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Validation

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Chair-Rising Power as Digital Biomarker: Validation against Jumping Power and Chair-Rising Time in Adults Aged 32–92 Years

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Keywords

Sit-to-stand test · Digital mechanography · Geriatric assessment · Rehabilitation

Abstract

Introduction: The chair-rising test (CRT) is being widely used to assess lower body power. The test provides valuable information about functional capacity and other health outcomes. However, most centers use timing-based outcomes, which may compromise its suitability in younger people and fitter geriatric patients, and which may also introduce confounding effects of body height. We, therefore, aimed to compare the traditional use of timing-based outcome with digitally assessed measurements of neuromuscular power. ***Methods:*** Data were collected from a longitudinal population-based study that examined changes in muscle and bone health. CRT and jumping mechanography were performed on a ground reaction force plate. In 346 people (age: 32–92 years), chair-rising rate (fCRT) was manually assessed, and peak chair-rising power (PCRT) and jumping power (PJMG) were computed. Statistical analyses targeted breakpoints in the relationships between fCRT, PCRT, and PJMG. Effects of age, body height, and sex were assessed with linear and partial regression analyses. ***Results:*** Breakpoints were found at (fCRT = 0.778 Hz, PJMG = 35.2 Watt/kg, $p < 0.001$) and at (fCRT = 0.669 Hz, PCRT = 9.9 Watt/kg, $p < 0.001$). Slow chair-risers, defined by fCRT <0.669 Hz, were older than fast chair-risers ($p < 0.001$), albeit with a largely overlapping age range (fast chair-risers: 32–90 years, slow chair-risers: 32–92 years). Body height was correlated with fCRT ($p < 0.001$) and PCRT ($p = 0.009$) but not with PJMG ($p = 0.59$). ***Conclusion:*** Timing-based CRT does not unequivocally reflect neuromuscular power. Its association with chair-rising power holds only in people who take more than 75 s for 5 stand-ups. For jumping power, the cutoff is at 6.4 s. Slow and fast chair-risers cannot be easily discerned by age. Bias by body height can substantially obscure age effects in timing-based CRT assessments. We conclude that chair-rising power represents a more universally applicable biomarker and is less influenced by body height compared to timing-based chair-rising assessments.

Plain Language Summary

The chair-rising test (CRT), also known as the sit-to-stand test, is widely used to examine neuromuscular power in geriatrics and rehabilitation medicine. However, for mechanical reasons, the timing-based outcome values from this test may be prone

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to ceiling effects and contaminated by body height. For defining a digital biomarker, we compared traditional timing-based values with power-based outcomes from digital force plate recordings during chair-rising. Second, we compared the digital power-based outcomes of the CRT and vertical jumping tests as the latter is a widely accepted test of neuromuscular fitness. To compare the different outcome values, we used data from 346 people between 32 and 92 years of age. Statistical analyses revealed a "ceiling" effect for timing-based assessment, so that it becomes moot in people who could perform 5 chair-rises within approximately 7 s or less. Moreover, we found that timing-based assessments are contaminated by effects of body height. This latter effect can obscure age effects in the order of magnitude of 10 years. Chair-rising power was highly correlated with vertical jump power, and no breakpoints with age and no substantial contamination by height were found for either of the power-based assessments. We conclude that digital power assessments are superior to the traditional timing-based chair-rising assessments. Most importantly, these digital assessments are applicable over an ample age range. We suggest using chair-rising power as a widely applicable biomarker.

Introduction

The chair-rising test [1] (CRT), also known as the sit-to-stand test, is commonly used in medical research and in practice to assess lower body power and functional mobility. Technically, it measures the speed of repeated rising from a seated position without using the arms for assistance. It provides valuable information about functional capacity and mobility [2], can predict falls and disability [3], and it is, therefore, used to evaluate the effectiveness of clinical interventions [4]. Moreover, CRT is often used as part of a test battery, such as the Short Physical Performance Battery [5], and it shares the sit-to-stand element with the timed up-and-go (TUG) test. However, manual timing is a source of variation and potentially introduces bias. Digital mechanographic methods of assessment are nowadays available for examining neuromuscular power [6–8]. Thus, jumping mechanography (JMG) has been shown to capture the effects of age, sex, and even athletic specialization in numerous studies [9]. Moreover, it is also possible to perform the traditional CRT on a force platform and thereby convert it into a digital mechanographic assessment. Unfortunately, however, such methods have not yet found their way into clinical routine.

