Heliyon 9 (2023) e20123

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Which trunk muscle parameter is the best predictor for physical function in older adults?

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ARTICLE INFO

Keywords:
Back extension strength
Trunk flexion strength
Relative strength
Trunk lean mass
Trunk muscle quality

ABSTRACT

Background: Despite preliminary evidence demonstrating the relevance of trunk muscle strength for physical function in older adults, it is not clear which muscle-related trunk parameter is the best predictor for physical functions. Therefore, this study aimed to compare trunk muscle morphology or strength parameters regarding their predictive ability for physical functions.
Methods: Seventy-four older adults (38 men, 36 women, mean age 76.85 years) were tested for maximum absolute and relative isokinetic trunk flexion and extension strength, trunk lean mass, and trunk muscle quality. Functional assessment included normal and fast walking speed, repeated sit-to-stand transfer, timed up and go, and postural sway during a closed-feet and a semi-tandem stance adjusted for body height. Pearson's correlations were used to compare relationship between trunk strength adjusted and unadjusted for body weight to physical functions. Linear regression analysis including sex and age as co-variables was performed between trunk muscle and functional test parameters.
Results: Relative back extension strength was the most consistent significant predictor for all physical function tests ($p = 0.004$–0.04) except for postural sway. Relative trunk flexion strength was related to normal walking speed ($p = 0.024$). Trunk lean mass was related to timed up and go performance ($p = 0.024$).
Conclusion: Relative back extension strength is associated with better performance in nearly all standard tests for physical function in older adults, while trunk flexion strength and lean mass seem to play a minor role. Our findings emphasize the importance of trunk muscle strength, especially the back extensor muscles, for physical function in older adults.

1. Introduction

In everyday life, we depend on skeletal muscle strength to produce movement for interacting with our environment [1]. Aging results in a decline of muscle strength, which is an established risk factor for a variety of adverse events (e.g. falls, fractures, and hospitalization) and negative health-related outcomes (e.g. shorter life expectancy, loss of physical independence, and mortality) [2–7]. By the year 2050, a quarter of Europe's population will be over 65 years, and medical costs associated with this demographic progression present a serious socioeconomic burden [8].

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https://doi.org/10.1016/j.heliyon.2023.e20123
Received 31 May 2023; Received in revised form 11 September 2023; Accepted 12 September 2023

Research to diagnose and counter aging-related physical decline has consistently focused on the lower limb muscles due to their strong correlations with basic physical functions [9,10]. However, the trunk which connects the lower limbs and upper body has not received similar or adequate attention. Aging is also accompanied by degenerative changes of the intervertebral disc which influences spinal biomechanics [11]. Mika et al. [12] reported that changes in back extension strength may influence the severity of thoracic kyphosis. Kyphotic changes of the spine have been linked with limited mobility and balance impairments in both elderly women [13], and in elderly men [14]. In this context, it seems that trunk muscles are twofold important as a stabilizer during movement as well as an intrinsic support to influence posture [15,16].

Despite the plausible link between trunk strength or morphology with physical function, a systematic review spanning research from 1972 to February 2013 [17] found only six studies [18–22] which examined the connection between trunk strength or morphology with physical function in older adults. All included studies reported small-to medium, mostly statistically significant, links between variables of trunk muscle strength and functional performance in older adults. Further, since this review of Granacher et al. [17], we could identify only five further studies [23–27] concerning this topic. With the currently available evidence, it is not clear which muscle-related trunk parameter (e.g., absolute strength, strength adjusted for body weight, muscle size, muscle quality) is the best predictor for physical functions. Although research for lower limbs indicates that relative strength is superior to size and muscle quality [28], this hierarchy is not clear for the trunk region.

Additionally, this question has rarely been examined with consideration for sex. Generally, men and women experience a decline in strength and physical function at different rates, with reports demonstrating a steeper decline in men than in women [2]. There is also evidence that women and men exhibit unique motor pattern strategies for certain physical tasks, which conceivably influences trunk muscle demands [29,30]. Lastly, the available studies present major methodological differences (type of strength testing devices, functional assessment modalities, number or test trials etc.) which make them difficult to compare to each other [23].

Therefore, the goal of this study is to comprehensively examine the relationship of various trunk muscle parameters with an array of physical function tests in older adults. Results should explain which trunk parameters are related to a specific functional task and if these trunk-function relationships are specific to sex.

2. Methods

2.1. *Participants*

Participants provided written informed consent, and approval was acquired from the local Ethics Commission (protocol number: FSV 18/49).

