Assessing Upper Extremity Motion: An Innovative Method to Identify Frailty

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OBJECTIVES: To objectively identify frailty using wireless sensors and an innovative upper extremity motion assessment routine that does not rely on gait.

DESIGN: Validation study.

SETTING: Southwestern tertiary academic medical center, Tucson, Arizona.

PARTICIPANTS: Convenience subsample of the Arizona Frailty Cohort, a community-dwelling older adults (≥65; n = 117; 50 nonfrail, 51 prefrail, 16 frail).

MEASUREMENTS: Wireless sensors were attached to the upper arm and forearm with bands, and subjects performed repetitive elbow flexion for 20 seconds on each side. Information was extracted on objective slowness, weakness, exhaustion, and flexibility measures, and associations between parameters and Fried frailty categories were determined.

RESULTS: Speed of elbow flexion (slowness) was 29% less in prefrail and 59% less in frail than in nonfrail controls ($P < .001$), power of movement (weakness) was 61% less in prefrail and 89% less frail ($P < .001$), and speed variation (exhaustion) was 35% more in prefrail and 272% more in frail ($P < .001$). Using elbow flexion parameters in regression models, sensitivity and specificity of 100% were achieved in predicting frailty and sensitivity of 87% and specificity of 95% in predicting prefrailty compared to Fried frailty category.

CONCLUSION: The suggested innovative upper extremity frailty assessment method integrates low-cost sensors, and the physical assessment is easily performed in less than 1 minute. The uniqueness of the proposed technology is its applicability in older nonambulatory individuals, such as those in emergency settings. Further improvement is warrant to make it suitable for routine clinical applications. **J Am Geriatr Soc 63:1181–1186, 2015.**

Key words: frailty; upper limb; kinematics; immobile; geriatric

Older adults are at a high risk of disability, long-term hospitalization, unfavorable discharge, and death after injury, but age itself is a poor indicator of risk because of the heterogeneity of older adults.[1–3] The concept of "frailty" is used to identify homeostenotic older adults with low physiological reserves and vulnerability to illness and high risk of disability, institutionalization, and death.[4,5] Despite increasing evidence of the benefit of assessing frailty to provide optimal decision-making, the common approaches to identifying frailty are limited; most are clinically cumbersome and time consuming (e.g., Rockwood)[6] or are based on gait-centered measures (e.g., Fried),[4] which are not useful for mobility-impaired individuals. A sensitive and specific measure of frailty that does not rely upon gait parameters would be useful for older adults across settings.

An innovative method of identifying frailty categories using assessment of upper extremity frailty (UEF), incorporating several kinematic and kinetics parameters of elbow flexion, is presented. Previous studies have demonstrated that slowness of movements and weakness, measured using gait speed and grip strength, are markers of frailty.[4] Upper extremity range of motion (flexibility) and muscle fatigue (exhaustion) have also been observed as frailty features.[4,7] In the current study frailty groups were classified based on slowness, weakness, flexibility, and exhaustion while performing a short-duration upper extremity elbow flexion task.

METHODS

UEF Validation Using Motion Capture System

One triaxial wearable gyroscope sensor (sample frequency 100 Hz, BioSensics LLC, Brookline, MA) was attached to the upper arm near the biceps and one to the wrist using a band attached with hook and loop straps to estimate

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three-dimensional angular velocity of the upper arm and forearm segments and ultimately elbow flexion. Because the UEF task involves repetitive elbow flexion, to evaluate the accuracy of wearable UEF system, angles measured during the task were compared with angles measured using a motion capture system (Vicon Ltd. UK, Oxford, UK) as the reference system. For this purpose, five healthy young adults (60% male; age 24 ± 4.5, height 172.2 ± 11.7 cm, weight 67.4 ± 13.9 kg) were recruited after providing informed consent (as approved by the University of Arizona institutional review board). Comparing elbow flexion measurement of the two systems, mean root mean square errors and correlation coefficients (r) of 9.2 degrees and 0.99 for slow and 9.5 degrees and 0.99 for fast elbow flexion, respectively, were observed, indicating high agreement between sensor- and reference-derived body segment angles.

Participants

A community-dwelling convenience subsample of the Arizona Frailty Cohort of older adults (≥65) from a southwestern tertiary academic medical center with no major mobility or upper extremity disorders was recruited, provided informed consent, and was seen at home. Participants with Mini-Mental State Examination (MMSE)[7] scores less than 24 were excluded.