Using digital mechanography does not only have potential for improving test reliability and reducing bias, but it also allows the calculation of neuromuscular power. This could be beneficial for the following reasons. From a mechanical viewpoint, the CRT task represents an elevation of the body's center of gravity (CoG), and hence attainment of potential energy. To accomplish that potential energy, muscles accelerate the CoG on the way up, while acceleration on the way down is solely driven by gravity. If the upward acceleration at stance onset exceeds 1 *g*, this will result in take-off and a subsequent flight phase. All that expands the time required for task, which will penalize fitter people. There is, therefore, an implicit boundary condition contained for optimal test performance, which consists in attaining 1 *g* at stance onset. This will make it physically difficult to supersede a given rate of chair-rising rate, thereby construing a ceiling effect for fitter people. Based on these considerations, we hypothesized that such ceiling effect would indeed exist, and we ventured to the neuromuscular power breakpoint that it is related to. In support of our hypothesis, such a breakpoint was previously specified at a peak jumping power of 23.7 W/kg in the relationship with TUG [10].

Furthermore, the energy was involved in CoG-elevation scales with body height. This is because the CoG must cover a greater vertical displacement in talker than in shorter people. This effect must be expected to penalize tall stature, which is a potential source of measurement bias. However, to the best of our knowledge that effect hast not yet been studied. We hypothesized that stature would be negatively associated with chair-rising time.

Therefore, our objective was to compare power-based outcomes of neuromuscular power with the traditional timing-based CRT. We, therefore, ventured to compare classically assessed, timing-based CRT readings with power-based CRT and (JMG). For this purpose of this article, we re-analyzed data from the Prodigy study [11], which has assessed CRT and JMG in a cohort with a wide range of physical abilities. We hypothesized that timing-based CRT assessment would show a "ceiling" effect for younger people with greater neuromuscular power. To test this hypothesis, we analyzed CRT time, JMP power and JMG power by (a) breakpoint analysis and (b) linear correlation and regression for association with body height.

Methods

Participants

The present article is a secondary analysis of data that were collected as part of the German project "Prodigy." The purpose of this longitudinal cohort study was to examine changes over time in body composition (primary endpoint), bone health, muscle strength, and muscle

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power in a randomly selected sample of 20- to 90-year-old women and men in Berlin, Germany. The subjects recruited for the baseline evaluation were randomly selected and age and sex stratified from the resident registration office in Berlin, Germany (n = 780).

After 6 years, the subjects of the baseline examination were invited for follow-up. For the current manuscript, data of the participants who attended the second investigations were used. The exclusion criteria for both visits were (1) lack of feasibility of whole body composition using DXA, (2) contraindications for X-ray exposure, (3) pregnancy, (4) cognitive impairment that prevented informed consent. All examinations were performed at the Centre for Muscle and Bone Research at the Charité – Universitätsmedizin Berlin.

Test Methods

Body weight was determined to the nearest 0.1 kg, and stature was assessed to the nearest 0.1 cm using a digital weight scale and stadiometer (Seca 764). CRT was performed on a Leonardo GRF platform (Novotec Medical, Pforzheim, Germany) with the integrated standard bench with 45 cm height. Only one repetition was allowed, as is typically done for CRT in most settings. Time required for 5 consecutive stand-ups and sit-downs was manually recorded with a stopwatch. In addition, the Leonardo software was used to compute the peak chair-rising power (P_{CRT}). From the GRF, peak power of the COG (P_{JMG}) was computed in W/kg by the integrated Leonardo software (version 4.2). This software computes the COG's vertical power as the product of force and velocity, with velocity being obtained from the integration of acceleration [12, 13]. JMG was likewise performed and recorded with the Leonardo hardware and software. Participants were asked by an experienced examiner to perform countermovement jumps, with their hands moving freely. We chose to assess 3 JMG repetitions as that number is used in most settings. When participants were not willing or unable to perform a test, reasons were documented.

