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REVIEW

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How wearable sensors have been utilised to evaluate frailty in older adults: a systematic review

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Abstract

Background: Globally the population of older adults is increasing. It is estimated that by 2050 the number of adults over the age of 60 will represent over 21% of the world's population. Frailty is a clinical condition associated with ageing resulting in an increase in adverse outcomes. It is considered the greatest challenge facing an ageing population affecting an estimated 16% of community-dwelling populations worldwide.

Aim: The aim of this systematic review is to explore how wearable sensors have been used to assess frailty in older adults.

Method: Electronic databases Medline, Science Direct, Scopus, and CINAHL were systematically searched March 2020 and November 2020. A search constraint of articles published in English, between January 2010 and November 2020 was applied. Papers included were primary observational studies involving; older adults aged > 60 years, used a wearable sensor to provide quantitative measurements of physical activity (PA) or mobility and a measure of frailty. Studies were excluded if they used non-wearable sensors for outcome measurement or outlined an algorithm or application development exclusively. The methodological quality of the selected studies was assessed using the Appraisal Tool for Cross-sectional Studies (AXIS).

Results: Twenty-nine studies examining the use of wearable sensors to assess and discriminate between stages of frailty in older adults were included. Thirteen different body-worn sensors were used in eight different body-locations. Participants were community-dwelling older adults. Studies were performed in home, laboratory or hospital settings. Postural transitions, number of steps, percentage of time in PA and intensity of PA together were the most frequently measured parameters followed closely by gait speed. All but one study demonstrated an association between PA and level of frailty. All reports of gait speed indicate correlation with frailty.

Conclusions: Wearable sensors have been successfully used to evaluate frailty in older adults. Further research is needed to identify a feasible, user-friendly device and body-location that can be used to identify signs of pre-frailty in community-dwelling older adults. This would facilitate early identification and targeted intervention to reduce the burden of frailty in an ageing population.

Keywords: Wearable sensor, Frailty, Older adults, Physical Activity, Mobility

Introduction

Globally the population of older adults is increasing. It is estimated that by 2050 the number of adults over the age of 60 will have almost doubled, representing over 21% of the world's population [1]. This has huge implications

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for society not least because of the increase in physical decline and chronic illness associated with ageing.

Frailty is a clinical condition associated with ageing, characterised by multi-system decline resulting in an increase in adverse outcomes such as falls, hospitalisation, institutionalisation and mortality [2]. Fried's Frailty Phenotype (FFP) [2], the most commonly used frailty assessment tool [3] defines frailty as the presence of three or more of the five identified phenotypes; sarcopaenia, weakness as demonstrated by reduced grip-strength and slow gait-speed, fatigue and reduced level of activity [2]. It is considered the greatest challenge facing an ageing population [4, 5] affecting an estimated 16% of community-dwelling populations worldwide [6] and 21.5% of over 65's in Ireland [5]. Frailty is associated with, but is not an inevitable part of ageing and it is thought to be transitional. Research suggests that with intervention people can transition between stages of frailty, from pre-frail (PF) to robust or non-frail (NF) and albeit to a lesser extent, from frail (F) to robust [7, 8]. Robust or NF is defined as the absence of phenotypes while PF, considered the prodromal stage of frailty is defined as the presence of one or two phenotypes [2].

The association between physical inactivity and frailty is well documented [9–13]. Physical activity (PA) and physical fitness are inversely related to chronic disease and all-cause mortality, including frailty [14]. As a result, the World Health Organisation has developed guidelines and an action plan to promote PA, healthy ageing and reduce functional decline, with the view to reducing the burden of sequelae of inactivity on both the individual and the health system [15]. More recent guidelines include advice on reducing sedentary time [16]. It is thought however, that only one in four adults over the age of 18 meet guidelines for minimum activity levels [15]. Results for older adults (> 65 years of age) meeting the recommendations varies from zero [11] to between 15% [17] and 87% [18].

Traditionally, measurement of mobility and PA has relied on the use of self-reported questionnaires, surveys or diaries, or direct observation of physical performance tests, each with inherent difficulties and limitations. While these methods can be cost-effective and simple to administer they carry a risk of bias from recall, desire to perform better and participant reactivity, a well-recognised phenomenon of behaviour change due to the awareness of being observed [19].

Recent advances in technology provide the opportunity for objective measurement of mobility and PA through the use of wearable sensors. This allows for unbiased examination of PA patterns and behaviours which can inform guidelines and promote more widespread participation [11, 20, 21]. 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 [22]. 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, antero-posterior and medio-lateral. Pedometers measure the number of steps taken and correlate well with uni-axial accelerometers [23]. 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 [24].

Considering the increasing population of older adults, ninety-five percent of who are community-dwelling [25], identifying a way for individuals to independently and objectively monitor their risk of developing frailty is vital. Earlier reviews have reported on the use of wearable sensors in relation to gait analysis [26], falls risk [27], rehabilitation [28] and levels of PA in hospitalised frail elderly [29] and community-dwelling older adults [21]. The aim of this systematic review is to examine the literature to explore how wearable sensors have been used to identify frailty and pre-frailty in older adults and compare with a traditional frailty classification tool. Specifically it aims to discern which parameters of mobility and PA obtained from wearable sensors have been best used to quantify frailty in older adults, the type of body-worn sensors used to provide these parameters, the sensor-placement used and how the parameters of mobility and PA are associated with the discrimination of frailty stages.

Methods

Search strategy

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [30] and is registered with the International prospective register of systematic reviews (PROSPERO) (registration number CRD42020163082). Using the PICO framework (Population, Intervention, Comparator and Outcome) to develop search terms, one investigator searched the electronic databases MEDLINE, Science Direct, Scopus, and CINAHL as per previous reviews [7, 21, 31]. The search was carried out in March 2020 and updated November 24th, 2020 to ensure all recently published articles meeting the criteria were included. The search strategy was developed in consultation with a librarian. The complete search strategy used in MEDLINE and adapted to the other electronic sources is shown in Appendix 1. Reference lists of eligible papers were manually searched for additional studies.

Study selection

Papers were selected if they were available in English and met the following criteria: Primary observational studies, performed in a laboratory, clinical or free-living (home/community) environment; Recruited older adults > 60 years of age; Involved the use of any consumer, research or medical-grade wearable sensor to provide quantitative measurements of mobility and/or PA, and included a standardised frailty classification tool.

Studies were excluded if they used non-wearable sensors (e.g. ambient sensor) for outcome measurement, or outlined mobility/PA algorithm or application development exclusively.

Titles and abstracts were screened by one investigator. Full texts of studies identified by this review were screened for eligibility by three investigators independently. Consensus was reached through discussion.

Data extraction

Data extracted from each study included first author, year of publication, number of participants and age profile, study setting, wearable sensor used; make, model and manufacturer, study objectives and methods, parameters of PA/ Mobility measured, frailty measure, reported findings and their statistical analysis. The methodological quality of the selected studies was assessed using the Appraisal Tool for Cross-sectional Studies (AXIS) [32].

Analysis

Due to the heterogeneity of the study methodology, methods of analysis and outcomes reported, a meta-analyses was not possible for this review.

Results

Literature search

The initial search identified 376 papers published since 2010. Following screening of titles and abstracts and removal of duplicates, 35 articles were deemed appropriate for full text screening. Five further articles were identified from manual search of references of eligible studies. One paper [33] was published after the updated search but was included when discovered incidentally. Of the 40 articles reviewed, 11 were excluded (See Appendix 2). The remaining 29 were included in the review (Table 1). Figure 1 outlines the selection process.

Study characteristics

All studies included in the review were either validation (< 25%) or observational cross-section design. One study [17] was a mixed methods design but only the objective quantitative results were included in the report. The studies were carried out in varying settings; home: n = 14 [11, 17, 24, 34–44], laboratory: n = 8 [42, 45–51], hospital: in-patient n = 2 [52, 53], out-patient n = 2 [34, 54], community centre n = 1 [55] and not specified: n = 4 [33, 56–58]. Participant numbers ranged from n = 30 to n = 718. Criteria of frailty classification included Fried's Frailty Phenotype (n = 19) [17, 33, 34, 38–41, 43–47, 49–51, 54, 56–58], modified Frailty Phenotype (n = 3) [35, 36, 55], Rockwood's Frailty Index (n = 2) [24, 48] Trauma-Specific FI (n = 2) [52, 53], Identification Seniors At Risk-Hospitalized Patients' questionnaire (ISAR-HP) (n = 1) [11] and Tilburg Frailty Indicator (n = 1) [42].

Of the studies included, 13 different body-worn sensors were used in eight different body-locations. Details of sensors are provided in Table 2. One study used an iPhone as a body-worn sensor by affixing to the chest and was thus included in the study, data from which is presented in two separate articles [47, 51]. Sensor placement included the lumbar spine (LSp) (n = 8), chest (n = 7), shin/ankle (n = 7), wrist and upper-limb combination (n = 3), wrist (n = 2), waist (n = 3), hip (n = 3), thigh (n = 3), foot (n = 1) and not specified (n = 3). Nineteen studies used just one body location [11, 17, 34–37, 40–42, 45–48, 50, 51, 54–56, 58], three studies, measuring elbow kinetics specifically, used a combination of above elbow and wrist [39, 52, 53] while six others used multiple body-locations of LSp and shin [57], and chest, LSp, thigh, shin and foot [24, 33, 38, 43, 49].

Seven different measures of mobility and PA were reported. Mobility measures included temporal-spatial gait parameters of speed, total steps, double support, stride length, time and variability [24, 33, 38, 47, 49, 50, 54, 56], postural transitions: acceleration counts of sit to stand (STS), stand to walk, stand to sit [24, 40, 41, 46, 48, 49, 58], trunk angular velocity [47, 50], upper limb kinematics [39, 52, 53], intensity of PA and percentage of time in walking, standing, sitting and lying [11, 17, 24, 35–38, 40–43, 55]. Two studies examined PA intensity with the aim to objectively define and compare with the low PA criterion of a frailty classification tool [34, 44]. Balance parameters included sway of ankle, hip and centre of mass [30, 36, 41, 24] and chair-stand kinematics including number of STS cycles, acceleration and trunk displacement [46, 48, 49, 58].