Frailty Evaluation

The Fried criteria[4] were used as the criterion standard (unintentional weight loss, self-reported exhaustion, weakness (grip strength), slow walking speed, low physical activity). Individuals with three or more positive Fried criteria were considered frail, with one or two prefrail, and with none nonfrail.

In-Home UEF Procedure

Each participant performed an approximately 50-second trial of elbow flexion, during which they repetitively fully flexed and extended their elbow as quickly as possible in the seated position in a chair while wearing the UEF system. First, each participant performed a short practice trial to become familiar with the protocol. Then the UEF procedure started with 20 seconds of elbow flexion of the right arm, 10 seconds rest, and 20 seconds of elbow flexion of the left arm; no specific instruction was used regarding upper arm motion. Twenty seconds of flexion was used based on pilot data indicating time needed to capture alterations in elbow angular velocity due to exhaustion in healthy persons to avoid ceiling effects. The protocol was explained to participants, and they were encouraged only once, before elbow flexion, to perform the task as fast as possible. (Participants were not further encouraged during the task.)

UEF Outcome Measures

Several outcome measures representing kinematics and kinetics of elbow flexion were derived using angular velocity and anthropometric data (height and weight). The assessor was blinded to the Fried frailty score. Outcome measures were speed, flexibility, power, rise time, moment, jerkiness, and speed reduction. Speed was calculated as the mean value of elbow angular velocity range (maximum minus minimum speed) during 20 seconds of flexion. Similarly, flexibility was determined as the mean value of elbow flexion range. Angular acceleration of elbow flexion was calculated, and the mean value of product of the angular acceleration range and the range of angular velocity within 20 seconds of elbow flexion was considered as “power.”[8] Rise time was defined as the mean value of time required to reach the maximum angular velocity. Similar to previous work,[9] moment on elbow ($\vec{M}$) within each flexion and extension was estimated from moment of inertia of forearm and hand (I) and elbow angular velocity ($\vec{\omega}$) and angular acceleration ($\vec{\alpha}$), as follows:

$$\vec{M} = I.\vec{\alpha} + \vec{\omega} \times (I.\vec{\omega})$$

Moment of inertia was calculated from sex and anthropometric data.[10] The mean value of maximum moments during 20 seconds was considered the “moment” parameter. Jerkiness was estimated as the coefficient of variation (standard deviation divided by the mean) of angular velocity range, and speed reduction was calculated as the difference in angular velocity range between the last and the first 5 seconds of elbow flexion and reported as a percentage of initial angular velocity range. The total number of elbow flexions for each arm was also measured. These parameters were defined to quantify slowness, weakness, and exhaustion as Fried frailty criteria[4] and flexibility as an additional frailty marker.[11] Slowness was assessed by measuring speed and rise time, weakness was assessed by measuring power and moment, and exhaustion was assessed by measuring jerkiness and speed reduction.

For all outcome measures, the mean values of the right and left arms were quantified, using forearm and upper arm sensors to estimate elbow angle. In addition, the analysis was repeated for three additional scenarios: two sensor–single arm: Condition 1 (data from both sensors were extracted from each arm (each arm was assumed as an independent sample)), single sensor–two arms: Condition 2 (data from a single sensor attached to the forearm were extracted from both arms (data were averaged between the right and left arms)), and single sensor–single arm: Condition 3 (data from a single sensor attached on forearm were extracted only from the right arm).

Statistics

UEF parameters of three frailty groups were compared using separate analyses of variance (ANOVAs) with age, sex, and body mass index (BMI) as covariates; post hoc Tukey honestly significant difference (HSD) tests were performed for three pairwise comparisons of UEF parameters among frailty groups. Multivariate logistic regression models were used to compare the accuracy of the UEF model in predicting prefrailty and frailty with that of the Fried index. Accordingly, independent associations between UEF parameters and frailty were assessed, using frailty (indicated using Fried index) as the dependent variable; UEF parameters as independent variables; and age, sex, and, BMI as covariates. The sensitivity and specificity of prefrailty and frailty predictions using UEF parameters and odds ratios were estimated. Linear correlations were calculated between gait speed and UEF parameters and between grip strength and UEF parameters to compare continuous measures in the Fried index (slowness and weakness) and UEF measures. Differences between UEF parameters and dichotomous measures in the Fried index (weight loss, exhaustion, physical activity criteria) were assessed using ANOVA, and effect sizes were calculated. All analyses were conducted using JMP version 10 (SAS Institute, Inc., Cary, NC), and statistical significance was set at $P < .05$.

RESULTS

Participants

One hundred seventeen older adults participated in the study (50 (43%) nonfrail, 51 (43%) prefrail, 16 (14%) frail based on Fried criteria; Table 1).