2.2. *Study design*

Participants attended the biomechanics laboratory for a single session of cross-sectional testing (Fig. 1.). Testing sessions occurred between 8am and 6pm and were carried out by an investigator with multiple years of experience in both geriatric physical function testing and strength testing. Participants were asked to avoid strenuous physical activity 48 h before attending the testing session. No fasting was required, and participants could maintain their habitual nutrition and hydration regime. Whenever urinary urgency was present, participants had the opportunity to empty their bladder. A temperature between 20 and 21 °C and a humidity level between 30 and 50% was maintained with an air conditioner.

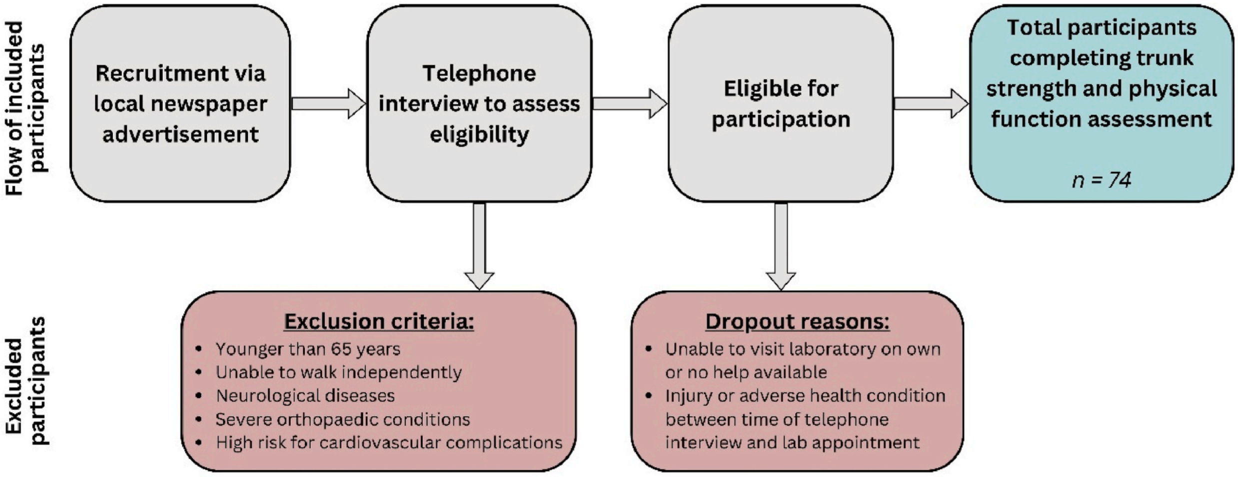

Fig. 1. Flowchart illustrating study enrollment from recruitment to finished assessment.

3. Assessment

3.1. Anthropometry and body composition

A stadiometer was used to measure height. Body composition including skeletal muscle mass, fat mass, body fat percentage, trunk lean tissue mass and total body weight was collected via the Inbody 720 (JP Global Markets GmbH, Eschborn, Germany). Valid total body and segmental body composition in adults can be obtained with the bioimpedance analysis via Inbody 720 [31].

3.2. Functional assessment

For physical function assessments, habitual (normal) and fast walking speed, sit-to-stand time, timed up and go time, and postural sway with a closed-feet and a semi-tandem stance was measured in a predefined sequence. These tests were chosen due to their reliability and validity in geriatric research and play an important role for activities of daily living.

3.3. Walking speed

Two trials of habitual paced walking and fast walking over a distance of 6 m were performed by the participants. The time to cross the central for meters was timed with a stopwatch [32]. The fastest time of each condition was chosen for statistical analysis.

3.4. Sit-to-stand test

Participants were instructed to rise from a chair to full upright standing as fast as possible 10 times in a row with arms crossing the chest. The correct movement pattern was practiced before testing. Two test trials were timed with a stopwatch and the faster test trial was used for further analysis. A standardized chair height of 40 cm was used. The sit-to-stand transfer has been previously validated for its use in healthy and frail older adults [33].

3.5. Timed up and go test

The timed up and go test was used to evaluate dynamic balance capabilities [34,35]. Participants were asked to rise from a chair, then walk as fast as possible 3 m towards and around a cone, walk back and sit again on the chair. Time was measured with a stopwatch. Previous studies [34,36] reported acceptable reliability and validity of the stopwatch measured timed up and go test. In order to prevent misunderstandings, a test trial was performed before the two test trials. The time of the faster trial was included in the data analysis.

3.6. Static balance

Postural sway (center of pressure path length) measured with a Kistler force plate (Kistler Instrumente GmbH, Sindelfingen, