

# Supplement: Sensor-Based Digital Biomarkers for Early Identification of Cognitive Frailty: A Systematic Review

Ruiyuan Wu, Keyi Huang, Kwok-Leung Tsui, Jianbang Xiang, and Yang Zhao, *Senior Member, IEEE*

SUPPLEMENTARY TABLE I  
DESCRIPTION AND ABBREVIATIONS OF DIGITAL BIOMARKERS

Domain	Name	Description
Gait and Motor Function (28)	1.Velocity/Gait Speed (Vel) 2.Normalized Gait Speed (NVel) 3.Coefficient of Variation (CV) of Gait Speed (VCV)	1.Walking speed or gait speed 2.Walking speed adjusted for height 3.Variability in walking speed
	1.Gait Cycle Time (GCT) 2.CV of Step Time (StCV) 3.CV of Stride Time (STCV) 4.Cadence (Cad)	1.Time for one complete walking cycle 2.Variability in time per step 3.Variability in time per stride 4.Steps per minute
	1.Stride Length (SL) 2.Normalized Stride Length (NSL) 3.CV of Stride Length (SLCV) 4.Step Width (SW)	1.Distance between two consecutive steps of the same foot 2.Stride length to height ratio 3.Variability of stride length compared to average 4.Lateral distance between feet while walking
	1.Swing Time Variability (SWCV) 2.Double Support Time Variability (DTCV) 3.Double Support Time (DT) 4.Dual Task Cost (DC)	1.Variability in leg swing time 2.Variability in time with both feet on the ground 3.Time spent with both feet on the ground during the walking cycle 4.Percentage decrease in walking speed during dual-task walking test
	1.Step Regularity (StR) 2.Stride Regularity (SR) 3.Symmetry (Sym)	1.Consistency of step lengths between legs 2.Consistency of strides with the same leg 3.Balance between legs during walking, calculated as SR/StR
	1.Root Mean Square (RMS) 2.Approximate Entropy (ApEn) 3.Harmonic Ratio (HR) 4.Total Harmonic Distortion (THD)	1.Intensity of the walking signal 2.Unpredictability and complexity of walking pattern 3.Measure of regularity and symmetry based on gait signal periodicity 4.Effect of higher-frequency components on overall gait signal, reflecting rhythm complexity or distortion
	1.Slowness 2.Weakness 3.Exhaustion 4.Frailty Index (FI)	1.Derived from elbow speed and movement count during rapid flexion-extension 2.Average torque around the elbow during repeated movements 3.Based on movement jerkiness and velocity decline over time 4.Composite score derived from slowness, weakness, exhaustion, rigidity, and obesity, assessed through upper-limb motor performance and Body Mass Index (BMI)
	1.Rotate 60°-30°(RA) 2.Ratio of rotation from 30°-90° to that from 60°-90° (RA ratio)	1.Acceleration difference to reduce start-position bias 2.A ratio comparing movement across two angular ranges, used to normalize performance and account for variability in motion trajectory

SUPPLEMENTARY TABLE I (continued)  
DESCRIPTION AND ABBREVIATIONS OF DIGITAL BIOMARKERS

Domain	Name	Description
Body Composition (7)	1.Skeletal Muscle Mass (SMM) 2.Skeletal Muscle Index (SMI) 3.Body Fat Mass (BFM) 4.Low Muscle Mass (LMM) 5.Appendicular Skeletal Muscle Mass Index (ASM) 6.Fat Free Mass (FFM) 7.Percentage Body Fat (PBF)/Total Body Fat (TBF)	1.Mass of skeletal muscles 2.SMM normalized by height 3.Total amount of fat in the body 4.SMI below 7.0 kg/m <sup>2</sup> in men or 5.7 kg/m <sup>2</sup> in women 5.Muscle mass in the arms&legs, normalized by height 6.All body components except fat 7.Proportion of body fat in total body weight, equivalent to TBF
Cardiovascular-related (4)	1.Systolic Blood Pressure (SBP) 2.Diastolic Blood Pressure (DBP) 3.Hypertension (HTN) 4.Cardio-Ankle Vascular Index (CAVI)	1.Peak pressure during heart contraction 2.Lowest pressure during heart relaxation 3.Diagnosed when SBP $\geq$ 130 mmHg or DBP $\geq$ 80 mmHg 4.Calculated using SBP, DBP, and Pulse Wave Velocity (PWV), reflecting vascular elasticity; average CAVI obtained from multiple sites
Physical Activity (11)	1.Moderate-to-Vigorous-intensity Physical Activity (MVPA) 2.Light-intensity Physical Activity (LPA) 3.Inactivity Time (IT)	1.The Euclidean Norm Minus One (ENMO) $\geq$ 104 Mg 2.ENMO between 57 mG and 104 mG 3.Period of inactivity, with ENMO $\leq$ 57 mG
	1.Sedentary Time (Sed) 2.Light Activity Time (Lig) 3.Moderate-to-Vigorous Activity Time (MtV)	1.Energy expenditure < 1.5 METs 2.Energy expenditure 1.5-2.9 METs 3.Energy expenditure $\geq$ 3.0 METs
	1.Posture Times (sitting, standing, walking, and lying) 2.Number of Steps (Nos)	1.Proportion of time spent sitting, standing, walking, and lying 2.Daily step count
Sleep Health (8)	1.Time in Bed (TB) 2.Total Sleep Time (TST) 3.Sleep Onset Latency (SOL) 4.Wake After Sleep Onset (WASO) 5.Sleep Efficiency (SE) 6.Sleep Posture Percentages (supine, prone, and side)	1.Total time spent in bed 2.Actual sleep duration 3.Time taken to fall asleep 4.Time spent awake after falling asleep 5.Percentage of time asleep relative to time in bed 6.Proportion of time spent in supine, prone, and side sleeping positions
Hearing Health (3)	1.Speech-frequency Hearing Threshold (SHT) 2.High-frequency Hearing Threshold (HHT) 3.Hearing Loss (HL)	1.Avg. threshold (better ear, 0.5–4 kHz) for speech-related hearing 2.Avg. threshold (better ear, 4–8 kHz) for high-frequency hearing 3.Calculated from thresholds at four frequencies; Mild hearing loss: 25 dB < Pure-Tone Average (PTA) $\leq$ 40 dB; Moderate-to-severe hearing loss: PTA > 40 dB
Oral Health(1)	1.Tongue Pressure (TP)	1.Measured with a soft rubber balloon or sensor in the mouth, pressure readings recorded in kilopascals (kPa)
Eye Health(4)	1.Retinal Nerve Fiber Layer (RNFL) 2.Ganglion Cell–Inner Plexiform Layer (GC-IPL) 3.Interocular RNFL Asymmetry (IRA) 4.Interocular GC-IPL Asymmetry (IGA)	1.Mean RNFL thickness across both eyes 2.Mean GC-IPL thickness across both eyes 3.Difference in RNFL thickness between eyes 4.Difference in GC-IPL thickness between eyes
EEG(4)	1.Occurrence 2.Duration 3.Coverage 4.Transition Probability (TP)	1.Frequency a microstate appears per second 2.Mean time spent in a microstate 3.Proportion of total time occupied 4.Probability of switching between states; TPA/TPB/TPC/TPD indicate transition probabilities from microstates A/B/C/D to others