UEF Prediction

From ANOVA, all parameters extracted from the UEF task were significantly different between frailty groups (Table 2). Results from Tukey HSD tests indicated that speed, flexibility, power, rise time, moment, speed reduction, and number of flexions were significantly different between nonfrail and prefrail participants. Speed, flexibility, rise time, jerkiness, speed reduction, and number of flexions were significantly different between prefrail and frail participants (Table 2), with speed, power, and jerkiness having the largest effect sizes. Speed of elbow flexion was 29% slower in prefrail than nonfrail participants and 42% slower in frail than prefrail participants. Likewise, power of movement was 61% less in prefrail than nonfrail participants and 70% less in frail than prefrail participants. The results from elbow flexion showed that jerkiness was 35% greater in prefrail than nonfrail participants and 175% greater in frail than prefrail participants.

From the logistic regression model, sensitivity and specificity of 100% were achieved in predicting frailty (Table 2). Similarly, in predicting prefrailty, sensitivity was 87% and specificity 95%. These results suggest 49% better accuracy in frailty predictions and 110% better accuracy in prefrailty predictions than when only age, sex, and BMI were used as independent variables.

As expected, Fried gait speed had the strongest correlation with rise time, which is related to the slowness frailty marker (Table 3). Fried grip strength had the strongest correlation with elbow moment among UEF parameters, which represents weakness. From ANOVA, the greatest effect sizes between the exhaustion, physical activity, and weight loss Fried categories were found for the speed reduction, jerkiness, and moment parameters, respectively.

From two sensor–single arm data (Condition 1), prefrail categorical sensitivity of 85% and specificity of 98% were achieved when data from only the right side were used; corresponding values were 74% and 97% when left-side data were used. From single sensor–two arm data (Condition 2), sensitivity was 87% and specificity 89% for the prefrail. Finally, using single sensor–single arm data (Condition 3), it was possible to predict prefrailty with 85% sensitivity and 93% specificity. For all these conditions, frailty was predicted with 100% sensitivity and specificity.

DISCUSSION

Advantages of UEF Frailty Meter

As hypothesized, it was possible to categorize frailty groups with high sensitivity and specificity using a quick, simple upper extremity task. Previous studies suggested that, to identify frailty efficiently, the method should cover a wide range of physiological factors related to frailty.[12,13] The proposed method takes into account all Fried frailty features except weight loss. Overall, the slowness marker

Table 1. Participant Demographic Characteristics and Fried Criteria

Characteristic	Nonfrail, n = 50 (43%)	Prefrail, n = 51 (43%)	Frail, n = 16 (14%)	*P*-Value	Effect Size
Male, n (%)	9 (18)	15 (29)	1 (6)	.08	
Age, mean ± SD	75.3 ± 6.8	79.7 ± 8.7	85.4 ± 7.0	<.001	0.45
Height, cm, mean ± SD	159.3 ± 7.4	160.0 ± 8.3	156.6 ± 10.3	.36	0.13
Weight, kg, mean ± SD	68.3 ± 12.8	77.2 ± 20.6	75.3 ± 20.1	.04	0.24
Body mass index, kg/m^2, mean ± SD	26.9 ± 4.6	30.1 ± 7.6	30.6 ± 6.5	.02	0.27
Mini-Mental State Examination score, mean ± SD	29.1 ± 1.3	28.6 ± 1.5	28.6 ± 1.8	.26	0.16
Grip strength from Fried index, kg, mean ± SD	25.9 ± 6.2	22.7 ± 7.3	16.1 ± 5.8	<.001	0.49
15-foot walking time from Fried criteria, seconds, mean ± SD	4.7 ± 0.8	7.2 ± 2.4	16.1 ± 10.0	<.001	1.02
Observed Fried criteria, n (%)					
Weight loss	0 (0)	3 (6)	3 (19)	.01	
Weakness	0 (0)	19 (37)	13 (81)	<.001	
Slowness	0 (0)	28 (55)	15 (94)	<.001	
Exhaustion	0 (0)	12 (24)	12 (75)	<.001	
Low activity	0 (0)	7 (14)	12 (75)	<.001	

Participant classification based on Fried criteria.
SD = standard deviation.

