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Prototype sensor system for analyzing frailty in older people: a pilot study

Protótipo de sistema de sensores para análise de fragilidade em idosos: um estudo piloto

Prototipo de sistema de sensores para analizar la fragilidad en personas mayores: un estudio piloto

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Abstract
Introduction: Frailty syndrome is characterized by reduced physical and cognitive reserves, making older people vulnerable to adverse events. This study describes a prototype sensor system developed for assessing frailty through physiological parameters and frailty markers. Methods: A prototype combining four sensors in network and a software package was developed and tested in four long-term care facility senior residents of both sexes, aged 60 and older, showing no locomotive syndrome or severe cognitive impairment. Three of them were frail and able to walk without aid (P1), holding onto the wall (P2) or with a cane (P3), and a non-frail participant (P4) walked without aid. Results: Regarding mean acceleration, P1 and P4 showed the lowest and highest values, respectively, on the antero-posterior axis; P4 had the lowest value on the medio-lateral axis; and P3 presented the highest value on the vertical axis. All participants showed similar roll angular velocity; P4 presented the lowest pitch angular velocity; and P1 and P4 had the highest mean yaw angular velocity. A sarcopenic participant (P2) exhibited the lowest force of muscle contraction. Conclusion: The device has potential to detect frailty markers for adverse outcomes in older people, such as postural instability and increased risk of falls.
Keywords: Biomedical technology assessment; Frail elderly; Computer peripherals; Diagnostic equipment.

Resumo
Introdução: A síndrome da fragilidade é caracterizada por reservas físicas e cognitivas reduzidas, tornando os idosos vulneráveis a eventos adversos. Este estudo descreve um protótipo de sistema sensor desenvolvido para avaliação de fragilidade por meio de parâmetros fisiológicos e marcadores de fragilidade. Métodos: Um protótipo combinando quatro sensores em rede e um pacote de software foi desenvolvido e testado em quatro residentes de longa permanência de ambos os sexos, com idade igual ou superior a 60 anos, sem síndrome locomotora ou comprometimento cognitivo grave. Três delas eram frágeis e conseguiam deambular sem auxílio (P1), apoiando-se na parede (P2) ou com bengala (P3), e uma participante não frágil (P4) deambulava sem auxílio. Resultados: Em relação à aceleração média, P1 e P4 apresentaram os menores e maiores valores, respectivamente, no eixo ântero-posterior; P4 teve o menor valor no eixo médio-lateral; e P3 apresentou o maior valor no eixo vertical. Todos os participantes apresentaram velocidade angular de rolagem semelhante; P4 apresentou a menor velocidade angular de pitch; e P1 e

P4 tiveram a maior velocidade angular média de guinada. Um participante sarcopênico (P2) exibiu a menor força de contração muscular. Conclusão: O dispositivo tem potencial para detectar marcadores de fragilidade para desfechos adversos em idosos, como instabilidade postural e aumento do risco de quedas.
Palavras-chave: Avaliação da tecnologia biomédica; Idoso fragilizado; Periféricos de computador; Equipamentos para diagnóstico.

Resumen
Introducción: El síndrome de fragilidad se caracteriza por la reducción de las reservas físicas y cognitivas, lo que hace que las personas mayores sean vulnerables a eventos adversos. Este estudio describe un prototipo de sistema sensor desarrollado para evaluar la fragilidad a través de parámetros fisiológicos y marcadores de fragilidad. Métodos: Se desarrolló y probó un prototipo que combinaba cuatro sensores en red y un paquete de software en cuatro residentes de la tercera edad de ambos sexos, de 60 años o más, que no presentaban síndrome locomotor ni deterioro cognitivo severo. Tres de ellos eran frágiles y podían caminar sin ayuda (P1), apoyándose en la pared (P2) o con un bastón (P3), y un participante no frágil (P4) caminaba sin ayuda. Resultados: En cuanto a la aceleración media, P1 y P4 presentaron los valores más bajos y más altos, respectivamente, en el eje anteroposterior; P4 tuvo el valor más bajo en el eje medio-lateral; y P3 presentó el mayor valor en el eje vertical. Todos los participantes mostraron una velocidad angular de balanceo similar; P4 presentó la menor velocidad angular de cabeceo; y P1 y P4 tenían la velocidad angular media de guiñada más alta. Un participante sarcopénico (P2) exhibió la menor fuerza de contracción muscular. Conclusión: El dispositivo tiene potencial para detectar marcadores de fragilidad para resultados adversos en personas mayores, como inestabilidad postural y mayor riesgo de caídas.
Palabras clave: Evaluación de la tecnología biomédica; Anciano frágil; Periféricos de computador; Equipo para diagnóstico.