Table 1 Data extraction

Lead Author	Population, Frailty Classification, Setting	Objectives and Methods	Sensor and Location	Measure of Mobility / PA	Reported Findings
Martinez-Ramirez (2011) (45)	N=56 community dwelling or assisted living volunteers (28 male, 28 female). FFP; 14 F (age: 79±4 years), 18 PF (age: 80±3 years), 24 NF (age: 40±3 years). Laboratory	To examine signals from a tri-axial sensor during quiet standing balance tests in a frail, pre-frail and healthy population. Participants were monitored during 10 s of quiet standing under 4 different conditions: FTO, FTC, FSO, FSC	MTx XSENS worn on lumbar spine (L3).	Postural sway (s)	Postural sway showed no significant differences among groups (NF, PF, F) under all conditions p > 0.05 Frail group showed greater values in FTC p < 0.018 compared with NF, PF.
Theou (2012). (24)	N = 50 community dwelling female volunteers (age range: 63-90 years). FI (Deficit model); 17 high frailty tertile, 17 moderate frailty tertile, 16 low frailty tertile. Home	To examine the association of frailty with 5 PA assessment tools and determine if PA is different across levels of frailty. Participants wore all sensors simultaneously during normal daily activities at home for 10 hours. Maximum voluntary exertions of Vastus Lateralis (VL) and Biceps Brachii (BB) were performed. A PA questionnaire was also administered.	ActiTrainer worn at the waist. Polar WearLink HR monitor at the chest. Garmin forerunner405 GPS at the wrist. Biometrics DataLOG P3X8 EMG on VL and BB.	Acceleration counts (n) Gait speed (m/s) Total step count (n) Time in non-sedentary activity (counts/min) Bursts of VL & BB	The FI was most significantly correlated with accelerometer **Parameter** / **r value** / **p value** **PA Minutes** -0.617 p<0.01 **MLTAQ** -0.603 p<0.01
Millor (2013) (46)	N = 47 community dwelling or assisted living volunteers (26 male, 21 female). FFP; 13 F (age: 85±5 years), 16 PF (age: 78±3 years), 18 NF (age: 54±6 years). Laboratory.	To obtain kinematic measurements from 30 second chair sit to stand (CST) that can identify frailty. Participants were instructed to stand up and sit down from a standardised chair at their preferred speed as many times as possible within 30 seconds.	MTx XSENS worn on lumbar spine (L3).	Chair kinematics: Postural sway (s). Acceleration of STS (m/s^2). Velocity (m/s) in vertical (Z) and AP (Y). No. of cycles of CST (n) Impulse phase duration (s).	Healthy participants performed a significantly greater n of STS cycles compared with PF and F. F participants had greater sway than PF or Healthy Velocity of STS showed significantly greater values among PF compared with F Acceleration of STS and St-Si differentiated between PF and F (p ≤ 0.001) **Parameter** / **NF** / **PF** / **F** / **p value** **STS (n)** 22±7 15±5 6±1 p ≤ 0.001 **Sway (s)** 5 15 30 P < 0.001 **Z Velocity of STS (m/s)** 0.8 0.5
Galan-Mercant (2013) (51)	N = 30 volunteers aged > 65 years. Dwelling not specified. FFP; 14 F (age: 83.72±6.37 years), 16 NF (age: 70.25±3.32 years). Laboratory	To measure and describe variability in 3D acceleration, angular velocity and trunk displacement during the STS and St-Si transitions of 10-m Extended Timed Get Up and Go (ETGUG) test in F and NF participants and to analyse the difference	IPhone4 secured to chest.	Acceleration (m/s) in 3 axes. Angular velocity (deg/s) in 3 axes: Medial-Lateral (X),Vertical (Y) and Antero-Posterior (Z) of STS and St-Si transitions	Significant differences were found between the groups in accelerometry and angular displacement variables of both transitions **STS** / **F Mean (SD)** / **NF Mean (SD)** / **p value** **X Axis Min Acceleration** -1.443 (1.211) -3.136 (1.198) <0.001 **Y Max** 3.069 (1.240) 6.248 (1.913) <0.001 **Y Min** -1.471 (0.788) (-6.182 (2.415) <0.001 **RV Max** 7.065 (2.233) 8.962 (2.506) 0.025 **St-Si** / **F Mean (SD)** / **NF Mean (SD)** / **p value** **Y Axis Max Acceleration** 3.567 (2.028) 6.200 (1.752) <0.001 **Y Min** -2.950 (2.441) -9.003 (4.334) <0.001 **Z Min** -3.770 (1.928) -6.645 (2.374) <0.001 **RV Max** 7.213 (2.566) 10.652 (3.510) 0.003 **RV Min** 0.364 (0.255) 0.808 (0.479) 0.002

Table 1 (continued)

		between the two groups. Participants performed a 10-m ETGUG test.			**X Axis Max Angular Velocity** / F Mean (SD) / NF Mean (SD) / P value **STS** 18.924 (8.843) / 165.437 (120.989) / <0.001 **St-Si** 38.146 (18.918) / 145.150 (129.161) / <0.001
Galan-Mercant (2013) (47)	N = 30 volunteers aged > 65 years. Dwelling not specified. FFP; 14 F (age: 83.72±6.37 years), 16 NF (age: 70.25±3.32 years). Laboratory.	To measure and describe variability in 3D acceleration, angular velocity and trunk displacement in the turn transition of 10-m Extended Timed Get Up and Go (ETGUG) test in F and NF participants and to analyse the difference between the two groups. Participants performed a 10-m ETGUG test.	IPhone4 secured to chest.	Acceleration (m/s) in 3 axes. Angular velocity (deg/s) in 3 axes: Medial-Lateral (X),Vertical (Y) and Antero-Posterior (Z) Measurements of only the turning transition were examined.	Significant differences were found between the groups in accelerometry (p < 0.01) and angular displacement variables (*P* < 0.05) during the turn transition **Parameter** / F Mean (SD) / NF Mean (SD) / p value **X Axis Min Acceleration** -2.05 (0.962) / -5.77 (2.43) / <0.003 **Y Max** 26.332 (9.271) / 112.81 (147.91) / 0.022 **Y Min** -2.04 (0.945) / -9.448 (6.937) / <0.001 **Z Min** -1.815 (1.619) / -7.204 (2.438) / <0.001 **X Axis Max Angular Velocity** 25.5 (14.21) / 134.55 (135.52) / <0.001
Greene (2014) (50)	N = 399 community dwelling volunteers aged > 60 years. FFP; 30 F, 185 PF, 184 NF Laboratory.	To investigate an automatic, non-expert quantitative assessment of the frailty state based on a simple protocol employing body-worn inertial sensors. Participants performed a 3-m TUG test.	SHIMMER sensor worn on each shin.	Temporal-Spatial gait, Angular velocity & Turn parameters of 3-m TUG test NOTE: results of sensor-derived data are not detailed in this article. Discussed in previous article in relation to falls (60,63)	Mean Accuracy % (95% CI) Parameter / **Sensor** / **TUG time** / **Max Grip Strength** All 72.88 / 72.09 / 66.93 Male 78.09 / 73.97 / 76.83 Female 72.30 / 69.76 / 78.47 Mean (M/F) 75.20 / 71.87 / 77.65
Greene (2014) (49)	N = 124 community dwelling volunteers aged > 65 years FFP; 66 F, 58 NF Laboratory	To develop classifier models to assess frailty (and falls risk) using sensor-derived features of TUG, Five Time Sit to Stand (FTSS) and Balance tests. Participants performed 3 tests: A 3-m TUG test. FTSS in which they were instructed to stand up and sit down from a standardised chair as quickly as possible five times. Balance was assessed during 40-s of quiet standing, feet 30-cm apart under conditions of eyes open (EO) and eyes closed (EC).	SHIMMER sensor worn on each shin, right thigh, lumbar spine (L5) and sternum. A pressure sensor platform was also used for balance data collection	Temporal-Spatial gait, Angular velocity & Turn parameters of 3-m TUG test Time and acceleration parameters of FTSS Postural Sway distance, velocity NOTE: results of sensor-derived data are not detailed in this article. Discussed in previous article in relation to falls (60,63–65).	Combining sensor data from all three tests to a single classifier model, stratified by gender yielded Accuracy in discriminating between F and NF: Male 94%; Female 84% (95% CI) **Accuracy % (95% CI)** **Parameter** / **TUG** / **BAL** / **FTSS** / **Three Tests Combined** **Male** 89 / 78.48 / 73.33 / 94 **Female** 72.3 / 68.46 / 80.11 / 84
Chen (2015) (44)	N = 1527 community dwelling volunteers aged > 65 years. FFP; 142 F, 670 PF, 715 NF Home	To define the low PA domain of the CHS (Cardiovascular Health Study) frailty phenotype. Participants wore an accelerometer for one week with a minimum of 600-minutes per day and 3 days wear-time	Active style Pro Body-location not specified	Low energy expenditure (defined as scoring in the lowest 20% of energy expenditure of PA per day) (kcal/kg)	Results demonstrate satisfactory internal construct validity of a frailty phenotype using accelerometer-based measurement of the low PA domain. Internal Construct Validity Self-Reported LPA 19.5% Sensor-Based LPA 19.1%
Schwenk (2015) (38)	N = 125 community dwelling or assisted living volunteers aged > 65 years. FFP; 21 F, 60 PF, 44 NF. Home.	To evaluate the ability of sensor-based home assessment of established outcomes to identify PF and F. To explore new objective parameters which might increase the accuracy of frailty assessments. Gait assessment was carried out	LEGSys, BalanSens, PAMSys with sensors located at shanks, thighs and lumbar spine.	Gait speed (m/s) Stride time (s) Stride length (m) Double support (% of stride time) Gait variability (CV) of stride velocity (%) Sway ankle, hip (deg^2) COM in AP and ML direction (cm) PA (Daily duration of postural transitions and movements such as walking, standing, sitting, or lying) as % of 24-h	Gait parameters stride length and double support had highest validity to separate NF from PF and PF from F in age-adjusted model (AUC .857 & .841). **p value (Cohen's d)** **Gait Parameter** / **NF vs PF** / **PF vs F** / **NF vs F** **Stride length** 0.005 (1.07) / 0.015 (0.85) / < 0.001 (1.64) **Double support** <0.001 (0.93) / 0.043 (0.70) / <0.001 (1.56) **Balance Parameter (Hip Sway)** 0.004 (0.62) / 0.999 (0.01) / 0.254 (0.53) **PA Parameters:** Walking bout duration variability was most sensitive for discriminating between frailty levels (AUC 0.818). **PF screening** Single-task walking speed had Highest Validity (AUC 0.802). Number of steps was most sensitive (AUC 0.763).

Table 1 (continued)

<table>
<tr><td></td><td></td><td>under single and dual-task (counting backwards in 1's from 100) conditions. Participants walked 4.57m over-ground in their home at self-selected speed. Balance was assessed during 15s quiet standing with feet together, eyes closed.
PA was measured over a 24-hour period in participants home or assisted living setting.</td><td></td><td></td><td></td></tr>
<tr><td>Martinez-Ramirez (2015) (56)</td><td>N = 718 community dwelling or assisted living volunteers (319 males, 399 females).

FFP;
65 F (age: 80±5.6 years),

327 PF (age: 76.5±5.6 years),

326 NF (age: 73.4±5.5 years).

Setting not specified.</td><td>To examine the acceleration signals obtained from a tri-axial inertial sensor and to extract parameters that will provide complementary information to identify frail populations.