Table 2. Results for UEF Parameters for Nonfrail, Prefrail, and Frail Groups

Parameter	Group	Mean ± Standard Deviation	P-Value (ES)	Group	Pairwise P-Value (ES)	Pairwise 95% CI	OR (95% CI)
Speed, degrees/s	Nonfrail	1,117 ± 247	<.001 (1.05)	N and P	<.001 (1.48)	165–382	1.00 (0.98–1.02)
	Prefrail	792 ± 187		N and F	<.001 (2.83)	378–704	1.10 (1.09–1.12)
	Frail	461 ± 215		P and F	<.001 (1.64)	118–416	1.00 (0.95–1.05)
Flexibility, degrees	Nonfrail	134 ± 22	<.001 (0.65)	N and P	.006 (0.83)	4–29	1.04 (0.97–1.13)
	Prefrail	115 ± 24		N and F	<.001 (1.99)	24–62	1.67 (1.59–1.84)
	Frail	87 ± 28		P and F	<.001 (1.07)	9–43	1.03 (0.88–1.22)
Power, $degrees^2/s^3 \times 100,000$	Nonfrail	205.1 ± 116.3	<.001 (1.02)	N and P	<.001 (1.44)	63.8–148.4	1.00 (0.99–1.01)
	Prefrail	79.3 ± 40.5		N and F	<.001 (2.19)	71.9–201.0	1.00 (0.99–1.01)
	Frail	23.5 ± 15.7		P and F	.45 (1.82)	–28.9–89.5	1.00 (0.99–1.01)
Rise time, seconds/100	Nonfrail	26.0 ± 4.5	<.001 (0.75)	N and P	.01 (1.05)	9.9–1.0	1.08 (0.82–1.40)
	Prefrail	32.6 ± 7.7		N and F	<.001 (1.33)	21.3–7.9	3.63 (2.58–4.40)
	Frail	43.6 ± 18.1		P and F	.001 (0.79)	15.2–3.1	0.95 (0.66–1.21)
Moment, Nm	Nonfrail	59.5 ± 26.4	<.001 (0.64)	N and P	<.001 (0.64)	7.1–27.5	1.00 (0.99–1.01)
	Prefrail	43.6 ± 23.4		N and F	<.001 (2.26)	15.8–48.5	1.00 (0.99–1.01)
	Frail	15.4 ± 8.1		P and F	.05 (1.61)	0–30.0	1.00 (0.99–1.01)
Jerkiness, %	Nonfrail	8.8 ± 2.7	<.001 (0.94)	N and P	.45 (0.76)	10.9 to –3.6	0.70 (0.46–0.99)
	Prefrail	11.9 ± 5.1		N and F	<.001 (0.93)	35.2–12.7	2.12 (1.30–2.75)
	Frail	32.7 ± 36.3		P and F	<.001 (0.80)	30.5–10.1	1.01 (0.82–1.20)
Speed reduction, %	Nonfrail	1.7 ± 5.1	<.001 (0.76)	N and P	.04 (0.81)	10.7–0	0.95 (0.81–1.10)
	Prefrail	7.4 ± 8.5		N and F	<.001 (1.26)	28.6–10.8	1.31 (0.94–1.55)
	Frail	22.8 ± 23.1		P and F	<.001 (0.88)	22.4–6.1	0.98 (0.79–1.22)
Number of flexions	Nonfrail	23.7 ± 5.0	<.001 (0.78)	N and P	<.001 (1.14)	1.7–6.0	1.40 (0.92–2.23)
	Prefrail	18.5 ± 4.1		N and F	<.001 (2.12)	4.0–10.5	4.33 (3.51–5.97)
	Frail	13.4 ± 4.7		P and F	.02 (1.16)	0.4–6.4	1.49 (0.59–3.88)

Odds ratios (ORs) from regression models for predicting frailty are presented.
N = nonfrail; P = prefrail; F = frail; CI = confidence interval; ES = effect size.

Table 3. Association Between Fried Criteria and Upper Extremity Frailty Parameters

Criterion	Speed	Flexibility	Power	Rise Time	Moment	Jerkiness	Speed Reduction	Number of Flexion
Walking time/15 feet, *r* (*P*-value)	–0.60, (<.001)	–0.38, (<.001)	–0.43, (<.001)	0.68, (<.001)[a]	–0.41, (<.001)	0.58, (<.001)	0.60, (<.001)	–0.56, (<.001)
Grip strength, *r* (*P*-value)	0.58, (<.001)	0.32, (.001)	0.47, (<.001)	–0.52, (<.001)	0.67, (<.001)[a]	–0.33, (.004)	–0.38, (.001)	0.53, (<.001)
Exhaustion, ES (*P*-value)	1.33, (<.001)	0.85, (<.001)	1.20, (<.001)	0.81, (<.001)	1.07, (<.001)	1.32, (<.001)	1.38, (<.001)[a]	1.19, (<.001)
Physical activity, ES (*P*-value)	1.20, (<.001)	0.88, (<.001)	1.19, (<.001)	0.73, (<.001)	0.97, (<.001)	1.38, (<.001)[a]	0.85, (<.001)	0.97, (<.001)
Weight loss, ES (*P*-value)	0.53, (.22)	0.68, (.20)	1.13, (.10)	0.22, (.59)	0.99, (<.05)[a]	0.13, (.81)	0.12, (.85)	0.84, (.10)