Statistical Methods

From the 3 P_{JMG} values within each participant, the median was used for further processing as the most robust value [14]. Statistical processing was performed with R (www.r-project.org, version 4.2.1) and the RStudio environment (version 2023.03.0). For a given physical work (e.g., CoG elevation), power is inversely related to the time for accomplishment. Therefore, CRT time (t_{CRT}) was converted into a measure of power by computing chair-rising rate as $f_{CRT} = 5/t_{CRT}$, given in Hz.

Differences between sexes and between those who did or did not perform JMG were assessed by unpaired t-tests and Chi-squared tests. Breakpoint analyses [15] were performed with the R-package "segmented". The effect of body height on muscle-power estimate y was assessed with the R-function "lm", using the formula y = age + sex + body height. From the statistical models thus obtained, partial regression analyses were performed with the function "r2beta" from the R-package "r2glmm". Sensitivity analysis for the effects of body height on fCRT was performed with the R-function "predict.lm". The level of statistical significance was set to 5%.

Results

Recruitment and data collection lasted from November 2014 until December 2016. As shown in Table 1, men and women were comparable in age (p = 0.23), but men had greater body height, body mass, and body mass index than women (all $p < 0.01$). As can be seen from Table 2, twelve participants (8 women, 4 men) refrained from JMG. These participants were characterized by use of walking stick, an older age and lesser f_{CRT} and P_{CRT} (all $p < 0.001$), but similar in terms of body height (p = 0.18), body mass (p = 0.54), and BMI (p = 0.83).

Breakpoint Analysis

As shown in Figure 1a, analyses revealed breakpoints at 9.9 W/kg and 0.669 Hz (i.e., 7.5 s for 5 stand-ups) in the P_{CRT}-f_{CRT} relationship ($p < 0.001$), and at 35.2 W/kg and 0.778 Hz (i.e., 6.4 s for 5 stand-ups) in the P_{JMG}-f_{CRT} relationship ($p < 0.001$), as depicted in Figure 1b. These breaking points correspond to the 39%-ile and the 76%-ile, respectively, of the f_{CRT} distribution. No breakpoint was detectable between P_{JMG} and P_{CRT} (p = 0.24), as depicted in Figure 1c. To further explore the age distribution of data points below and above the P_{CRT}-breakpoint, data were split at 0.669 Hz into "fast" and "slow" CRT participants. As shown in Table 3, slow chair-risers were older and had lesser P_{CRT} and P_{JMG} than fast chair-risers (all $p < 0.001$), but did not differ in body height (p = 0.66), body mass (p = 0.27), or BMI (p = 0.065). However, although age differences between slow and fast chair-risers were statistically significant, there was substantial overlap between these two groups, as depicted in Figure 1d. As revealed by Figure 2, there were no breakpoints identified for the age-relationships of P_{JMG}, P_{CRT}, f_{CRT} or body height (all $p > 0.20$).

Effects of Body Height

As shown in Figure 2d, body height was negatively associated with age ($p < 0.001$). Table 4 presents results of regression and partial regression analyses for f_{CRT}, P_{CRT},

Table 1. Demographic characteristics and p values for the effect of sex

	Women (N = 185)	Men (N = 161)	Total (N = 346)	p value
Age, years				0.23
Mean (SD)	61.48 (14.86)	62.64 (15.35)	62.02 (15.08)	
Range	32–89	32–92	32–92	
Body height, cm				<0.001
Mean (SD)	163.61 (6.79)	176.44 (6.95)	169.58 (9.38)	
Range	144–185	157–199	144–199	
Body mass, kg				<0.001
Mean (SD)	70.09 (12.17)	86.33 (13.64)	77.65 (15.20)	
Range	46.4–106.7	54.7–130.1	46.4–130.1	
BMI, kg/m^2				0.002
Mean (SD)	26.20 (4.34)	27.70 (3.85)	26.90 (4.18)	
Range	18.50–38.50	17.88–41.07	17.88–41.07	

Table 2. Comparison of demographic data and chair-rising test (CRT) endpoints between those who performed jumping mechanography (JMG) and those who refrained from it