Participants walked in a straight line at self-selected speed over a distance of 3m.</td><td>MTx XSENS worn on lumbar spine (L3).</td><td>Temporal-Spatial gait parameters: Gait velocity, Step Regularity, Stride Regularity, Symmetry, Step Time variability</td><td>All parameters in vertical acceleration demonstrated significant differences between each frailty group (<0.05)

The sensitivity, specificity, accuracy and precision for prediction of frailty are significantly higher using a model combining gait velocity and gait parameters of step regularity.

<table>
<tr><td></td><td>Gait Velocity (GV) AUC</td><td>GV and Gait Parameters AUC</td><td>p value</td></tr>
<tr><td>NF</td><td>0.782</td><td>0.863</td><td>0.004</td></tr>
<tr><td>PF</td><td>0.535</td><td>0.683</td><td>0.028</td></tr>
<tr><td>F</td><td>0.823</td><td>0.896</td><td><0.001</td></tr>
</table></td></tr>
<tr><td>Toosizadeh (2015) (57)</td><td>N = 122 community dwelling volunteers aged > 65 years.

FFP;
19 F, 59 PF, 44 NF.

Setting not specified.</td><td>To use open-loop and closed-loop mechanisms to explore differences in postural balance mechanisms between NF, PF and F individuals.

Participants performed two 15s balance trials, standing, feet close together, not touching, arms folded across chest, under two conditions; eyes open (FTO) and eyes closed (FTC).</td><td>BalanSens located on lumbar spine and shin.</td><td>Postural sway
Hip and ankle joint sway AP and ML
OLCL parameters: Δt(s); slope (cm^2/s); sway (cm^2)</td><td>AP sway was higher in F group but with no significant difference between groups.
No significant result observed in ML sway between groups.
<table>
<tr><td>Parameter</td><td colspan="2">NF vs PF p value (ES)</td><td colspan="2">NF vs F p value (ES)</td><td colspan="2">PF vs F p value (ES)</td></tr>
<tr><td></td><td>EO</td><td>EC</td><td>EO</td><td>EC</td><td>EO</td><td>EC</td></tr>
<tr><td>OLslope AP</td><td>0.31 (0.56)</td><td>0.21 (0.43)</td><td>0.04 (0.49)</td><td><0.001* (0.89)</td><td>0.31 (0.26)</td><td>0.01 (0.58)</td></tr>
<tr><td>CLslope AP</td><td>0.95 (0.11)</td><td>0.59 (0.37)</td><td>0.03 (0.55)</td><td>0.03* (0.47)</td><td>0.04 (0.49)</td><td>0.12 (0.33)</td></tr>
<tr><td>OL AP Sway</td><td>0.01 (0.84)</td><td>0.19 (0.39)</td><td>0.05 (0.64)</td><td><0.01* (0.77)</td><td>0.99 (0.02)</td><td>0.17 (0.42)</td></tr>
</table>
Frailty prediction using Body Sway Vs OLCL parameters:
<table>
<tr><td></td><td colspan="4">PF Prediction, %</td><td colspan="4">F Prediction, %</td></tr>
<tr><td></td><td colspan="2">EO</td><td colspan="2">EC</td><td colspan="2">EO</td><td colspan="2">EC</td></tr>
<tr><td></td><td>Sens</td><td>Spec</td><td>Sens</td><td>Spec</td><td>Sens</td><td>Spec</td><td>Sens</td><td>Spec</td></tr>
<tr><td>Body Sway (and age/BMI)</td><td>74</td><td>76</td><td>69</td><td>78</td><td>74</td><td>93</td><td>74</td><td>83</td></tr>
<tr><td>OLCL (and age/BMI)</td><td>89</td><td>96</td><td>74</td><td>89</td><td>94</td><td>98</td><td>100</td><td>83</td></tr>
</table></td></tr>
<tr><td>Toosizadeh (2015) (39)</td><td>N = 117 community dwelling volunteers aged > 65 years.

FFP;
16 F, 51 PF, 50 NF.

Home.</td><td>To objectively identify frailty using wireless sensors and an upper extremity flexion motion assessment routine that does not rely on gait.

Participants performed a 50s trial of elbow flexion in a seated position in a chair at home while wearing the upper limb sensors. The 50s trial consisted of 20s of elbow flexion on both sides with 10s rest in-between.</td><td>BioSensics LLC on upper arm near biceps muscle and wrist.</td><td>Speed of elbow flexion (deg/s)
Flexibility (deg)
Power (deg^2/s^2
Rise-time (s/100)
Moment (Nm)
Jerkiness (%)
Speed-reduction (%)
Flexion no. (n)</td><td>All parameters extracted from elbow flexion task were significantly different between frailty groups (p<0.05).
Speed had the largest effect size between NF/PF and NF/F. Power had the largest effect size between PF/F.
<table>
<tr><td>Parameter</td><td>NF Mean (SD)</td><td>PF Mean (SD)</td><td>F Mean (SD)</td><td>Pairwise p value (ES)</td></tr>
<tr><td>Speed</td><td>1,117 (247)</td><td>792 (187)</td><td>461 (215)</td><td>NF/PF: 0.001 (1.48)
NF/F: 0.001 (2.83)
PF/F: 0.001 (1.64).</td></tr>
<tr><td>Flexibility</td><td>134 (22)</td><td>115 (24)</td><td>87 (28)</td><td>NF/PF: 0.006 (0.83)
NF/F: p<0.001 (1.99)
PF/F p<0.001 (1.07).</td></tr>
<tr><td>Power</td><td>205.1 (116.3)</td><td>79.3 (40.5)</td><td>23.5 (15.7)</td><td>NF/PF: p<0.001 (1.44)
NF/F: p<0.001 (2.19)
PF/F: p = 0.45 (1.82)</td></tr>
</table></td></tr>
</table>

Table 1 (continued)

Jansen (2015) (11)	N = 84 community dwelling volunteers aged > 65 years. ISAR-HP; 10 F, 74 NF. Home.	To assess differences in indoor and outdoor PA in older adults using GPS and accelerometers between NF and F older adults. Participants were instructed to wear the sensor during waking hours for seven consecutive days.	ActigraphGT3X+ worn on right side of waist.	PA Intensity (minutes per day) (classified in counts per minute (cpm). (Sedentary 0-50; Light PA 51-759; MVPA > 760). Metabolic Equivalent (MET) (minutes) Distance walked / cycled (m).	No significant differences between frailty groups are reported (p<0.05) **Parameter** — **F Vs NF p value** **LPA (Weekly)** 0.79 **MVPA** 0.181 **MET minutes** 0.22 **Distance walked** 0.336 **Distance cycled** 0.75
Toosizadeh (2016) (53)	N = 101 hospital in-patients aged > 65 years. TSFI (Rockwood); 49 F (age: 80±9 years), 52 NF (age: 78±10 years). Hospital.	To validate the accuracy of Upper-Extremity-Frailty (UEF) assessment in distinguishing between F and NF participants Participants performed a 20s trial of elbow flexion-extension as quickly as possible in supine position	BioSensics LLC on upper arm near biceps muscle and wrist.	Speed of elbow flexion (deg/s) Flexibility (deg) Power (deg^2/s^2) Rise-time (s/100) Moment (Nm) Speed-variability (%) Speed-reduction (%) Flexion no. (n)	— **Sensitivity** — **Specificity** **UEF Predicting Frailty** 78% 82% **Parameter with highest effect size** — **F vs NF p value (Cohen's d)** **Speed** <0.0001 (1.50) **Flexion (n)** <0.0001 (1.18) **Power and Moment** <0.0001 (1.10) Speed was 45% less among F group.
Millor (2017) (58)	N = 718 community dwelling volunteers (319 male, 399 female). FFP; 31 F (age: 79±6 years), 206 PF (age: 73±5 years), 194 NF (age: 74±5 years) Setting not specified.	To establish a set of objective and quantitative parameters of 30-s CST that can classify frailty status. Participants performed as many CST repetitions as possible within 30-s, at self-selected speed, starting from seated position, with arms folded across chest, and one 3-m walking test in a straight line over-ground at self-selected speed.	MTx Orientation Tracker worn at the lumbar spine (L3).	No. of CST cycles (n) Gait velocity (GV) (m/s) Chair kinematics (CK) (range of AP orientation (deg), acceleration (m/s) and power (Nm)) in 3 directions (vertical, ML, AP) and in 3 phases (Impulse, Up, Down)	Sensitivity, specificity, accuracy and precision values were significantly higher for the model based on CK (e.g., range of AP orientation, acceleration and power) than gait velocity or no. of cycles. **AUC (95% CI)** **Parameter** — **NF** — **PF** — **F** **nCycles** 0.65 (0.529-0.789) 0.53 (0.410-0.650) 0.657 (0.536-0.765) **GV** NF 0.65 (0.529-0.789) 0.763 (0.649-0.856) 0.516 (0.395-0.635) **CK** 1.000 (0.649-0.856) 0.938 (0.395-0.635) 0.936 (0.852-0.980). Top 3 important parameters measured: (p<0.05) **Mean (SD)** **Parameter** — **NF** — **PF** — **F** **Impulse AP Orientation range:** 18.81 (9.60) 22.01 (9.73) 25.76 (12.00) **V Max power STS** 88.37 (50.75) 65.40 (40.18) 38.13 (34.75) **Impulse V acceleration StSi** 1.21 (0.37) 1.10 (0.39) 0.79 (0.30)
Parvanneh (2017) (40)	N = 120 community dwelling volunteers. FFP; 76 F/PF (age: 80.7±8.68 years), 43 NF (74.23±6.15 years). Home.	To monitor and assess postural transition differences among frailty levels. Spontaneous daily PA were recorded for a period of 48 hours. The first 24h was used for the purpose of this study	PAMSys worn at the sternum in a shirt-embedded pocket.	Postural transitions: STS, St-Si, stand-to-walk, walk-to-stand, sit-to-walk, and walk-to-sit (further classified into 'cautious' or 'quick' sitting) (n), Ratio of cautious sitting (%)	Between group comparisons (with adjustment for age) demonstrate statistical significance in: **Parameter** — **NF** — **PF** — **p value** **Total transition (n)** 1,174 ±468 878±-333 p = 0.032 **St-walk** 475±208 332±148 p = 0.011 **Wlk-st** 453±202 314±141 p = 0.011 The ratio of cautious sitting was significantly higher (6.2%) in the PF/F compared to the NF group (p = 0.025, Cohen's d = 0.22
Huising-Scheetz (2018) (35)	N = 651 community dwelling volunteers (341 Female; 310 Male). Aged >62 years Modified Frailty Phenotype 94 F 317 PF 240 NF	To determine how hourly activity level is related to clinical frailty criteria in older adults. Participants were instructed to wear the sensor continuously for 72 consecutive hours	ActiWatch Spectrum worn on the non-dominant wrist	Mean hourly cpm	Mean hourly CPM was approximately 7% lower per frailty point β -0.03 p≤0.001
Lee (2018) (52)	N = 100 hospital in-patients (age: 78.9±9.1 years) TSFI (Rockwood); 49 F, 51 NF.	To provide a physical frailty phenotype assessment tool using a single wrist-sensor. Participants wore sensors while performing elbow flexion and extension as	LEGSys worn at wrist and upper arm.	No. of cycles (n) Mean, CV and % Decline (PD)of kinematic parameters of elbow Flexion / Extension: Angular velocity range (deg/s) Angle range (deg) Power range (deg^2/sec^3) Rising time, falling time, rising and falling time (ms) Flexion time, extension time (ms) Flex/ext rate (n/min)	Model developed from single (wrist) sensor identified 5 dominant features with 80.0% accuracy in identifying Frailty (95%CI: 79.7-80.3%): **Mean (SD)** — **p value** **NF** — **F** **Mean of angle range** 106.67 (25.89) 81.35 (31.0) <0.001 **PD of power range** -9.3 (26.95) -19.58 (24.01) 0.043 **CV of elbow extension time** 0.09 0.05) 0.17 (0.23) 0.014 **Mean of elbow flexion time** 419.98 (129.98) 644.18 (357.60) <0.001 **CV of elbow flexion time** 0.09 (0.05) 0.15 (0.15) 0.005