1. Introduction

Frailty is a syndrome characterized by a decline in physical and cognitive functioning, making older people more vulnerable to falls, loss of independence, hospitalization, and death (McDermid et al., 2011, Schoon et al., 2021), Its prevalence ranges from 7.7% to 42.6% in Latin America and the Caribbean (Da Mata et al., 2016). The Fried frailty phenotype model focusses on the physical dimension of frailty (e.g., unintentional weight loss, fatigue, and reduction in handgrip strength, physical activity, and walking speed) and stratifies older adults as “non-frail”, “pre-frail” and “frail” based on the presence of sarcopenia and neuroendocrine and immunological changes (McDermid et al., 2011, Schoon et al., 2021, Fried et al., 2001, Mello et al., 2014). Frailty will put an enormous burden on older adults and their family caregivers including impaired quality of life, loneliness (Hoogendijk et al., 2019), and increased healthcare costs (Maresova et al., 2019).

Sarcopenia is a progressive, generalized muscle disorder characterized by decreased strength, mass and quality of muscles associated with increased risk of falls, fractures, physical disability, and death (Cruz-Jentoft et al., 2018). Dynapenia is related to reduced muscle strength resulting from changes in muscle contractile properties or neurologic function. Reduced muscle strength is the first clinical manifestation of frailty (Cruz-Jentoft et al., 2019, Iwamura & Kanauchi, 2017). Calf circumference has been used as a predictor of muscle quantity (Kawakami et al., 2015) and muscle function (Rolland et al., 2003, Landi et al., 2014).

The association between physical inactivity and frailty is well documented. Physical activity (PA) and physical fitness are inversely related to chronic disease and all-cause mortality, including frailty (Vavasour et al., 2021).

Heart rate variability (HRV) and blood pressure variability (BPV) have been utilized to assess the integrity of the autonomic nervous system (ANS) (Singh et al., 2006). Low HRV is associated with reduced physiological complexity and considered a marker of frailty, because deterioration in dynamic interactions among the physiological systems that regulate vital processes, including heart rate, may contribute to frailty (Chaves et al., 2008).

The timed up and go (TUG) test (Podsiadlo & Richardson, 1991) is a standardized clinical assessment tool of functional mobility and the time taken to complete the test has been shown to be a strong predictor of frailty outcomes (Chaves et al., 2008, Podsiadlo & Richardson, 1991). Accelerometers are low-cost instruments that have been used to assess balance and mobility (Podsiadlo & Richardson, 1991). Accelerometry patterns and classification algorithms have been used in the kinematic analysis of human movement for the identification of normal and pathological gait and can provide insight into TUG performance in older adults (Podsiadlo & Richardson, 1991).

Wearable sensors are an alternative to assess frailty. They have the benefit of objectivity, portability, reliability, and low cost, making them useful for assessing frailty at home and in the community, and may overcome the limitations of the Fried frailty phenotype model (Savva et al., 2013. Greene et al., 2014).

Wearable sensors are devices that incorporate various technologies capable of physiological, biomechanical and motion sensing. They can be incorporated into shoes and clothing, worn as pendants, attached to the wrist, ankle or trunk, or carried in a pocket. Wireless inertial units are the most commonly used sensors in wearable systems. In the form of accelerometers, gyroscopes, pedometers or heart-rate monitors, wearable sensors have the capacity to measure activity frequency, duration and intensity. Accelerometers measure linear acceleration in real time and can detect movement in up to 3 planes, i.e. vertical, anteroposterior and medio-lateral. Pedometers measure the number of steps taken and correlate well with uni-axial accelerometers. Gyroscopes measure changes in orientation such as rotational or angular velocity, acceleration or displacement. Heart rate monitors are one type of sensor among others capable of capturing indications of physical activities that do not require trunk displacement and can be used to indicate energy expenditure and PA behaviours e.g. sedentary time (Zampogna et al., 2020).