	JMG performed (N = 334)	JMG not performed (N = 12)	p value
Sex			0.52
Women	177 (53.0%)	8 (66.7%)	
Men	157 (47.0%)	4 (33.3%)	
Walking aids			<0.001
None	334 (100.0%)	9 (75.0%)	
Cane	0 (0.0%)	3 (25.0%)	
Age, years			<0.001
Mean (SD)	60.94 (14.36)	77.17 (11.89)	
Range	32–92	54–90	
Body height, cm			0.18
Mean (SD)	169.68 (9.44)	166.67 (7.22)	
Range	144–199	155–177	
Body mass, kg			0.54
Mean (SD)	78.45 (14.86)	76 (13.18)	
Range	46.36–130.13	56.00–99.00	
BMI, kg/m^2			0.83
Mean (SD)	27.15 (4.04)	27.48 (5.19)	
Range	18.66–41.07	21.08–34.66	
f_{CRT}, Hz			<0.001
Mean (SD)	0.66 (0.17)	0.42 (0.17)	
Range	0.17–1.11	0.14–0.72	
P_{CRT}, Watt/kg			<0.001
Mean (SD)	10.86 (2.68)	6.61 (2.64)	
Range	4.99–17.72	1.74–12.42	

f_{CRT} stands for chair-rising rate (i.e., the inverse of chair-rising time) and P_{CRT} for chair-rising power.

and P_{JMG}, detailing their associations with sex, age, and body height. Total R^2 of the regression model was largest for P_{JMG} and lowest for f_{CRT}. While age contributed to all 3 regressions (all $p < 0.001$), sex contributed only to the regressions of P_{JMG} and P_{CRT} (both $p < 0.001$), but not to f_{CRT} ($p = 0.077$). Body height did not contribute to the regression of P_{JMG} ($p = 0.59$), and its contribution was small for f_{CRT} and P_{CRT} (both $p = 0.001$, $R^2 = 0.04$ and