Table 1 (continued)

<table>
<tr><td></td><td>Hospital</td><td>many times as possible within a 20-s timeframe, while in supine position.</td><td></td><td></td><td></td></tr>
<tr><td>Razjouyan (2018) (41)</td><td>N =153 community dwelling volunteers aged > 60 years.

FFP;
33 F,
78 PF,
42 NF.

Home.</td><td>To determine which sensor-derived parameters are capable of discriminating between the three frailty categories, to identify the most significant independent parameters to discriminate pre-frailty, and to build a composite model to discriminate the pre-frail stage from non-frail and frail stages.

Participants wore a pendant sensor continuously for 48hours while undertaking normal activity including sleep.</td><td>PAMSys worn at the sternum.</td><td>Total time (%&min)Walking, Sitting, Standing , Lying and Sedentary Time
Bouts(s) of Walking, Sitting, Standing , Lying
Intensity: light /moderate-vigorous activity
Total steps(n)

Sleep parameters</td><td>Significantly different between groups were:
<table>
<tr><td></td><td></td><td>Mean (SD)</td><td></td><td>P value (Cohen’s d)</td><td></td></tr>
<tr><td>Parameter</td><td>NF</td><td>PF</td><td>F</td><td>NV v PF</td><td>PF v F</td></tr>
<tr><td>Total % Walk</td><td>8.7 (3.9)</td><td>5.1 (3.3)</td><td>3.2 (3.2)</td><td>0.000 (1.02)</td><td>0.012 (0.57)</td></tr>
<tr><td>Longest unbroken walking bout (s)</td><td>351.3 (347.9)</td><td>187.9 (223.9)</td><td>110.3 (132.4)</td><td>0.001 (0.56)</td><td>0.002 (0.42)</td></tr>
<tr><td>Total n. of steps (N/1000)</td><td>12.2 (6.1)</td><td>6.7 (4.2)</td><td>4.3 (4.3)</td><td>0.000 (1.04)</td><td>0.018 (0.57)</td></tr>
<tr><td>Longest unbroken stepping bout</td><td>694.3 (743.0)</td><td>322.9 (411.0)</td><td>162.5 (184.2)</td><td>0.000 (0.620</td><td>0.006 (0.57)</td></tr>
<tr><td>Total duration of sedentary behaviour (h)</td><td>9.6 (2.6)</td><td>11.7 (3.2)</td><td>13.2 (4.2)</td><td>0.001 (0.73)</td><td>0.029 (0.40)</td></tr>
<tr><td>Mod to vigorous activity (%)</td><td>6.0 (4.0)</td><td>2.2 (2.4)</td><td>1.2 (1.5)</td><td>0.000 (1.13)</td><td>0.066 (0.50)</td></tr>
</table></td></tr>
<tr><td>Castaneda-Gameros (2018) (17)</td><td>N = 60 community dwelling volunteers aged > 60 years.

FFP;
10 F, 23 PF, 27 NF.

Home.</td><td>To examine the association between PA and sedentary time (ST), frailty and factors influencing PA behaviours in migrant older women from ethnically diverse backgrounds.

Participants were instructed to wear the sensor for a period of 7 days, only removing for bathing, swimming and sleeping. To be included in the analysis participants had to wear the device for at least 3 days including one weekend day, and for at least 10-h/day of valid wear time.</td><td>Actigraph GT3X worn at the hip.</td><td>PA Intensity (min/day) (classified in counts per minute) (cpm)
Low-Light PA (LLPA)(100-1040cpm)
High-Light PA (HLPA) (1,041-1,951cpm)
MVPA (>1,952cpm)

ST (<100 cpm) (min/day)</td><td>Only MVPA was significantly different between NF/PF and F groups
<table>
<tr><td></td><td></td><td>Mean (SD)</td><td></td><td></td></tr>
<tr><td>Parameter</td><td>NF</td><td>PF</td><td>F</td><td>p value</td></tr>
<tr><td>ST</td><td>523.7 (85.7)</td><td>533.1 (85.7)</td><td>576.7 (7.0)</td><td>0.48</td></tr>
<tr><td>LLPA</td><td>207.4 (57.8)</td><td>204.9 (66.7)</td><td>161.4 (68.7)</td><td>0.51</td></tr>
<tr><td>HLPA</td><td>27.1 (13.6)</td><td>29.8 (17.2</td><td>18.4 (23.0)</td><td>0.36</td></tr>
<tr><td>MVPA</td><td>18.4 (19.9)</td><td>18.7 (17.6)</td><td>3.4 (4.5)</td><td><0.01</td></tr>
</table>
<table>
<tr><td></td><td>F/NF p value</td><td>F/PF p value</td></tr>
<tr><td>MVPA</td><td>0.02</td><td><0.01</td></tr>
</table></td></tr>
<tr><td>Jansen (2019) (43)</td><td>N = 112 community dwelling volunteers aged > 65 years.

FFP; 19 F, 53 PF, NF 40

Home.</td><td>To investigate whether the association between motor capacity and mobility performance is moderated by frailty status in older adults.

Participants wore the LEGSys sensors while performing a walk test under two conditions: at self-selected speed over a distance of 4.57m and as quickly as possible over a distance of 10m.

Participants wore the PAMSys sensor for a period of 48 hours while carrying out normal activities</td><td>PAMSys sensor embedded in a shirt. Location not specified.

LEGSys sensors worn at bilateral shins, thighs and lumbar spine (specific location not indicated).</td><td>Percentage of time walking or standing (%).
Average number of steps per walking bout (n).
Max number of steps in one walking bout (n).
Normal walking speed (NWS) (m/s).
Fast walking speed (FWS) (m/s).</td><td>
<table>
<tr><td></td><td>Mean (SD)</td><td></td><td>P value</td><td></td></tr>
<tr><td>Parameter</td><td>NF</td><td>PF</td><td>F</td><td></td></tr>
<tr><td>% PA</td><td>25.0 (7.1)</td><td>18.9 (6.0)</td><td>16.4 (7.3)</td><td>< 0.001</td></tr>
<tr><td>Max steps in one bout</td><td>1668 (1724)</td><td>591 (556)</td><td>285 (387)</td><td>< 0.001</td></tr>
<tr><td>Average steps per bout</td><td>39 (24)</td><td>33 (15)</td><td>27 (12)</td><td>0.25</td></tr>
<tr><td>NWS</td><td>1.18 (0.15)</td><td>0.92 (0.22)</td><td>0.64 (0.25)</td><td>< 0.001</td></tr>
<tr><td>FWS</td><td>1.47 (0.22)</td><td>1.13 (0.27)</td><td>1.07 (0.12)</td><td><0.001</td></tr>
</table>
Using a moderation analysis to investigate how frailty changes the effect of motor capacity on mobility performance, association between motor capacity & mobility performance was found in PF and F groups only.</td></tr>
</table>

Table 1 (continued)

<table>
<tr><td>Zhou (2019) (54)</td><td>N =61 community dwelling volunteers aged > 60 years.
N = 17 volunteers aged 20 -35 years.

FFP; 8 F, 29 PF, 24 NF.

Out-patients clinic.</td><td>To examine whether parameters from an instrumented trail-making task (iTMT) can distinguish different frailty stages and could describe different frailty phenotypes

The iTMT included standing in front of a standard computer in double-leg stance and performing a series of virtual trail-making tests by rotating the ankle joint to move a computer-cursor. For gait speed participants were instructed to walk at habitual speed for 20m.</td><td>LEGSys worn on both shins</td><td>Gait Speed (m/s).
Sensor data (iTMT-derived parameters):
Time (s)
Velocity (unit/s)
Power (unit^2/sec^3)
Exhaustion (%) (% of decline in max ankle rotation velocity from Trials 1-5 and 11-15)
Variability (%) (CoV of ankle rotation velocity during the first 15 trials</td><td>Results indicate Gait Speed), iTMT Velocity and Power can significantly distinguish between NF/F and PF/F groups (p<0.05).
<table><tr><th>Parameter</th><th>NF</th><th>F (PF and F)</th><th>p value (Cohen's d)</th></tr><tr><td>Gait speed</td><td>1.06 (0.19)</td><td>0.94 (0.24)</td><td>0.032 (0.56)</td></tr><tr><td>iTMT: Velocity</td><td>6.31 (0.98)</td><td>5.67 (1.09)</td><td>0.025 (0.62)</td></tr><tr><td>Power</td><td>90.56 (26.73</td><td>73.70 (28.47)</td><td>0.040 (0.61)</td></tr><tr><td>Exhaustion</td><td>8.23 (15.19</td><td>9.41 (10.58)</td><td>0.698 (0.09)</td></tr><tr><td>Variability</td><td>20.92 (4.94)</td><td>23.05 (7.84)</td><td>0.241 (0.33)</td></tr></table>iTMT Velocity, Power, Exhaustion and Variability enable significant (p<0.05) discrimination between presence and absence of frailty phenotypes as determined by the FFC; slowness (d=1.40), weakness (d=1.38), exhaustion (d=0.98) and inactivity (d=0.90)</td></tr>
<tr><td>Mulasso (2019) (42)</td><td>N = 25 community dwelling volunteers aged > 65 years.

Part B of TFI;
14 F
11 NF

Laboratory and Home</td><td>To investigate the relationships between the Mobility Index (MI) provided by the ADAMO System and a mobility screening tool with frailty. To test the acceptance of the ADAMO System Carewatch for PA measurement (as part of project (SPRINTT) to validate and implement a practical and clinical prevention of frailty).