Monitoring older adults' behavioral changes could provide insight into how frailty develops. Assessing these changes in real life may help identify frailty early. Technologies may offer cost-effective opportunities for assessing frailty in older adults' real lives, such as home environments. Recent developments in sensor technologies for health monitoring have shown opportunities to monitor frailty signs at home. Wearable sensors from different manufacturers (e.g., BioSensics, Newton, MA, USA; Shimmer, Dublin, Ireland; Actibelt, Munich, Germany) were used to measure frailty criteria such as muscle strength, gait, and physical activities. Most existing systems focused on a single dimension of the multidimensional frailty and only on homogenous sensors such as wearables. Moreover, while Internet connectivity and remote access should become an essential design requirement for remote health monitoring systems, most existing systems for assessing frailty lack telecommunication capability, making the systems not convenient or scalable for real-life home deployment. Modern technologies such as the Internet of Things (IoT) and Cloud Computing have demonstrated their capabilities to overcome the remote access barrier in many health care applications (e.g., telemedicine, medical imaging, public health, and patient self-management) (Bian et al., 2022).

The aim of this study was to develop and test a prototype sensor system for assessing frailty through the measurement of physiological parameters and analysis of frailty markers.

2. Methods

This cross-sectional study was approved by the Research Ethics Committee of the Universidade do Vale do Sapucai (approval number 2.016.179) and performed in accordance with the ethical standards of the 1964 World Medical Association Declaration of Helsinki and its subsequent amendments. Written informed consent was obtained from all patients or their representatives prior to participation.

A low-cost prototype of a multifunctional sensor system was developed in partnership with the Universidade Federal de Itajubá and tested in older adults. It combines a 3-axis gyroscope, 3-axis accelerometer, load sensor, temperature sensor, heart rate sensor, and pulse oximeter for the assessment of movement quality, energy expenditure, gait speed, balance, quality of muscle contraction, and variability in pulse oximetry and HRV during physical activity. A pilot clinical study was performed to test the integration of the different components of the prototype and assess frailty in older adults. Data were collected and analyzed by custom software.

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The developed prototype sensor system was tested in a convenience sample of older adults. The inclusion criteria were long-term care facility (LTCF) residents of both sexes, 60 years of age or older, able to walk independently with or without walking aid, who agreed to participate in the study. Exclusion criteria were locomotive syndrome and severe cognitive impairment.

The 30-item Mini-Mental State Examination (MMSE) was used to detect cognitive impairment among selected candidates (Moraes & Moraes, 2010). The total MMSE score ranges from 0 to 30, with a cutoff score of 18 or less indicating cognitive impairment among illiterate or low-educated older adults, and a cutoff score of 26 or less indicating cognitive impairment among those with 8 years or more of education (Moraes & Moraes, 2010).

The Self-Reported Assessment of Frailty (SRAF) (Nunes et al., 2015) was applied at inclusion to measure frailty among study participants.

Calf circumference was measured with a flexible, non-stretch tape measure (Rolland et al., 2003, Landi et al., 2014).

2.1 Testing the prototype sensor system

The device was fixed on the quadriceps of the participant. The participants performed the TUG test and the six-minute walk test (6MWT), and were allowed to use walking aid devices during the tests, if necessary (Fleg et al., 2005. ATS, 2002). The parameters were measured by the prototype sensor system and captured in real time via WiFi.

The TUG test was selected because it is easy to perform, has shown excellent reliability and reproducibility, and is considered a strong predictor of frailty outcomes among older people (Podsiadlo & Richardson, 1991, Savva, 2013, Greene et al., 2014). Each participant was asked to safely perform the TUG test as rapidly as possible, by getting up from a chair, walking three meters, turning around, walking back to the chair, and sitting down (Podsiadlo & Richardson, 1991, Savva, 2013, Greene et al., 2014).

The participants were stratified into three categories, according to the time required for them to complete the TUG test: up to 10 seconds; 11-20 seconds, and above 20 seconds. Gait speed, energy expenditure, balance, and force of muscle contraction (FMC) were measured during the TUG test.

The 6MWT has been used to assess functional status and as a predictor of morbidity and mortality in patients with cardiopulmonary disease (ATS, 2002). The test measured the distance that a participant was able to walk in a hallway with a flat, hard floor in a period of 6 minutes. The participants were allowed to stop and rest during the test or interrupt the test due to exhaustion or any other reason. HRV and pulse oximetry were also evaluated during the 6MWT.

2.2 Statistical analysis

Descriptive analysis was conducted to determine mean, median, and standard deviation (SD) for continuous variables, and frequencies and proportions for categorical variables.

Statistical analysis was performed using the Coefficient of Variation (CV) and Spearman's correlation coefficient (r).

