON-DTW	TT014	91.66%	91.66%	91.66%	0.001	100.0%	66.67%	80.00%	0.001	00.00%	00.00%	00.00%	0.001
	TT015	100.0%	100.0%	100.0%	0.001	100.0%	10.00%	18.18%	0.001	00.00%	00.00%	00.00%	0.001
	TT017	90.00%	75.00%	81.81%	0.001	00.00%	00.00%	00.00%	0.001	00.00%	00.00%	00.00%	0.001
	TT021	100.0%	92.30%	96.00%	0.001	100.0%	30.76%	86.66%	0.001	00.00%	00.00%	00.00%	0.001
	TT022	91.66%	86.67%	92.85%	0.001	91.66%	73.33%	81.48%	0.001	00.00%	00.00%	00.00%	0.001
	TT024	87.50%	77.77%	82.23%	0.001	80.00%	44.44%	57.14%	0.001	00.00%	00.00%	00.00%	0.001
	TT026	90.90%	83.33%	86.95%	0.001	66.66%	16.66%	26.66%	0.001	00.00%	00.00%	00.00%	0.001
	TT027	92.85%	86.67%	89.65%	0.001	90.90%	66.66%	76.69%	0.001	00.00%	00.00%	00.00%	0.001
		92.53%	90.14%	91.48%	0.001	64.58%	26.00%	36.64%	0.001	00.00%	00.00%	00.00%	0.001
	TT003	91.66%	100.0%	95.65%	0.014	91.66%	100.0%	95.65%	0.130	78.57%	100.0%	88.00%	0.054
	TT004	90.00%	100.0%	94.73%	0.016	90.00%	100.0%	94.73%	0.263	81.81%	100.0%	90.00%	0.073
	TT005	86.66%	100.0%	92.85%	0.017	86.66%	100.0%	92.85%	0.107	86.66%	100.0%	92.85%	0.065
	TT006	90.00%	100.0%	94.73%	0.015	90.00%	100.0%	94.73%	0.163	81.81%	100.0%	90.00%	0.052
	TT010	90.00%	100.0%	94.73%	0.020	90.00%	100.0%	94.73%	0.107	69.23%	100.0%	81.81%	0.054
	TT013	92.30%	100.0%	96.00%	0.018	92.30%	100.0%	96.00%	0.107	80.00%	100.0%	88.88%	0.049
ON-GCVS	TT014	85.71%	100.0%	92.30%	0.015	85.71%	100.0%	92.30%	0.109	85.71%	100.0%	92.30%	0.050
	TT015	90.90%	100.0%	95.23%	0.016	90.00%	90.00%	90.00%	0.108	83.33%	100.0%	90.90%	0.073
	TT017	92.30%	100.0%	96.00%	0.014	85.71%	100.0%	92.30%	0.108	75.00%	100.0%	85.71%	0.059
	TT021	92.85%	100.0%	96.29%	0.014	76.47%	100.0%	86.66%	0.146	68.41%	100.0%	81.25%	0.033
	TT022	93.75%	100.0%	96.77%	0.013	88.23%	100.0%	93.75%	0.107	78.94%	100.0%	88.23%	0.062
	TT024	90.00%	100.0%	94.73%	0.050	90.00%	100.0%	94.73%	0.107	75.00%	100.0%	85.71%	0.025
	TT026	92.30%	100.0%	96.00%	0.021	92.30%	100.0%	96.00%	0.108	85.71%	100.0%	92.30%	0.059
	TT027	93.75%	100.0%	96.77%	0.047	93.75%	100.0%	96.77%	0.128	83.33%	100.0%	90.90%	0.052
		90.87%	100.0%	95.19%	0.020	88.77%	99.28%	93.65%	0.128	79.53%	100.0%	88.48%	0.054

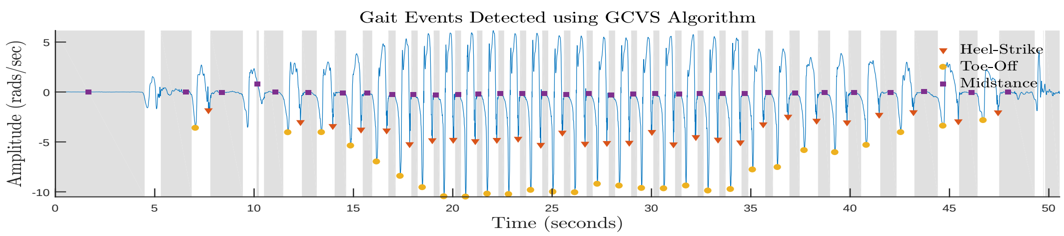
Appendix F



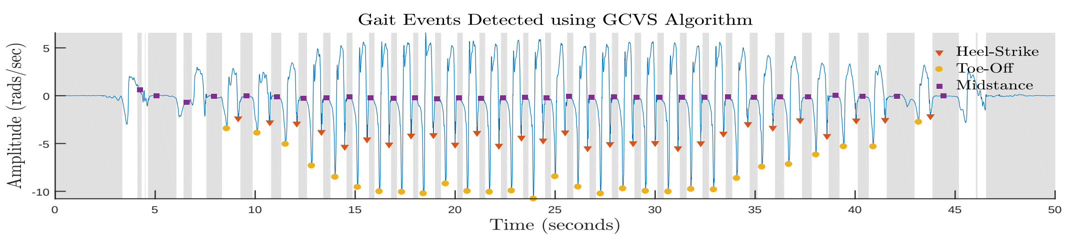
(a) Second trial.



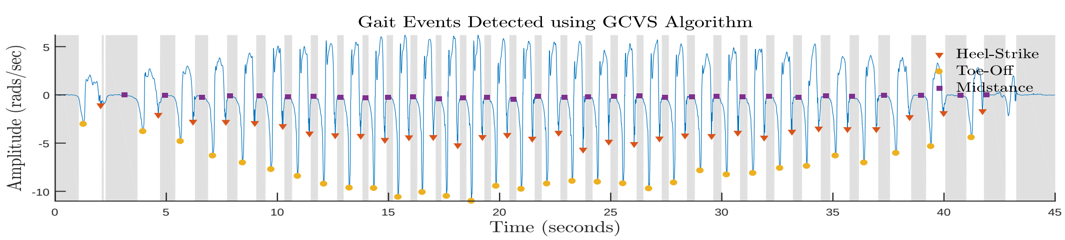
(b) Third trial.



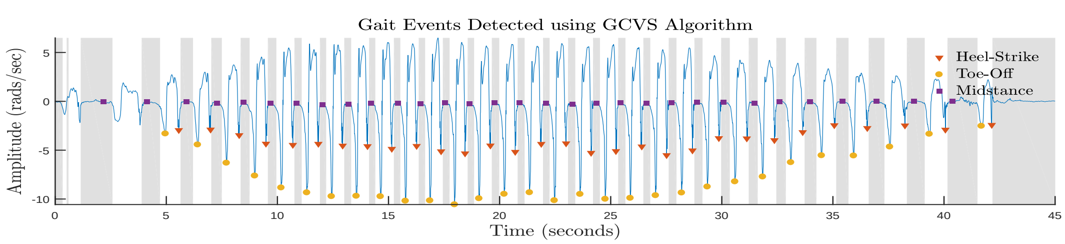
(c) Fourth trial.



(d) Fifth trial.



(e) Sixth trial.



(f) Seventh trial.

Fig. 3: Gait events midstance(■), toe-off(●), and heel-strike(▾) detected using the GCVS algorithm for right foot gyroscope sensor data in the sagittal plane. The zero-velocity event intervals are represented by gray background.