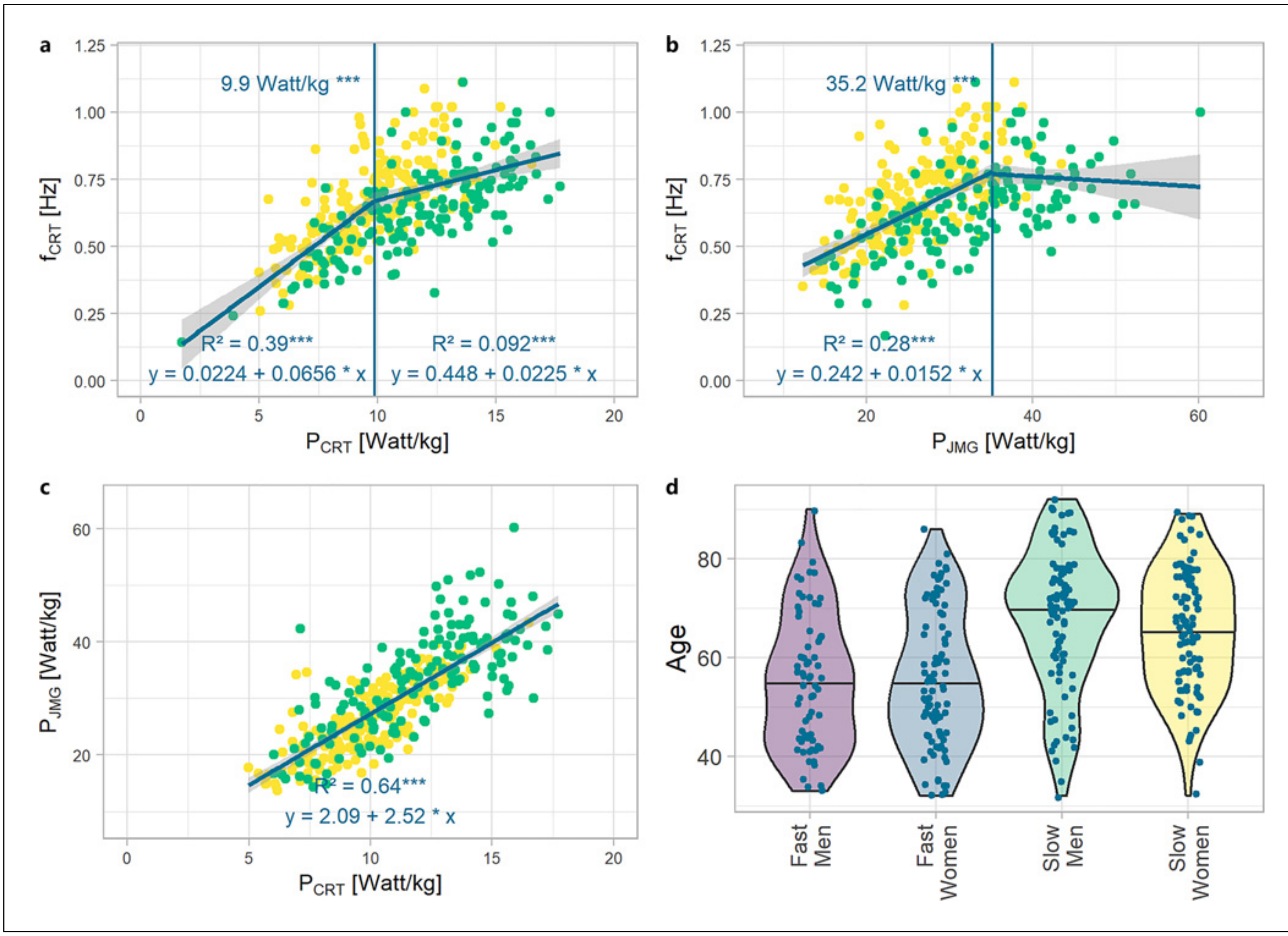

Fig. 1. Breakpoint analysis for timing-based CRT and digital mechanography. **a** Plotting peak jump power (P_{JMG}) versus chair-rising rate (f_{CRT}) reveals a breakpoint at 35.2 W/kg. **b** Peak chair-rising power (P_{CRT}), plotted versus f_{CRT} reveals a breakpoint at 9.9 W/kg. **c** No breaking point was found when plotting P_{JMG} against P_{CRT} (p = 0.24). **d** Age range for men and women who performed chair-rising rate above or below 0.669 Hz (fast and slow, respectively). Horizontal bars indicate the median for each group. Although age was different between slow and fast groups (p < 0.001), there was also substantial overlap.

R^2 = 0.02, respectively). Comparison of regression coefficients suggests that 1 year of age has the same effect on f_{CRT} as 1.43 cm of body height.

Discussion

Results confirm both hypotheses, namely, (a) existence of a breakpoint in the CRT-power relationship and (b) negative association between body height and CRT rate, even when adjusting for age and sex. Both findings limit the meaningfulness of timing-based CRT assessments and, thus, favor power-based CRT. Although Bohannon, for example, had criticized the inconsistency of the test protocols and the lack of recognized diagnostic cut-offs [16], and although other studies have suggested that gait speed [5, 17] or grip strength [18] may be a better predictor of hard clinical outcomes, there has been very little criticism on CRT to date, except for one recent study [19]. Therefore, and given the widespread use of chair-rising and TUG tests, these results are important for the community of geriatric and rehabilitation medicine.

Breakpoints

We have demonstrated that the relationship between the chair-rising rate and chair-rising power is broken at 9.9 Watts and that more half of the study cohort (61%,

Table 3. Comparison of demographic data and power endpoints between those who performed CRT at a rate above (=fast) or below 0.669 Hz (=slow)