SUPPLEMENTARY TABLE II  
OVERVIEW OF STUDY OUTCOMES AND MEASUREMENTS

Source	CF Definition	Cognitive Assessment Tool	Frailty Assessment Tool
Najafi	1.Outcome V	1.MoCA	1.Frailty Indices (FI)
Lee, W	1.Outcome II	1.NTB	1.Modified Fried's criteria
Tian	1.Outcome I 2.Outcome V	Unclear	1.Fried's criteria 2.FRAIL scale
Lee, Y	1.Outcome I 2.Outcome II	1.NTB 2.MoCA	1.Fried's criteria
Zhang	1.Outcome IV 2.Outcome V	1.CDR 2.MoCA	1.Fried's criteria
Ibrahim	1.Outcome V	1.NTB 2.MMSE 3.CDR	1.Fried's criteria
Akaida	1.Outcome V	1.NCGG-FAT	1.Modified Fried's criteria
Ghanbarnia	1.Outcome I 2.Outcome II	1.MMSE	1.FRAIL scale
Suprawesta	1.Outcome IV 2.Outcome V	1.CDR	1.Fried's criteria
Hwang	1.Outcome IV 2.Outcome V	1.CDR	1.Fried's criteria
Corral-Pérez	1.Outcome V	1.SPMSQ	1.Fried's criteria
Zhou	1.Outcome V	1.MMSE	1.Modified Fried's criteria
Ruan	1.Outcome IV 2.Outcome V	1.NTB	1.Fried's criteria
Katayama	1.Outcome V	1.NCGG-FAT	1.Modified Fried's criteria
Razjouyan	1.Outcome V	1.MMSE	1.Modified Fried's criteria
González	1.Outcome I	1.MMSE	1.Fried's criteria
Malek Rivan	1.Outcome V	1.NTB 2.MMSE	1.Fried's criteria
Kim, H	1.Outcome I	1.MMSE	1.Fried's criteria
Kim, M	1.Outcome I 2.Outcome II	1.NTB	1.Fried's criteria
Martínez-Ramírez	1.Outcome I	Unclear	1.Fried's criteria

Note: 1. The combination of the three cognitive and three physical status levels yields five outcome categories. Cognitive status is categorized as follows: Mild Cognitive Impairment (MCI), which is defined as objectively verified cognitive decline based on standardized assessments; Pre-MCI or Subjective Cognitive Decline (SCD), which is defined as the absence of objective impairment on cognitive tests but with self-reported decline; and Normal Cognition (NC), which is defined as neither objective nor subjective cognitive decline. Physical status is categorized as follows: Physical Frailty (PF), which is defined as meeting at least three of the five Fried's criteria (unintentional weight loss, exhaustion, reduced physical activity, slow gait speed, and weak grip strength), or equivalent thresholds when other criteria are applied; Pre-PF, which is defined as meeting at least two of the five indicators; and robust, which is defined as not meeting the above criteria.

2. Outcome I = PF + MCI; Outcome II = Pre-PF + MCI; Outcome III = Pre-PF / PF + Pre-MCI / MCI; Outcome IV = Pre-PF / PF + Pre-MCI; Outcome V = Pre-PF / PF + MCI.

3. Abbreviations: CDR = Clinical Dementia Rating; MoCA = the Montreal Cognitive Assessment Test; MMSE = the Mini-Mental State Examination; NTB = Neuropsychological Test Battery; NCGG-FAT = National Center for Geriatrics and Gerontology Functional Assessment Tool; SPMSQ = Short Portable Mental Status Questionnaire.