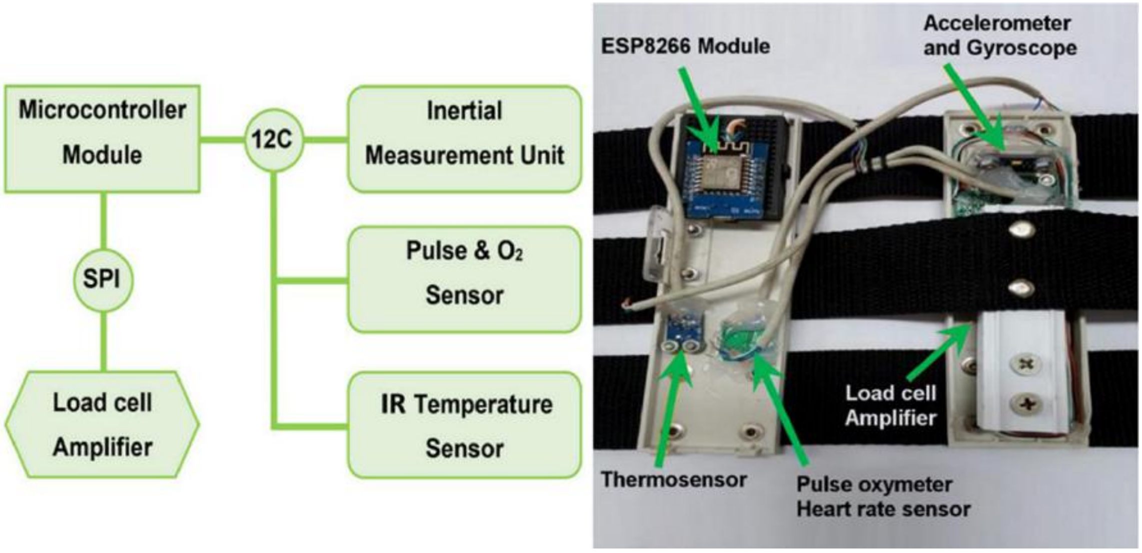
Spearman's correlation coefficient ranges from -1 to +1. A correlation coefficient of zero indicates that no correlation exists between two continuous variables. The strength of the correlation ($|r|$) was classified as very weak (0 to 0.29), weak (0.3 to 0.49), moderate (0.5 to 0.69), strong (0.7 to 0.89), and very strong (≥ 0.9).

There was no external funding for this study.

3. Results

A prototype of a wearable sensor system was developed for the assessment of physiological parameters. The device combines four sensors in network, including the MPU6050, a motion sensor composed of a 3-axis accelerometer and a 3-axis gyroscope; the MAX30100, a pulse oximeter and heart rate sensor, which can be connected to any part of the body that has an underlying artery; the HX711, a load cell amplifier for assessing FMC; and the MLX90614, an infrared temperature sensor. The integrated sensor network is connected to an ESP8266 microcontroller module, which transmits the collected data in real time via WiFi to a computer for data analysis. A diagram of the multifunctional sensor system and anterior view of the developed prototype device are shown in Figure 1.

Figure 1 - Diagram of the prototype sensor system (left) and anterior view of the developed prototype device (right). ESP8266, microcontroller module; Inertial measurement unit, featuring a 3-axis accelerometer and a 3-axis gyroscope; Pulse & O2, pulse oximeter and heart rate sensor; Thermosensor, infrared (IR) temperature sensor; I2C, inter-integrated circuits communication protocol; SPI, serial peripheral interface.



Fonte: Carlos Minoru Tamaki e Alexandre Carlos Brandão Ramos.

The inter-integrated circuits (I2C) communication protocol was used to transfer information between the microcontroller and multiple integrated circuits. A serial peripheral interface (SPI) was used for communication between the microcontroller and the load cell amplifier.

The prototype was tested with four sedentary LTCF residents (P1-P4) and placed in the medial thigh region for data collection. The sample included three women (P1-P3) and one man (P4); the mean age was 73 years (SD, 8.04; range, 68-85) and all participants had incomplete primary education. Three of them were frail and able to walk without aid (P1), holding onto the wall (P2), or with a cane (P3), and another (P4) was non-frail and able to walk without aid.

The 6MWT was performed by two participants (P1 and P4) because the other two (P2 and P3) had clinical problems. Only P4 completed the 6MWT, whereas P1 interrupted the test after 4 minutes because of knee pain.

The TUG test was performed by all participants. Raw sensor readings of acceleration, angular velocity, body temperature, and FMC for each participant are shown in Table 1. Participants P1 and P4 had the lowest and highest mean acceleration in the antero-posterior axis (X-axis), respectively; P4 showed the lowest value in the medio-lateral axis (Y-axis); and P3 presented the highest value in the vertical axis (Z-axis) (Table 1). All participants showed similar roll (X-axis) angular velocity; P4 presented the lowest pitch (Y-axis) angular velocity; and P1 and P4 had the highest mean yaw (Z-axis) angular velocity (Table 1). A sarcopenic participant (P2) exhibited the lowest FMC (Table 1).

Table 1 - Raw sensor readings of acceleration, angular velocity, body temperature, and force of muscle contraction obtained using the prototype sensor system.

P#	Variables	N	Mean	Median	SD	Min	Max	CV
P1	Acceleration							
	Antero-posterior (X-axis)	250	25837.9	13484.0	27400.3	36.0	65528.0	106.0
	Medio-lateral (Y-axis)	250	58813.6	59774.0	7456.9	448.0	65028.0	12.6
	Vertical (Z-axis)	250	14454.7	16158.0	4498.8	3456.0	22464.0	31.1
	Angular velocity							
	Roll (X-axis)	250	37128.1	61546.0	30986.1	0.0	65503.0	83.4
	Pitch (Y-axis)	250	24290.4	4609.0	28284.7	27.0	65500.0	116.4
	Yaw (Z-axis)	250	35177.5	55362.5	29470.8	11.0	65535.0	83.7
	Initial body temperature (°C)	250	32.1	32.1	0	32.0	32.1	0
	Final body temperature (°C)	250	32.1	32.1	0.1	32.6	32.9	0.2
	FMC	153	174.8	105.7	166.5	0	606.4	95.2
P2	Acceleration (m/s2)							
	Antero-posterior (X-axis)	128	28114.9	13664.0	27432.9	40.0	65516.0	97.5
	Medio-lateral (Y-axis)	128	56113.8	59956.0	13631.4	448.0	65288.0	24.2
	Vertical (Z-axis)	128	15463.9	16656.0	5731.2	520.0	32767.0	37.0
	Angular velocity (°/s2)							
	Roll (X-axis)	128	33109.5	55336.0	29947.6	142.0	65336.0	90.4
	Pitch (Y-axis)	128	31024.9	11875.0	27788.6	275.0	65418.0	89.5
	Yaw (Z-axis)	128	28926.9	12166.5	27544.2	179.0	65535.0	95.2
	Initial body temperature (°C)	128	32.3	32.3	0	32.3	32.4	0
	Final body temperature (°C)	128	33.3	33.3	0	33.1	33.6	0.2
	FMC	17	87.8	90.28	37.3	0	139.6	42.4
P3	Acceleration							
	Antero-posterior (X-axis)	279	28891.6	13032.0	29238.8	8.0	65520.0	101.2
	Medio-lateral (Y-axis)	279	60123.5	61052.0	8078.0	340.0	65480.0	13.4
	Vertical (Z-axis)	279	16185.6	16868.0	3426.7	6500.0	32028.0	21.1
	Angular velocity							
	Roll (X-axis)	279	33058.4	60610.0	31355.9	3.0	65480.0	94.8
	Pitch (Y-axis)	279	27000.8	5015.0	29146.9	103.0	65501.0	107.9
	Yaw (Z-axis)	279	31291.6	10594.0	29346.5	20.0	65525.0	93.7
	Initial body temperature (°C)	279	32.0	32.0	0	31.9	32.0	0
	Final body temperature (°C)	279	33.4	33.4	0	33.2	33.6	0.2
	FMC	38	187.82	175.12	136.423	0.00	375.2	72.6
P4	Acceleration							
	Antero-posterior (X-axis)	394	31128.9	15112.0	27825.9	28.0	65496.0	89.3
	Medio-lateral (Y-axis)	394	54446.1	61846.0	19852.2	52.0	65524.0	36.4
	Vertical (Z-axis)	394	15322.4	17136.0	5209.4	2688.0	32767.0	34.0
	Angular velocity							
	Roll (X-axis)	394	32856.5	57597.5	31188.8	3.0	65535.0	94.9
	Pitch (Y-axis)	394	21526.1	3922.5	27789.5	14.0	65438.0	129.1
	Yaw (Z-axis)	394	37046.3	58034.5	29185.0	4.0	65490.0	78.7
	Initial body temperature (°C)	394	32.8	32.8	0	32.7	32.9	0
	Final body temperature (°C)	394	34.6	34.6	0.2	34.0	37.1	0.3
	FMC	227	177.0	122.1	170.6	0	724.3	96.3

P#, participant number; N, number of readings; SD, standard deviation; Min, minimum value; Max, maximum value; CV, coefficient of variation; FMC, force of muscle contraction. Source: Authors.

The distribution of mean raw sensor readings of acceleration, angular velocity, body temperature, and FMC according to occurrence of falls, time taken to complete the TUG test, variation in body temperature, and calf circumference are seen in Table 2.

Table 2 - Distribution of mean raw sensor readings of acceleration, angular velocity, body temperature, and force of muscle contraction, according to participants' characteristics (n=4).

Variables	Falls in the last 12 months					
	Yes			No		
	N (P3)	Mean	SD	N (P1, P2, P4)	Mean	SD
Acceleration						
Antero-posterior	1	28891.6	-	3	28360.5	2654.03
Medio-lateral	1	60123.5	-	3	56457.8	2203.9
Vertical	1	16185.6	-	3	15080.3	546.4
Angular velocity						
Roll	1	33058.4	-	3	34364.7	2396.5
Pitch	1	27000.8	-	3	25613.8	4885.7
Yaw	1	31291.6	-	3	33716.9	4252.1
Initial body temperature (°C)	1	32.0	-	3	32.4	0.4
Final body temperature (°C)	1	33.4	-	3	33.6	0.9
FMC	1	187.8	-	3	146.5	50.8

	Time taken to complete the TUG test								
	Up to 10 s			11-20 s			> 20 s		
	N (P2)	Mean	SD	N (P1)	Mean	SD	N (P3, P4)	Mean	SD
Acceleration									
Antero-posterior	1	28114.9	-	1	25837.9	.	2	30010.3	1581.9
Medio-lateral	1	56113.8	-	1	58813.6	.	2	57284.8	4014.5
Vertical	1	15463.9	-	1	14454.7	.	2	15754.0	610.3
Angular velocity									
Roll	1	33109.5	-	1	37128.1	.	2	32957.4	142.8
Pitch	1	31024.	-	1	24290.4	.	2	24263.4	3871.2
Yaw	1	2896.9	-	1	35177.5	.	2	34169.0	4069.1
Initial body temperature (°C)	1	32.3	-	1	32.0	.	2	32.4	0.6
Final body temperature (°C)	1	33.3	-	1	32.7	.	2	34.0	0.8
FMC	1	87.8	-	1	174.8	.	2	182.4	7.5

	Variation between Initial and Final Body Temperatures					
	N (P4)	Mean	SD	N (P1, P2, P3)	Mean	SD
Acceleration						
Antero-posterior	1	31128.9	-	3	27614.8	1587.1
Medio-lateral	1	54446.1	-	3	58350.3	2044.5
Vertical	1	15322.4	-	3	15368.1	869.4
Angular velocity						
Roll	1	32856.5	-	3	34432.0	2335.0
Pitch	1	21526.2	-	3	27438.7	3388.5
Yaw	1	37046.3	-	3	31798.7	3155.9
Initial body temperature (°C)	1	32.8	-	3	32.1	0.1
Final body temperature (°C)	1	34.6	-	3	33.2	0.3
FMC	1	177.1	-	3	150.1	54.3

	Calf circumference					
	< 31 cm			> 31 cm		
	N (P4)	Mean	SD	N (P1, P2, P3)	Mean	SD
Acceleration						
Antero-posterior	1	31128.9	-	3	27614.8	1587.1
Medio-lateral	1	54446.1	-	3	58350.3	2044.5
Vertical	1	15322.4	-	3	15368.1	869.4
Angular velocity						
Roll	1	32856.5	-	3	34432.0	2335.0
Pitch	1	21526.1	-	3	27438.7	3388.5
Yaw	1	37046.3	-	3	31798.7	3155.9
Initial body temperature (°C)	1	32.8	-	3	32.1	0.1
Final body temperature (°C)	1	34.6	-	3	33.2	0.3
FMC	1	177.1	-	3	150.1	54.3

SD, standard deviation; TUG, timed up and go test; P1, P2, P3, participants number 1, 2, 3 (women); P4, participant number 4 (man); Acceleration: antero-posterior (X-axis), medio-lateral (Y-axis), and vertical (Z-axis); Angular velocity: roll (X-axis), pitch (Y-axis), and yaw (Z-axis); FMC, force of muscle contraction. Source: Authors.