	Fast CRT (N = 159)	Slow CRT (N = 187)	p value
Sex			0.33
Women	90 (56.6%)	95 (50.8%)	
Men	69 (43.4%)	92 (49.2%)	
Walking aids			
None	158 (99.4%)	185 (98.9%)	1.00
Cane	1 (0.6%)	2 (1.1%)	
Age, years			<0.001
Mean (SD)	55.47 (13.63)	66.63 (13.37)	
Range	32–90	32–92	
Body height, cm			0.66
Mean (SD)	169.82 (9.64)	169.37 (9.19)	
Range	144–189	148–199	
Body mass, kg			0.27
Mean (SD)	77.42 (14.81)	79.17 (14.78)	
Range	46.36–126.87	47.78–130.13	
BMI, kg/m^2			0.065
Mean (SD)	26.72 (3.81)	27.53 (4.26)	
Range	19.02–37.80	18.660–41.07	
P_{CRT}, Watt/kg			<0.001
Mean (SD)	12.26 (2.37)	9.40 (2.41)	
Range	5.40–17.72	1.74–15.50	
P_{JMG}, Watt/kg			<0.001
Mean (SD)	32.95 (7.46)	26.17 (8.01)	
Range	15.54–60.22	12.36–52.35	

to be precise) was above that threshold. The breakpoint for neuromuscular power which was found at 35.2 Watt/kg in this study, and Degens et al. [10] also found a breakpoint between TUG-time and jump power, albeit at 23.7 Watt/kg. Whether that breakpoint is more related to stand-up component or to the walking component is yet to be determined. In any case, our data demonstrate that timing-based CRT assessment is only meaningful when chair-rising rate is slower than approximately 0.67 Hz, i.e., when more than 7.5 s are required for 5 stand-ups. However, "slow" and "fast" chair-risers had comparable body height and body mass, and their age distributions largely overlapped, as shown in Figure 1d. To illustrate the practical implications, we consider that out of the 75 participants aged ≥75 years in this study, there were 17 (22.7%) fast risers and 58 slow risers (77.3%). This means that one in five participants in the older age group was hit by the CRT's ceiling effect.

Further, it is also important that the disparity between chair-rising rate and neuromuscular power can easily go unnoticed, as shown by the lack of any breakpoint in Figure 2c. How can this be explained? The age-related decline in neuromuscular performance is influenced by non-modifiable factors (e.g., genetic predisposition for fast or slow muscle fiber type [9, 20]) and modifiable factors (e.g., training state [13, 21, 22] and body composition [20]). The age-related power-decline, therefore, varies considerably between individuals, and the age at which the chair-rising rate becomes unequivocal also varies between individuals, which can explain the lack of a breakpoint for chair-rising rate vs. age. In other words, ceiling effects in CRT readings can easily go unnoticed when plotting chair-rising rate against age only, and not against a true measure of neuromuscular power. It should be noted also that the criticism is foremost applying to the timing-based assessment and not to the CRT per se as Figure 1c clearly shows that chair-rising power and JMG power truly reflect each other.

Body Height and Chair-Rising Rate

Our second hypothesis, which stated that body height would be associated with chair-rising rate, was also confirmed in this study, as shown in Table 4. Interestingly, another very recent study confirms this finding

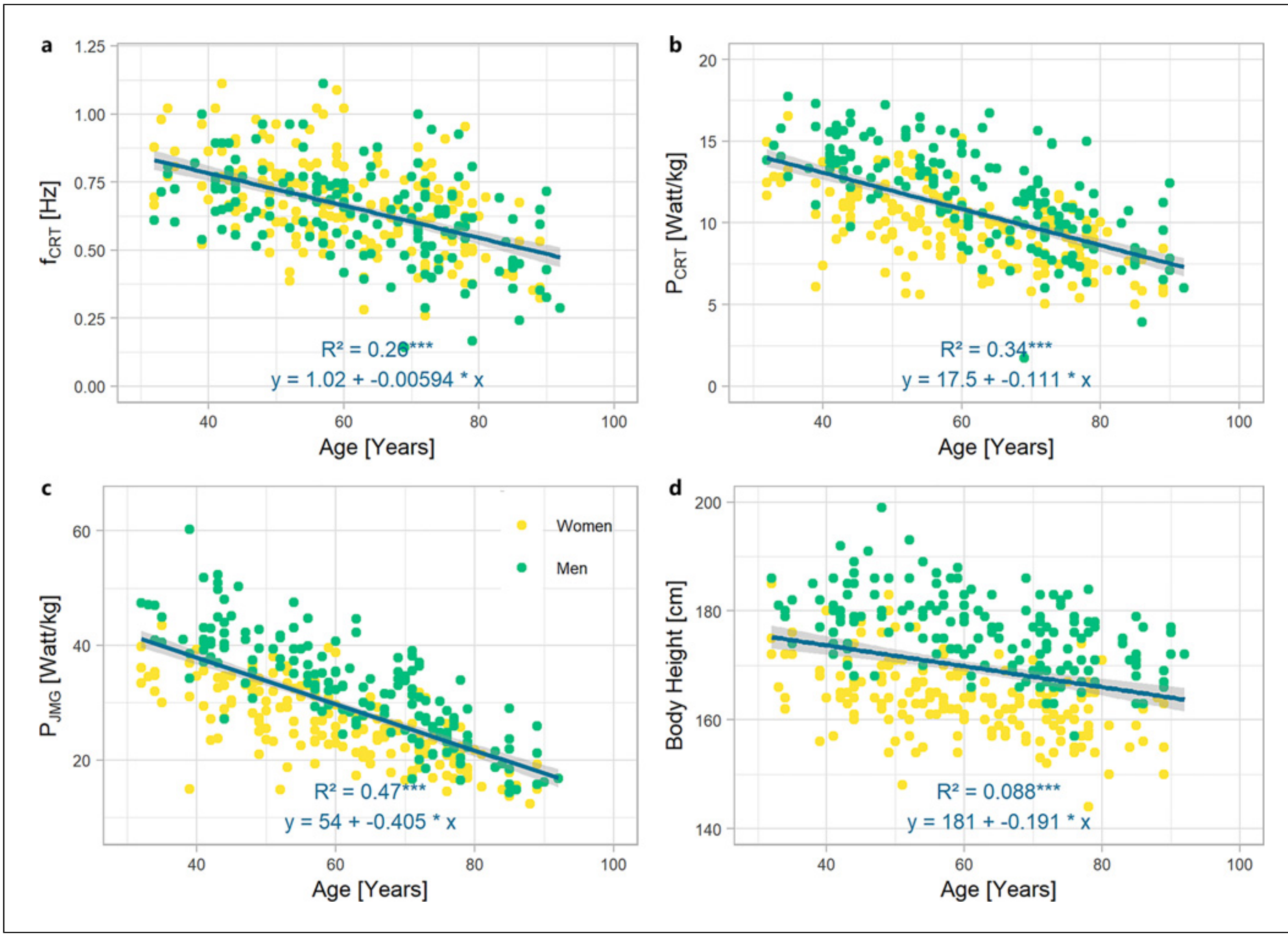

Fig. 2. Effects of age. Peak jump power (P_{JMG}) (**a**), peak chair-rising power (P_{CRT}) (**b**), chair-rising rate (f_{CRT}) (**c**), and body height (**d**) all revealed continuous negative associations with age (all $p < 0.001$), but there were no breakpoints identified (all $p > 0.20$).

Table 4. Regression and partial regression results

Variable	Regression	Total R^2	P(Sex)	R^2 sex	P(age)	R^2 age	P(body height)	R^2 body height
f_{CRT}, Hz	1.89 + 0.041 * sex − 0.0070 * age − 0.0049 * height	0.29	0.077	0.01	<0.001	0.28	<0.001	0.04
P_{CRT}, Watt/kg	8.45 + 1.447 * sex − 0.1050 * age + 0.0474 * height	0.49	<0.001	0.06	<0.001	0.31	0.009	0.02
P_{JMG}, Watt/kg	56.04 + 7.559 * sex − 0.4269 * age − 0.0247 * height	0.66	<0.001	0.21	<0.001	0.54	0.59	0.00