Participants attended a test centre and were timed walking 400m (8 laps of a corridor). They then at home wore a wrist-watch continuously for 7 days.</td><td>ADAMO System accelerometer on wrist</td><td>Time spent in Low, Mod, Vigorous Activity (%)
Time to complete walk test(s)</td><td>4oo-m walk test correlates with physical frailty only. The MI is strongly associated with total frailty (Physical, Psychological & Social)
Significant differences were observed between F and NF individuals for Low, Moderate and Vigorous activity.
<table><tr><th></th><th></th><th>Mean (SD)</th><th>p value (ES)</th></tr><tr><td>Variable</td><td>NF</td><td>F</td><td></td></tr><tr><td>Low activity</td><td>58.8 (6.6)</td><td>42.0 (8.3)</td><td>< 0.001 (0.657)</td></tr><tr><td>Mod activity</td><td>25.5 (7.6)</td><td>33.8 (10.6</td><td>0.008 (0.292)</td></tr><tr><td>Vigorous activity</td><td>15.7 (7.2)</td><td>24.2 (10.8)</td><td>0.035 (0.195)</td></tr></table></td></tr>
<tr><td>Lepetit (2019) (48)</td><td>N = 50 volunteers aged > 65 years.
.

FI (Rockwood); 24 healthy young (HY) (age: 25±3 years),

11 F (age: 87±6 years), 39 NF (Healthy Senior) (age: 70±4 years).

Laboratory.</td><td>To design a diagnostic tool to detect functional deficit based on a single sensor during STS.

Participants were asked to perform STS at self-pace without UL assistance, 3 - 5 repetitions as physical ability allowed.</td><td>APDM worn at the chest.</td><td>STS parameters including:
Task duration (TD)(s)
Trunk: COM velocity (m/s)
Angular velocity (rad/s)
Inclination (Incl)
Acceleration (m/s2).
Kinetic energy (mEK)(J)</td><td>Frailty significantly influences STS (p<0.01).
All mean-based parameters, max EK and max VG decreased significantly for FS group compared with HY & HS (NF) groups
<table><tr><th>Parameter</th><th>NF</th><th>F</th><th>p value</th><th>AUC</th></tr><tr><td>mVG</td><td>0.390 (0.065)</td><td>0.242 (0.049)</td><td><0.01</td><td>0.97</td></tr><tr><td>mOmega:</td><td>0.637 (0.165)</td><td>0.43 (0.152</td><td><0.01</td><td>0.825</td></tr><tr><td>TD</td><td>1.92 (0.38)</td><td>4.22 (2.02)</td><td><0.01</td><td>0.923</td></tr><tr><td>mAcc</td><td>1.69 (0.41</td><td>0.91 (0.39)</td><td><0.01</td><td>0.911</td></tr><tr><td>mAz</td><td>1.16 (0.33</td><td>0.54 (0.27)</td><td><0.01</td><td>0.935</td></tr><tr><td>mAxy</td><td>1.03 (0.23)</td><td>0.63 (0.23)</td><td><0.01</td><td>0.886</td></tr><tr><td>mEK</td><td>2.97 (1.24</td><td>0.90 (0.51)</td><td><0.01</td><td>0.965</td></tr></table></td></tr>
<tr><td>Yuki (2019) (37)</td><td>N = 401</td><td>To examine the association between frailty and PA

Participants were instructed to wear the device continuously > 10-hours for 7-days except when sleeping or bathing</td><td>Lifecorder. Location not specified</td><td>Steps (n)
LPA, (<3METs) MVPA (>3METs) (min)</td><td>Odds ratio for frailty:
<table><tr><th>Parameter</th><th>OR</th><th>CI</th><th>p value</th></tr><tr><td><5000 steps</td><td>1.85</td><td>95%</td><td><0.01</td></tr><tr><td>MVPA for <7.5 minutes</td><td>1.80</td><td>95%</td><td><0.01</td></tr></table>No significant association was observed between frailty and LPA</td></tr>
</table>

Table 1 (continued)

Ziller (2020) (34)	N = 47 community dwelling volunteers aged > 65 years FFP; 9 F, 15 PF, 23 NF Home and Clinic	To analyse the variance in prevalence of frailty by using different models and methods (cut-off points) for measuring the Low PA (LPA) criterion of the frailty assessment tools. Participants were instructed to wear the sensor during waking hours for seven consecutive days. Wear time of four to seven days with at least six hours were included in the analysis	Actigraph worn at hip	Energy expenditure (kcal/week) (Fried's cut off: <270kcal/week♀;<383kcal/week♂) MVPA-1 (> 1952 cpm) OR MVPA-2 (> 1041cpm) (min/week). Sedentary time (< 100 cpm) (hours/day). Daily steps (n/day)(<7000/day)	Prevalence varied depending on model and method for measuring LPA Prevalence: F / PF / NF FFP: 19% / 32% / 49% Accelerometer LPA: 15% / 36% / 49% MVPA1: 30% / 38% / 32% MVPA2: 15% / 36% / 49% Step counts (<7000 per day): 32% / 51% / 17%
Chen (2020) (55)	N = 819 community dwelling volunteers aged > 65 years. 98 F 228 PF 493 NF FRAIL J Community Centre	To investigate if sedentary behaviour, PA patterns and n steps are associated with frailty status and to determine optimal cut-off value of each to discriminate between F and NF. Participants were instructed to wear the sensor for during waking hours for 7 consecutive days. To be included in the analysis participants had to wear the device for at least 4 days and min 10-h per day	Active style Pro HJA- 350IT worn at the waist	Sedentary Time (≤ 1.5 METs) LPA (1.5 – 3 METs) MVPA ≥ (3 METs) (min/day) Steps (n)	Mean (SD): NF / PF / F / p value **Total sedentary time**: 460.1 (113.0) / 450.7 (104.4) / 455.3 (118.7) / 0.49 **Total MVPA**: 54.5 (33.3) / 52.8 (32.5) / 40.5 (32.7) / <0.001 ***Bouted MVPA**: 22.5 (24.1) / 21.2 (25.1) / 12.6 (20.5) / <0.001 **Steps**: 5872.2 (2699.7) / 5695.1 (2792.8) / 4451.7 (3057) / <0.001 *Bouted MVPA defined as ≥ 10 consecutive min, with an allowance for up to 2 min out of 10 to drop below the MVPA intensity threshold Cut-off value to discriminate between F and NF were: **MVPA (min/day)** 43.25 **Bouted MVPA** 9.13 **Steps (n)** 3841
Kikuchi (2020) (36)	N = 511 community dwelling adults aged > 65 years. J-CHS ; 13 F 234 PF 264 NF Home	To examine associations of intensity-specific physical activity and bout-specific sedentary time with frailty status. Participants were asked to wear a device for 7 consecutive days	Active style Pro HJA-750C worn at the hip	Bouts of ST (min/day) Intensity of PA (METs) (ST ≤ 1.5 METs, LPA 1.5 – 3 METs, MVPA ≥ (Mins) 3 METs)	MVPA and prolonged SB differed significantly between frailty levels **Parameter**: Mean (SD) **NF** / **PF** / **F**; p value **NF v PF** / **PF v F** / **NF v F** **Short-Bout of SB**: 273.1 (65.4) / 261.2 (61.7) / 231.0 (59.0); 0.287 / 0.0002 / 0.0001 **Prolonged Bout of SB**: 167.3 (115.5) / 186.0 (110.0) / 289.9 (158.7); 0.0003 / <0.0001 / <0.0001 **LPA**: 406.2 (97.4) / 374.1 (101) / 298.6 (157.9); 0.574 / 0.119 / 0.182 **MVPA**: 58.6 (40.1) / 47.4 (38.8) / 14.9 (21.1); 0.0003 / <0.0001 / <0.0001
Apsega (2020) (33)	N = 133 community dwelling adults aged > 60 years. 86 female 46 male FFP; 37 F 66 PF 30 NF Not Specified	To examine the ability of wearable sensor-based assessments of gait to discriminate between frailty levels and to determine the cut-offs of the most sensitive gait parameters that separated the frailty levels. Participants performed a 3-m TUG test	Shimmer sensors worn at bilateral thighs, shins and dorsum of feet.	Stance phase time (s) Swing phase time (s) Gait speed (cm/s) Stride time, on right and left leg accordingly (s) Double support time (ms) Cadence (steps/min).	Parameters for discriminating three frailty levels: PF vs. NF: OR / 95% CI / p Value; Frail vs. NF: OR / 95% CI / p Value TUG time: 2.36 / 1.68–3.31 / <0.0012; 0 .67 / 1.89–3.78 / <0.001 Dynamic gait Index score: 0.80 / 0.70–0.92 / 0.001; 0.71 / 0.60–0.83 / <0.001 Gait speed: 0.93 / 0.90–0.95 / <0.001; 0.92 / 0.89–0.95 / <0.001 Stride time: 1.006 / 1.003–1.009 / <0.001; 1.006 / 1.003–1.009 / <0.001 Swing phase: 1.007 / 1.001–1.013 / 0.028; 1.008 / 1.001–1.015 / 0.024 Stance phase: 1.009 / 1.005–1.013 / <0.001; 1.008 / 1.004–1.012 / <0.001 Double support: 1.02 / 1.01–1.03 / <0.001; 1.01 / 1.01–1.02 / 0.002 Cadence: 0.87 / 0.83–0.92 / <0.001; 0.83 / 0.78–0.89 / <0.00 Cut-off values of the most sensitive gait parameters that separated the frailty levels: F Vs PF or NF / PF or F Vs NF TUG Time: 11.6 / 9.27 DGI: 15.0 / 19.0 GS: 0.60 / 0.82 Stride: 1.27 / 1.19 Stance: 0.80 / 0.68 Swing: 0.48 / 0.48 DS: 0.16 / 0.14 Cadence: 99.54 / 101.22

Table 1 (continued)