[a] Highest association between upper extremity frailty parameters and each of the Fried criteria.
r = correlation coefficient; ES = effect size.

was more sensitive in discriminating prefrail from nonfrail participants, whereas weakness better distinguished frail from prefrail (Tables 1 and 2). Correspondingly, speed of elbow flexion showed the largest effect size in distinguishing between nonfrail and prefrail participants, and power of movement had the largest effect size for differentiating between prefrail and frail participants. Also, moderate to strong correlations or associations between UEF parameters and the Fried measures, specifically between walking speed and rise time, grip strength and elbow moment, and exhaustion and speed reduction, support the appropriateness of this method in accounting for several frailty features.

A major advantage of the current method is its independence from a walking test, which makes it suitable for bedbound individuals or where there is inadequate space. Handgrip strength is one of the five criteria for frailty assessment In the Fried index.[4] The UEF test is shorter and less strenuous than the handgrip test and covers several frailty markers in addition to weakness. In another study that involved arm motion for identifying frailty, participants were asked to perform a rapid focal arm-raising movement, pointing to a stimuli in standing posture, while their balance was measured using a force platform.[14] According to their results, slower hand movement was observed in frail participants than healthy controls; the prefrail category was excluded in their study. Another study used upper extremity function while picking up a full glass, touching the scapula, cutting with a knife, and unfastening a button in hospitalized older adults; the association between upper extremity tasks and adverse events, but not frailty status, was investigated.[15] The current study therefore examines the first methodology for identifying frailty that involves arm movement in the seated or supine position.

Alternative UEF Measurement Conditions

One limitation of using arm movement in elderly adults is the high prevalence of upper extremity osteoarthritis.[16,17] Therefore, performing the UEF task only on one side might be more feasible. Although there was a slight difference in UEF accuracy between the right and left arms, probably because of dominant arm strength, results showed that using two sensor–single arm UEF data provided acceptable accuracy for measuring frailty. It was also observed that participants kept their upper arms steady during the elbow flexion and that most of the motion resulted from forearm flexion. To confirm this, the procedure was repeated using data from one sensor considering only forearm movement, and negligible reduction in frailty prediction quality was observed. Overall, based upon a 20-second right arm elbow flexion task using one forearm sensor, it was possible to demonstrate high sensitivity and specificity (>85%), only slightly less than when using the two sensor–single arm data.

Limitations

As with measurement limitations in gait-based frailty measures, upper extremity disability or injury may limit measurement. It is likely that this limitation would also apply to measuring grip strength, which would also limit measurement of the Fried Frailty Index. Individuals with MMSE scores of less than 24 were excluded; the results should be validated in future studies in individuals with cognitive impairment. Also, although not significantly different, the percentage of female participants in frailty groups was larger. Sex was accounted for as a covariate in statistical analyses.

Summary and Clinical Implications

It was possible to identify frailty objectively using a simple, quick upper extremity motion. This method discriminated significantly between frailty categories in speed of elbow flexion (slowness marker), strength of muscles in performing the task (weakness marker), exhaustion in performing elbow flexion, and flexibility of upper extremity joints. It was possible to predict frailty and prefrailty with a sensitivity of 94% and a specificity of 98% when compared with the Fried criteria. Although evaluated in a small convenience sample of community-dwelling older adults, participants represented the ethnicity, racial, and sex distribution and frailty prevalence of a community cohort of elderly adults aged 65 and older. In addition, the sample included homebound elderly adults, who are often excluded from clinical studies. The findings are evidence of a quick, sensitive, specific UEF measurement method with high clinical promise for older adults in community and acute settings. UEF longitudinal outcomes, including hospitalization, falls, disability, institutionalization, and mortality, will be compared with frailty measures such as Fatigue, Resistance, Ambulation, Illness, Loss of weight,[18,19] the Fried criteria,[4] the Frailty Index,[6] and the Study of Osteoporotic Fractures.[20] The test–retest reliability and feasibility of the UEF frailty meter will be assessed in a larger sample size, in differing types of individuals in differing healthcare settings.

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