The older adult faller (P3) exhibited the highest mean acceleration in the medio-lateral and vertical axes, a high angular velocity in the pitch axis, and the highest FMC (Table 2). She had a tendency to oscillate to the left and in the vertical axis, resulting in postural instability.

Correlations among mean parameter values are shown in Table 3.

Table 3 - Correlations of mean MMSE scores, SRAF scores, acceleration and angular velocity on the three axes, body temperature, and muscle strength (n = 4).

Variables (n = 4)		MMSE Scores	SRAF Scores	Acceleration (α) X-axis	Acceleration (α) Y-axis	Acceleration (α) Z-axis	Angular velocity (ω) X-axis	Angular velocity (ω) Y-axis	Angular velocity (ω) Z-axis	Body Temp.	FMC
MEEM scores	r	1.000	-0.211	-0.800*	0.800*	-0.200	0.800*	0.200	-0.200	-0.800*	0.000
SRAF scores	r	-0.211	1.000	0.738*	0.105	0.211	-0.738*	-0.632	0.632	0.738*	0.949*
α (X-axis)	r	-0.800*	0.738*	1.000	-0.400	0.400	-1.000**	-0.400	0.400	1.000**	0.600
α (Y-axis)	r	0.800*	0.105	-0.400	1.000	0.400	0.400	0.400	-0.400	-0.400	0.400
α (Z-axis)	r	-0.200	0.211	0.400	0.400	1.000	-0.400	0.600	-0.600	0.400	0.400
ω (X-axis)	r	0.800*	-0.738*	-1.000**	0.400	-0.400	1.000	0.400	-0.400	-1.000**	-0.600
ω (Y-axis)	r	0.200	-0.632	-0.400	0.400	0.600	0.400	1.000	-1.000**	-0.400	-0.400
ω (Z-axis)	r	-0.200	0.632	0.400	-0.400	-0.600	-0.400	-1.000**	1.000	0.400	0.400
Body Temp.	r	-0.800*	0.738*	1.000**	-0.400	0.400	-1.000**	-0.400	0.400	1.000	0.600
FMC	r	0.000	0.949*	0.600	0.400	0.400	-0.600	-0.400	0.400	0.600	1.000

r, Spearman's rank correlation coefficient; * Correlation is significant at the 0.05 level (2-tailed); **, Correlation is significant at the 0.01 level (2-tailed).
MMSE, Mini-Mental State Examination; SRAF, Self-Reported Assessment of Frailty; α, Acceleration: X-axis (antero-posterior axis), Y-axis (medio-lateral axis), and Z-axis (vertical axis); ω, Angular velocity: X-axis (roll axis), Y-axis (pitch axis), and Z-axis (yaw axis); Body Temp, body temperature; FMC, force of muscle contraction. Source: Authors.

Strong negative correlations were found between MMSE scores and acceleration in the antero-posterior axis and body temperature, suggesting that the higher the cognitive performance, the lower the body temperature during physical activity (Table 3).

The HRV and pulse oximetry values were within normal limits, indicating that the prototype device effectively measured these parameters.

4. Discussion

A prototype of a multifunctional sensor system was built to measure cardiovascular parameters, quality of movement, gait speed, balance, and FMC. Increase in body temperature during physical activity was used as an indirect estimate of energy expenditure.

Pre-frail older adults show decreased walking activity and an increased percentage of sitting compared to those categorized as non-frail. Increased duration in walking episodes may be a predictor of falls among frail and pre-frail individuals.

Our results showed that the better the cognitive function, the lower the body temperature/energy expenditure during acceleration, and the higher the gait speed. Gait speed is an important predictor of survival in older people (ATS, 2002). Walking depends on movement control, energy availability, and cardiovascular, pulmonary, neuromuscular function. A low gait speed may be associated with ANS dysfunction and high energy expenditure (Studenski et al., 2010).

No correlation was observed between MMSE scores and FMC. However, a meta-analysis showed a positive correlation between sarcopenia and cognitive impairment (Chang et al., 2016).