N/n Number, *FFP* Fried's Frailty Phenotype, *F* Frail, *PF* Pre-Frail, *NF* Non-Frail, *s* seconds, *FTO* Feet Together Eyes Open, *FTC* Feet Together Eyes Closed, *FSO* Feet Semi-tandem Eyes Open, *FSC* Feet Together Eyes Closed, *L3* Lumbar Vertebrae n 3, *PA* Physical Activity, *GPS* Global Positioning System, *EMG* Electromyography, *m/s* metre per second, *VL* Vastus Lateralis, *BB* Biceps Brachii, *FI* Frailty Index, *r* Correlation coefficient, *CST* Chair Stand, *cpm* counts per minute, m/s^2 metre per second squared, *STS* Sit To Stand, *St-Si* Stand to Sit, *3D* 3-Dimensional, *ETGUG* Extended Timed Get Up and Go, *TUG* Timed Up and Go, *MGS* Maximum Grip Strength, *FTSS* Five Times Sit to Stand, *CI* Confidence Interval, *CHS* Cardiovascular Health Study, *kcal/kg* calorie per kilogram, *CV / CoV* Coefficient of Variation, *COM* Centre of Mass, *AP* Antero-Posterior, *ML* Medial–lateral; *h* hour, *AUC* Area Under Curve, *RMS* Root Mean Square, *OLCL* Open Loop Closed Loop; *Δt* Change in time, *MVPA* Moderate to Vigorous PA; *MET* Metabolic Equivalent, *ISAR-HP* Identification of Seniors At Risk-Hospitalised Patients Questionnaire; *TFI* Tilburg Frailty Index, *TSFI* trauma-Specific Frailty Index, *UEF* Upper-Extremity Frailty Assessment; *GV* Gait Velocity, *CK* Chair Kinematics; *SD* Standard Deviation, *ST* Sedentary Time, *LLPA* Low-Light PA, *HLPA* High-Light PA, *NWS* Normal Walking Speed, *FWS* Fast Walking Speed, *iTMT* instrumented Trail-Making-Task, *mVG* Mean value of the norm of the torso COM velocity; mOmega, mean value of the norm of the trunk angular velocity, *TD* Task Duration, *mAcc* mean Acceleration, *mAz* Acceleration in vertical axis; *mAxy* mean acceleration in horizontal plane, *mEK* mean kinetic energy, *Frail-J J-CHS* Frailty Indices adapted for Japanese older adults, *DGI* Dynamic Gait Index, *DS* Double Support

Participant characteristics

Participants ranging in age 63–90 years were recruited from community, assisted-living or hospital environments. Four studies [45, 46, 48, 54] included a healthy young cohort (age range 18–54 years) for comparison. For those studies that reported sex there was an overall predominance of females.

Quality assessment

With the exception of one study that scored 12, the methodological quality of studies demonstrated a minimum result of 70% (14 out of a possible 20, range 14–20) using the AXIS tool (Appendix 3). Quality appraisal of all 29 studies is presented in Table 3. The tool used does not apply a numerical score or rating because of the author's assertion of the non-linear weighting of each aspect of the assessment and each Sect. [59]. No study was excluded based on methodological score.

Discussion

This systematic review was undertaken to examine which parameters of mobility and PA obtained from a wearable sensor have been used to assess and quantify frailty, which type of body-worn sensors and specific body-locations have been used and how different parameters are associated with discrimination of stages of frailty. Of the 29 studies included in the review, seven different aspects of mobility and PA with a multiplicity of subdivisions were examined, using 13 different sensor brands on eight different body-locations. Some studies use a combination of body-locations. This heterogeneity makes comparison and analysis difficult and thus precludes recommendations on devices. It is worth noting however that while brands of sensors reported differ, the properties are comparable. Studies will be discussed under headings referring to the various mobility and PA parameters, sensors used and body-location of sensors.

Parameters of mobility and physical activity

Physical activity parameters

Time spent in non-sedentary activity is the most commonly examined parameter of mobility and PA in the literature reviewed. Subdivisions of PA patterns and PA behaviour examined include time spent in non-sedentary activity; time spent in various intensities of activity; number of postural transitions, number of bouts, length of unbroken bouts and variability in bouts of the different measurements of PA.

There was some commonality of metrics among the 12 studies in this group [11, 17, 24, 35–38, 40–43, 55] and some consensus. Razjouyan et al., [41] agree with earlier findings of Theou et al., [24] that total time spent in non-sedentary activity correlates well with a frailty index, demonstrating significant differences between levels of frailty. This is supported by Jansen et al., [43] in a study which examines the effect of frailty levels on motor capacity and mobility performance. The authors suggest that capacity does not necessarily determine performance or function but there is a strong association between the two and frailty. These findings are contradicted by Schwenk et al., [38] who suggest that percentage of time spent walking is a poor discriminator of frailty levels. These authors [38] suggest variability in walking bouts described as more static and less complex PA combined with shorter walking bouts as a more sensitive measure of frailty. Similarly, it is suggested that sedentary time is associated with frailty [36, 41] but this is refuted in another study [17].

Some studies measured intensity of PA, but as is common with many of the parameters in the studies included in this review, there is little consistency in how the metrics are defined or measured. Categories of PA intensity are consistent insofar as they are referred to as variations of low, medium or high [11, 17, 34, 36, 37, 41, 42, 44, 55] but how each category is defined differs, from measurement of acceleration counts per minute [11, 17] to metabolic equivalents (MET) [11, 36, 37, 41, 55] and magnitude of mobility e.g. lying, sitting, walking pace [42]. Counts per minute as a metric of PA intensity are not universal and there is marked disparity between the scales used [11, 17, 34, 35].

There is some agreement that moderate to vigorous activity is inversely related to frailty. Those studies that differentiate between levels of frailty agree that PA

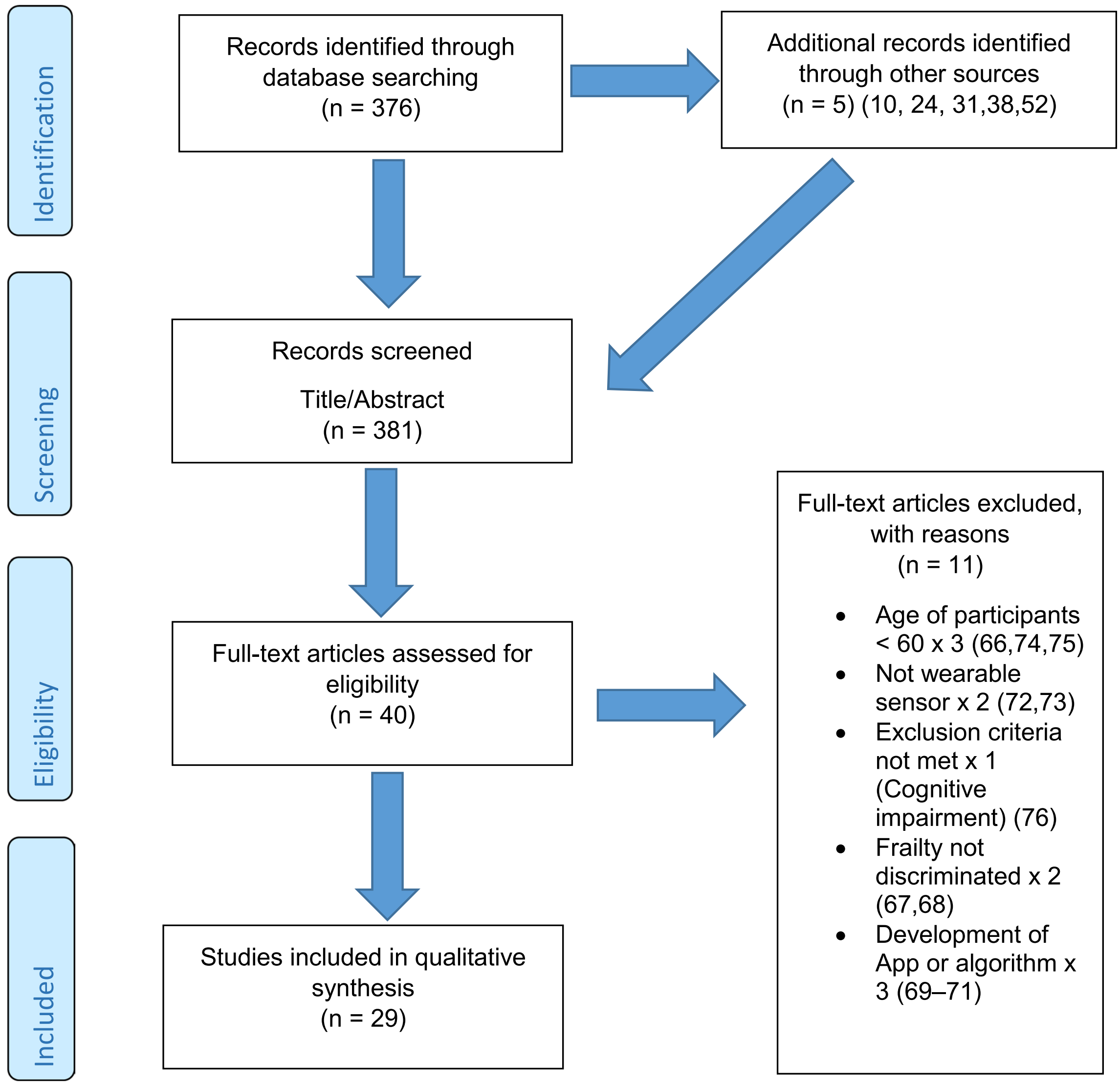

Fig. 1 PRISMA 2009 flow diagram

intensity discriminates NF from PF and to a lesser extent PF from F [17, 36, 37, 41, 55]. This is refuted by Jansen et al. [11] who found no significant between-group differences. The much lower counts per minute used in this study may account for this finding. Acceleration counts as measured in one study [24] are referred to as postural transitions or counts per minute (CPM) in others [34, 35, 37]. One study [40] in which postural transitions are further defined as sit to stand, stand to sit, stand to walk etc. purports the ability of the number of postural transitions to discriminate between levels of frailty while the others suggest discrimination between F and NF only [34, 35].

Within the literature included in the review, the most common correlation between frailty levels and PA demonstrated are moderate – vigorous PA (MVPA) [17, 36, 37, 41, 55], bouts of PA [38, 41, 43, 55] and total number of steps [24, 37, 41, 43, 55].

Temporal-spatial parameters of gait including trunk kinematics

Seven studies [24, 25, 29, 30, 40, 41, 43,] examined gait speed, velocity or time to complete a walk test as part of their research. Five included gait speed with temporal-spatial parameters including step time, regularity; stride time, length regularity; percentage of time in double support and trunk kinematics of angular velocity and trunk displacement [33, 38, 49, 50, 56]. One study examined trunk kinematics only, during the STS, Stand to Sit (St-Si) and turn transitions of 10-m Timed Up and Go (TUG) test [47, 51]. While there is consensus regarding the association between gait speed/velocity and the identification of frailty [24, 33, 38, 47, 54] there is disparity in the significance of the results. All agree on the ability of gait speed/velocity to discriminate between NF and F however the effect size varies considerably, even between studies using the same body-location [38, 54]. Variation in the methodology of gait speed measurement may be a contributory factor in the disparity, with distance over which speed was measured varying from 3 to 20 m. One study suggests that the ability to distinguish between PF and F, arguably a more important distinction, lies within the development of models including capacity and performance [43]. This study included measures of normal and fast walking speed as measures of capacity.