[19]. Similar to the breakpoint effect, the interference from body height is also virtually eliminated if power rather than rate is used as the CRT result. This can have implications for interpretation of timing-based CRT readings in cross sectional study. Many studies into aging report shrinkage of body height with age (probably due to secular effects [23]). The body height-associated measurement bias associated with timing-based CRT readings will accordingly underestimate the true age-related decline in neuromuscular power, with the latter being established from longitudinal studies [24] will under-estimation of age-related decline in chair-rising rate. To give an example from the data in Figure 2, height at age 80 was on average 7.7 cm shorter than at age 40. Thus, the finding that 1 year of age had comparable effects on f_{CRT} as being 1.43 cm taller (see Results) suggests that f_{CRT} underestimates the genuine age effects by 1.43 7.7 = 11 years, which is approximately one quarter of the overall age effect. This calculation is also corroborated by predicting age-declines from statistical models in Figure 2, which yield changes for f_{CRT} and P_{CRT} by 30% and 34%, respectively, between the age of 40 and 80, while PJMG declines by 43% over the same age range. Moreover, the test's dependency on body height also has potential for clinical bias as shorter people's CRT readings will make them appear fitter than they really are. To make an example, being 10 cm shorter could camouflage 14.3 years' worth of age-decline in fitness, which can clearly misinform clinical decision-making.

A possible option to overcome body height related bias could consist in adjusting the height of the chair to the body height of the tested person. However, that would probably not be as straightforward as it seems, given that the relative contribution of back extensors, hip and leg extensor muscles are difficult to estimate, and that these contributions may be subject to change with age or training state.

Strengths and Limitations

There are specific strengths and limitations of our study. First, the study was organized longitudinally, and potential participants were randomly drawn from the resident registration office. This enhances the generalizability of results to a wider population. However, data have been utilized retrospectively as breakpoints and analysis body height effects were not among the primary objectives of the overall Prodigy study. Future prospective studies can naturally replicate the approach and even physically demonstrate the mechanisms responsible for the fCRT breakpoint, and we feel that results of this large population-based study serve as a foundation to guide such future studies.

Second, 12 participants (including all those who used a walking stick) took part only in CRT but not in JMG. Unfortunately, there is no detailed information on reasons for these refusals. However, it seems clear that both physical frailty and apprehension are the main causes. From a biomechanical point of view, it is actually surprising that a person should able to stand up from a crouched position (e.g., from a chair) when being unable to perform a brisk upward movement from a very shallow squat, possibly without any jump. In that case, the instructions must of course be adapted by requesting a quick upward movement instead of a jump. We are, therefore, confident that the feasibility of JMG, which was already 334/346 = 96.5% in the present study, can be further improved.

Third, chair-rising and jumping power were assessed with a ground reaction force plate, which in the current implementation only allows laboratory-based assessments. However, it would be straightforward from a physical point of view to replace force information by 3D-accelerometry applied to the center of mass. Such an implementation would then be more unobtrusive and open the applicability to a wider set of settings. Thus, a recent study has demonstrated feasibility, reproducibility and validity of chair-rising power as an indicator of motor function in older people [25].

In conclusion, results of this study revealed two important limitations of the timing-based CRT assessment, namely, a discontinuity at 0.67 Hz and a significant interference with body height. As a result, timing-based CRT assessment is not reflecting neuromuscular power unequivocally. The limitations can be largely eliminated when using digital mechanographic assessments of neuromuscular power, rather than timing-based chair-rising assessments. Future implementations of the CRT should attempt to replace force plates by 3D-accelerometery, thereby allowing lab-based testing as well as real-world assessments of chair-rising power.

Acknowledgments

This publication is dedicated to Dieter Felsenberg, who conceived this study. Throughout his lifetime, he was a protagonist in clinical musculoskeletal research and a source of inspiration. Professor Dr. med. Jörn Rittweger passed away while working on this paper. He will be remembered as an outstanding scientist, a valued colleague, inspirator, mentor, and friend.

Statement of Ethics

This study protocol was reviewed and approved by the Ethics Committee of Charité – Universitätsmedizin Berlin (approval for baseline-part: EA4/021/14; approval for follow-up part: EA4/095/05). Written informed consent was obtained from all participants.

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

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Author Contributions

J.R. and M.G. conceived the research question. R.D. and G.A. provided existing data from the Prodigy study. J.R. performed data analyses and prepared the first draft of the manuscript. M.G. corrected first draft. All authors reviewed, corrected, and approved final draft of manuscript.

Data Availability Statement

Data have been uploaded as supplementary material at https://doi.org/10.1159/000545395. Further inquiries can be directed to the corresponding author.

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