SRSF scores had a strong positive correlation with FMC. The older adult faller (P3) had the highest mean FMC. The sarcopenic patient (P2) had the smallest calf circumference (< 31 cm). Increased FMC may be associated with reduced muscle mass and may be an indicator of dynapenia, an early marker of frailty. Dynapenia has been reported as a better predictor of disability and death compared to sarcopenia alone (Chang et al., 2016).

Measurements of gait speed and balance during the TUG obtained by inertial sensors were associated with frailty. This simple assessment of frailty is effective, rapidly performed, and may be conducted by generalists (Greene et al., 2014).

The older adult faller (P3) exhibited the highest mean acceleration in the medio-lateral and vertical directions, a high pitch angular velocity, and the highest FMC. The motion parameters indicated that the participant had a tendency to oscillate to the left and in the vertical axis, presenting postural instability and increased risk of falling.

There is a strong bidirectional association between cardiovascular disease and frailty with a stepwise response seen from robust to frail. Prefrailty and frailty are independently associated with a higher risk of developing major adverse cardiovascular outcomes and frailty can predict adverse geriatric outcomes including physical and cognitive decline, impaired mobility, and inability to perform activities of daily living (Ijaz et al., 2022).

The non-frail participant (P4) exhibited a higher HRV compared to a frail older adult (P1), which is consistent with the literature (Landi et al., 2014). The assessment of HRV in older adults is essential in determining the cardiopulmonary aspects of frailty (Landi et al., 2014).

It was observed that P1 had a cautious gait and the lowest acceleration, whereas P4 showed an atypical gait and the highest acceleration in the antero-posterior axis. The participant P4, who was tall and slim, had also the lowest mean and the highest median acceleration in the medio-lateral axis, with low tendency to gait oscillation and long strides.

The non-frail participant (P4) also presented the lowest mean and median pitch angular velocity, which is indicative of body balance, whereas the frail older adult (P2), who had sarcopenia (calf circumference < 31 cm) showed the highest mean and median values, indicating increased risk of falls.

The participants P2 and P3, who were able to walk holding onto the wall and with a cane, respectively, had the lowest mean and median values on yaw angular velocity. Older people who use walking aid devices may have reduced rotation in the yaw axis and be at risk of falls.

A study on the use of the 6MWT as a measure of frailty showed that the distance covered during the test allowed the categorization of participants as frail, pre-frail, and non-frail, indicating the usefulness of the sensor system, as the one developed here, may provide important additional information, including measurements of cardiovascular parameters, when applying the 6MWT (Boxer et al., 2008).

Technologies measuring new criteria of physical frailty such as muscle, weight, and exhaustion, or measuring the same gait criteria but used a different way than extant literature, could be a future research area for assessing physical frailty (Bian et al., 2020).

Recently, study presented the design, development, and validation of a sensor-based toolkit for assessing frailty in home settings. The toolkit's design focused on ambient sensing of behavioral and physical signs of frailty using different ambient sensors, a smart speaker, and a smart weight scale. The prototype of the toolkit was deployed and tested in a simulated home lab. Statistical analysis of sensor data showed excellent concurrent validity for the ambient sensors and the smart speaker (Bian et al., 2022).

Multifunctional sensor systems can be used in combination with validated assessment instruments for older people, resulting in new interventions to prevent the negative impact of frailty syndrome on healthy aging (Mello et al., 2018). The prototype of the multifunctional sensor system developed in this study has the benefit of objectivity and portability, and to the best of our knowledge, no other wearable sensor system combining the same features in a single device has been described in the literature.

The small sample size was the major limitation of this pilot study. Further studies with a larger number of participants are necessary for calibration of the device and to determine cutoff values for the different parameters, allowing differentiation of frailty phenotypes among older adults.

5. Conclusion

The prototype of a wearable multifunctional sensor system was developed by combining four sensors in network for the simultaneous assessment of multiple physiological parameters, including HRV, pulse oximetry, body temperature, gait speed and balance, and FMC. Correlations among data on different parameters suggested that the device has potential to detect frailty markers for adverse outcomes in older people, such as postural instability and increased risk of falls. Further studies are warranted to investigate possible clinical applications to this instrument.

After completion of its final version, validation in a larger cohort, and creation of appropriate protocols, the multifunctional sensor system may be used by health professionals to assess frailty in older adults and be able to design and evaluate interventions to improve or maintain their physical functioning and quality of life. The device may also be useful to assess individuals with neurodegenerative diseases, physical conditioning in patients with cardiopulmonary diseases, physical activity and fitness in children and adults, and athletic performance.

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