Balance

Balance is measured in different ways throughout the literature varying in the nature of the assessment, the conditions under which the assessment took place and duration of each task. Those that assessed balance during a period of quiet standing did so over different time periods ranging from 10 – 40-s [38, 45, 49, 57]. Conditions varied between participants standing with feet together, feet semi-tandem, eyes open and/or eyes closed while another measured balance during a 30-s chair-stand exercise [46]. Balance was evaluated by examining displacement of trunk [38, 45, 46, 49], hip and ankle [38, 57] in anteroposterior and medial–lateral directions and during different phases of the task [46].

Studies that investigated the effect of balance parameters on the identification of frailty agree on a greater anteroposterior sway in frail groups under conditions of feet together, eyes closed but no between-group significance [38, 45, 57]. Millor et al., [46] concur to some extent in their assessment of lateral sway. However synthesis of data is difficult because of the study characteristics. These studies varied greatly in their methodology and analysis. One study [45] proposes analysis of the orientation and acceleration signal-intensity as a novel and perhaps more appropriate approach to discriminating between frailty levels than sway or power variables of balance tests. Results of this study indicate that the higher frequencies of orientation and acceleration signals obtained through wavelet decomposition analysis in healthy populations are distinguished from the lower frequencies typical of a frail population.

One study that examined a broad range of variables suggests that the predictive validity of balance parameters is inferior to those of gait and PA parameters [38]. Subsequently it has been suggested that kinematics of STS have greater sensitivity, specificity, accuracy and precision values than those of gait parameters, specifically velocity [58]. This is supported by one study which, using a model combining data from balance, PA and chair kinematics, yields a higher accuracy percentage in identifying frailty than each of the individual tests [49].

Upper limb kinematics

Three studies [39, 52, 53] examined kinematics of the upper limb, specifically the elbow, in the development of a frailty assessment tool that does not rely on gait. All agree on the ability of the variables derived from an elbow flexion/extension task to distinguish between levels of frailty.

Sensors and body-location

With the exception of two studies [24, 37] in which a uni-axial accelerometer was used, all studies report the use of either a tri-axial accelerometer, gyroscope or a combination of both, with the inclusion of a tri-axial magnetometer reported in eight studies [33, 45–48, 54, 56, 58]. The uni-axial accelerometer was positioned at the waist and used to record steps in conjunction with acceleration counts [24] and total number of steps with PA intensity [37]. The most common body-location for the tri-axial sensors was the lumbar spine [38, 43, 45, 46, 49, 56–58], but in other studies these sensors were positioned at the chest [24, 40, 41, 47–49, 51], shins [33, 38, 43, 50, 54, 57, 60], wrist [35, 39, 42, 52, 53], waist [11, 55], hip [17, 36] thigh [33, 38] and foot [33].

There was some commonality with the body-locations used and metrics obtained, for example all balance parameters were obtained using a tri-axial gyroscope positioned at the LSp [38, 45, 46, 57, 60]. However in some studies a sensor positioned at the LSp was used to examine temporal-spatial parameters of gait [56, 58]. One study used a combination of LSp and shin to measure balance parameters, presumably because the study examined open-loop and closed-loop postural control strategy [57].

Body-location of sensors measuring PA included chest [38, 40, 41, 43, 51, 60], wrist [35, 42], hip [17, 36] and waist [24, 55]. One study in this group [38] used a

Table 2 Sensor details

Author (Reference n.)	Sensor type,Location and properties where provided	Acquisition, processing and analysis
Martinez-Ramirez [45]	MTx XSENS,Xsens Technologies B.V. Enschede, Netherlands Tri-axial accelerometer, gyroscope & magnetometer worn at L 3 combines nine individual MEMS sensors to provide drift-free 3D orientation as well as kinematic data: 3D acceleration, 3D (rate gyro) and 3D magnetometers	A wavelet-based algorithm using Fourier Technique, Wavelet Decomposition, Principal Component Analysis
Theou [24]	ActiTrainer Uni-axial accelerometer worn on waist Records data in 1-min epochs Polar WearLink HR monitor worn on chest, Garmin forerunner405 GPS worn on wrist Biometrics DataLOG P3X8 EMG worn on Vastus Lateralis and Biceps Brachii	Data downloaded or wirelessly transmitted to Custom Software EMG sampling frequency 1000 Hz
Millor [46]	MTx XSENSXsens Technologies B.V. Enschede, Netherlands Tri-axial accelerometer, gyroscope & magnetometer worn at L3	Sampling frequency 100 Hz, Automated raw data analysis using Matlab (Mathworks Inc., Natick, MA., USA)
Galan-Mercant [47, 51]	iPhone4 secured to chest Tri-axial accelerometer, gyroscope & magnetometer Apple uses a LIS302DL accelerometer in iPhone4	Sampling frequency 32 Hz. Data obtained through the use of an Application xSensor Pro, Crossbow Technology Inc., available from Apple *AppStore*
Greene [50]	SHIMMER, Dublin, Ireland Tri-axial accelerometer & gyroscope worn on each shin Sensor axes aligned with the vertical, medio-lateral and anterior–posterior axes of the body,	Sampling frequency 102.4 Hz, Low-pass filtered with zero-phase 2nd order Butterworth filter, 20 Hz corner frequency. Raw data analysis using Matlab (Mathworks Inc., Natick, MA., USA)
Greene [49]	SHIMMER, Dublin, Ireland Tri-axial accelerometer & gyroscope worn on each shin, lateral aspect of right thigh, Sternum above L5	Inertial sensor Sampling frequency 102.4 Hz, 2nd order Butterworth filter. Pressure sensor 40 Hz. Raw data analysis using Matlab (Mathworks Inc., Natick, MA., USA)
Chen [44]	Active Style Pro, HJA350-IT, Omron Healthcare, Co. Ltd, Kyoto, Japan) Tri-axial accelerometer. Location not specified	Details not provided
Schwenk [38]	LEGSys™, BalanSens™, PAMSys™ Locomotion Evaluation and Gait System, (BioSensics, Cambridge, MA) Tri-axial accelerometer, gyroscope, magnetometer sensors worn on shanks, thighs, and L	Sampling frequency 100 Hz Custom software LEGSys™, BalanSens™,
Martinez-Ramirez [56]	MTx XSENS,Xsens Technologies B.V. Enschede, Netherlands Tri-axial accelerometer, gyroscope & magnetometer worn at L3	Gait features were detected using automatic peak detection and identified using wavelet decomposition (Coif5 level 3)
Toosizadeh [57]	BalanSens ™ BioSensics (LLC, Brookline, Mass., USA) Triaxial accelerometer, gyroscope, magnetometer worn at shank and trunk	Sampling frequency 100 Hz Real time quaternions were converted to Eular angles
Toosizadeh [39]	BioSensics LLC Tri-axial gyroscope worn on Upper Arm near Biceps muscle and wrist	Sampling frequency 100 Hz Further details of sensor-data extraction not provided
Jansen [11]	ActiGraph GT3X + (ActiGraph, Pensacola, Florida) and BT-Q1000XT (QStarz International Co) Tri-axial accelerometer and GPS receiver worn on waist	ActiLife v5.8.3 Firmware v2.2.0, was used to process accelerometer data
Toosizadeh [53]	BioSensics LLC Tri-axial gyroscope worn on Upper Arm near Biceps muscle and wrist	Sampling frequency 100 Hz Further details of sensor-data extraction not provided
Millor [58]	MTx Orientation Tracker (WSENS, Xsens Technologies B.V., Enschede, Netherlands) Tri-axial accelerometer, gyroscope & magnetometer worn at LSp3	Sampling frequency 100 Hz. Nine individual MEMS sensors provided kinematic data. Drift-free orientation data was also provided using Kalman filters. Automated data analysis using Matlab (Mathworks Inc., Natick, MA., USA)
Parvanneh [40]	PAMSys TM (BioSensics LLC, Watertown, MA, USA), Tri-axial accelerometer worn at Sternum	Sampling frequency 50 Hz. Custom software / algorithm (PAMWare, BioSensics Cambridge, MA, USA)

Table 2 (continued)

Author (Reference n.)	Sensor type,Location and properties where provided	Acquisition, processing and analysis
Huisingh-Scheetz [35]	ActiWatch Spectrum Tri-axial piezo-electric accelerometer worn on wrist	Sampling frequency 32 Hz. Data processed using Actiware® software
Lee [52]	LEGSys™(Biosensics LLC, Watertown, MA) Tri-axial gyroscope worn on wrist and Upper arm	Sampling frequency 100 Hz, Automated raw data analysis using Matlab (Mathworks Inc., Natick, MA., USA). An algorithm was developed using zero crossing technique, with no filtering, to automate phenotype extraction
Razjouyan [41]	PAMSys™ (BioSensics LLC, Watertown, MA, USA) Tri-axial accelerometer worn at sternum	Sampling frequency 50 Hz. The raw data were processed with a band-pass filter at cut-off frequencies of 0.1953 Hz and 12.5 Hz
Castaneda-Gameros [17]	Actigraph GT3X accelerometer (Actigraph, Pensacola, FL) worn on Hip. Programmed to record activity in 60-s epochs	Data were cleaned and scored using ActiLife software V6.2
Jansen [43]	LEGSys™ (BioSensics, Cambridge, Mass., USA) Tri-axial accelerometer, gyroscope, magnetometer worn on shanks, thighs, and L	Algorithm based on accelerometer data with low-pass filtering (as described in author's earlier publication)
Zhou [54]	LEGSysTM (BioSensics, MA, USA) Tri-axial accelerometer, gyroscope, magnetometer worn on both shins	Quaternion components of ankle rotation were converted to Eular angles. Sampling frequency 100 Hz
Mulasso [42]	ADAMO System (Caretek S.r.l., Turin, Italy) Tri-axial accelerometer worn on wrist	Embedded step-count algorithm. Sampling frequency 50 Hz
Lepetit [48]	APDM (Opal, Portland, USA) Tri-axial accelerometer, gyroscope, magnetometer worn on chest	Fusion algorithm. Sampling frequency 128 Hz
Yuki [37]	Lifecorder (Suzuken, Aichi, Japan) Uniaxial accelerometer. Body-location not specified	Data recorded in 4-s epochs. No further information available
Ziller [34]	ActiGraph wGT3x-BT Tri-axial accelerometer worn at hip	Sampling frequency 100 Hz, 10-s epochs. Data processing using ActiLife Software 6, ActiGraph, LLC
Chen [55]	Active style Pro HJA- 350IT, Omron Healthcare, Kyoto, Japan Triaxial accelerometer worn at the waist	Data recorded in 60-s epochs. No further detail available
Kikuchi [36]	Active style Pro HJA-750C; Omron Healthcare, Kyoto, Japan Triaxial accelerometer worn at the hip	Data recorded in 60-s epochs. Analysis using application developed by Omron Health-care Co., Ltd to read METs data from accelerometer
Apsega [33]	SHIMMER, Dublin, Ireland Tri-axial accelerometer & gyroscope worn on each thigh, shin and dorsum of foot	Sampling frequency 256 Hz. Butterworth second order low pass filter with an 8 Hz cut-off and an additional least square method 25th order filter with a 10 Hz cut-off for composite foot acceleration data. A gait event detection algorithm was developed

Table 3 AXIS methodological quality assessment

Study	Q1	2	3	4	5	6	7	8	9	10	11	12	13*	14	15	16	17	18	19*	20	Total
Martinez-Ramirez [45]	1	1	0	1	1	0	0	1	1	1	1	1	0	0	1	1	1	1	1	1	15
Theou [24]	1	1	1	1	1	0	0	1	1	1	1	1	0	0	1	1	1	1	1	1	16
Millor [46]	1	1	0	1	1	0	0	1	1	1	1	1	0	0	1	1	1	0	1	1	14
Galan-Mercant [51]	1	1	0	1	1	0	0	1	1	1	1	1	0	0	1	1	1	0	1	1	14
Galan-Mercant [47]	1	1	0	1	1	0	0	1	1	1	1	1	0	0	1	1	1	1	0	1	14
Greene [50]	1	1	1	1	1	0	0	1	1	1	1	0	0	0	1	1	1	1	0	1	14
Greene [49]	1	1	0	1	1	0	0	1	1	1	1	0	0	0	0	1	1	1	0	1	12
Chen [44]	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	0	1	1	1	1	18
Toosizadeh [57]	1	1	1	1	1	0	0	1	1	1	1	1	0	0	1	1	1	1	1	1	16
Toosizadeh [39]	1	1	1	1	1	0	0	1	1	1	1	1	0	0	1	1	1	1	1	1	16
Schwenk [38]	1	1	0	1	1	0	0	1	1	1	1	1	0	0	1	1	1	1	1	1	15
Martinez-Ramirez [56]	1	1	0	1	1	0	0	1	1	1	1	1	0	0	1	1	1	1	1	1	15
Jansen [11]	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	20
Toosizadeh [45]	1	1	0	1	1	0	0	1	1	1	1	1	0	0	1	1	1	1	1	1	15
Parvanneh [40]	1	1	1	1	1	0	0	1	1	1	1	1	0	0	1	1	1	1	0	1	15
Millor [58]	1	1	0	1	1	0	0	1	1	1	1	1	0	0	1	1	1	1	0	1	14
Huisingh-Scheetz, [35]	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	20
Lee [52]	1	1	0	1	1	0	0	1	1	1	1	1	0	0	1	1	1	1	0	1	14
Castaneda-Gameros [17]	1	1	1	1	1	0	0	1	1	1	1	1	0	0	1	1	1	1	1	1	16
Razjouyan [41]	1`	1	0	1	1	0	0	1	1	1	1	1	0	0	1	1	1	1	0	1	14
Mulasso [42]	1	1	0	1	0	0	0	1	1	1	1	1	0*	1	1	1	1	1	0	1	14
Zhou [54]	1	1	0	1	1	0	0	1	1	1	1	1	0	0	1	1	1	1	0	1	14
Lepetit [48]	1	1	0	1	1	0	0	1	1	1	1	1	0	0	1	1	1	1	1	1	15
Jansen [43]	1	1	0	1	0	0	0	1	1	1	1	1	0	0	1	1	1	1	1	1	14
Yuki [37]	1	1	1	1	1	0	0	1	1	1	1	1	0	0	1	1	1	1	1	1	16
Ziller [34]	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	19
Chen [55]	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	20
Kikuchi, [36]	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	18
Apsega (33)	1	1	1	1	1	0	0	1	1	1	1	1	0	0	1	1	1	1	1	1	16

AXIS Methodological Quality Assessment (Yes = 1, No = 0, Not known = 0)

*Q 13 "Does the response rate raises concerns about non-response bias?" *Q19 "Were there any funding sources or conflicts of interest that may affect the authors' interpretation of the results? 'No' is a positive response, therefore 'No' counts as '1'

combination of body-locations but reports that data for PA was retrieved from only the sensor located at the chest.

Correlation between accelerometer counts and step counts in one study [24] was less in the higher FI cohort, which is surprising considering both were obtained from the same device. This perhaps suggests less sensitivity in accelerometers in detecting lower intensity of movement. This supports the idea mooted that activity below a cut-off point considered in some research as non-wear time may in fact reflect low intensity activity [61]. The same study [24] found that minute-by-minute accelerometer-derived step-count and acceleration-counts correlated positively with HR values. This is interesting considering as referred to previously, heart rate monitors capture indications of physical activities that do not require trunk displacement and can be used to indicate energy expenditure and physical activity behaviours e.g. sedentary time.

Limitations

While every effort has been made to ensure a thorough search of the relevant databases it is possible that some literature was missed. An updated search performed prior to journal submission reduces the risk of any over-sight. The inclusion of English-only publications may have resulted in omission of some relevant studies. Applying the age profile criteria of > 60 years in the inclusion may be perceived as a limitation but this was done to optimise the literature included and is in accordance with the World Health Organization and the United Nations who have adopted > 60 years in reference to older adults as opposed to the arbitrary 65 years commonly adopted [62]. Due to the heterogeneity of metrics, the variation in body-location of sensor placement and the difference in methods of analysis among the studies included in the review, meta-analysis was not possible. This however does not invalidate the findings. Many studies involved small numbers of participants and some combined frail and pre-frail cohorts for statistical analysis. This reduces the potential to discriminate between levels of frailty which is considered an important objective.

Conclusions

Despite its limitations, this review, the first to comprehensively synthesise data from the last decade of research in this field, makes a valuable contribution to identifying how wearable sensors have been utilised to assess frailty in older adults, the body-locations of sensor-placement used and the parameters of PA and mobility that best assist in the discrimination of frailty levels. The review highlights the heterogeneity of parameters examined in relation to frailty identification and the body-locations used. Measurements of PA have proved to be the most frequently used parameter when all variations of number of postural transitions, number of steps, percentage of time in PA and intensity of PA are considered. Only one study failed to demonstrate an association between PA and levels of frailty. Gait-speed was found to be the next most prevalent parameter examined, with all studies included in the review demonstrating a correlation between walking speed and levels of frailty. A higher sensitivity compared with other mobility parameters is noted.

Considering the facts that up to ninety-five percent of older adults are community-dwelling, that not all older adults develop frailty and that research suggests older adults can transition between levels of frailty, this review highlights the need for further research to identify a feasible, user-friendly device and body-location that can be used to independently identify and objectively measure signs of pre-frailty in community-dwelling older adults. This could facilitate early identification and targeted intervention to reduce the burden of frailty in an ageing population. Future reviews could focus on important open research questions related to wearable technology and older adults including acceptance, feasibility and facilitation of ageing in place.

Appendix 1. Medline (Ebsco) Search strategy / terms

Search Alert: "AB (elderly OR aged OR older OR elder OR geriatric OR elderly people OR old people OR senior) AND AB (frailty OR frail OR "frailty syndrome") AND AB (wearable technology OR wearable devices OR body-worn sensor OR inertial sensor OR inertial measurement unit OR IMU OR accelerometer OR accelerometry OR actigraphy OR pedometer OR activity monitor OR daily steps OR GPS OR global positioning system OR activity tracker OR fitness trackers OR physical activity tracking OR physical fitness tracker OR biosensing OR biosensor) AND AB (physical activity OR physical function OR mobility OR gait OR walking OR ambulation OR function OR locomotion OR mobility OR speed OR postural transition OR sit to stand OR chair stand) AND AB (validity OR validation OR validation study OR reliability OR reliability study OR accuracy OR comparison OR comparison study) Date of Publication: 20,100,101–20,201,231 AND Apply equivalent subjects on 2020–03-31 06:13 AM".

Appendix 2. Excluded studies

Author and year	Reason for exclusion
Mueller [67]	Proof of concept study. Doesn't use parameters to identify frailty
Keppler [68]	Not frailty
Chigateri [69]	Comparing algorithm with video
Soaz [70]	Validation of step-detection algorithm
Fontecha [71]	Development of app
Da Silva [72]	Used non-wearable sensors
Chkeir [73]	Used non-wearable sensors
Thiede [66]	Population studied aged < 60 year
Zhong [74]	Population studied aged < 60 year
Rahemi [75]	Population studied aged < 60 year
Martinez-Ramirez [76]	Population studied included people with cognitive impairment

Appendix 3. AXIS TOOL

AXIS Critical Appraisal Tool Yes [1] / No [0] / Don't Know [0]

Introduction

1Were the aims/objectives of the study clear?

Methods

2 Was the study design appropriate for the stated aim(s)?

3 Was the sample size justified?

4 Was the target/reference population clearly defined? (Is it clear who the research was about?).

5 Was the sample frame taken from an appropriate population base so that it closely represented the target/reference population under investigation?

6 Was the selection process likely to select subjects/participants that were representative of the target/reference population under investigation?

7 Were measures undertaken to address and categorise non-responders?

8 Were the frailty assessment tool and outcome variables measured appropriate to the aims of the study?

9 Were the frailty assessment tool and outcome variables measured correctly using instruments/ measurements that had been trialled, piloted or published previously?

10 Is it clear what was used to determined statistical significance and/or precision estimates? (e.g., p values, CIs).

11 Were the methods (including statistical methods) sufficiently described to enable them to be repeated?

Results

12 Were the basic data adequately described?

13 *Does the response rate raise concerns about non-response bias?

14 If appropriate, was information about non-responders described?

15 Were the results internally consistent?

16 Were the results for the analyses described in the methods, presented?

Discussion

17 Were the authors' discussions and conclusions justified by the results?

18 Were the limitations of the study discussed? Other.

19 *Were there any funding sources or conflicts of interest that may affect the authors' interpretation of the results?

20 Was ethical approval or consent of participants attained?

*Negative answer results in 'Y' Yes = 0; No = 1.

Abbreviations

AXIS: Appraisal Tool for Cross-sectional Studies; CPM: Counts per minute; F: Frailty; FI: Frailty Index; FFP: Fried's Frailty Phenotype; ISAR-HP: Identification Seniors At Risk-Hospitalized Patients' questionnaire; LSp: Lumbar Spine; MVPA: Moderate – Vigorous Physical Activity; NF: Non-Frail; PICO: Population, Intervention, Comparator and Outcome; PF: Pre-Frail; PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses; PROSPERO: Prospective Register Of Systematic Reviews; STS: Sit To Stand; St-Si: Stand to Sit; TUG: Timed Up and Go.

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Authors' contributions

Concept and Design: OMG, GV. Data acquisition: GV. Full text screening: GV, OMG JD, Data extraction: GV. Manuscript preparation and editing: GV, OMG, JD and DK. All authors read and approved the final manuscript.

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Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

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Competing interests

The authors declare that they have no competing interests.

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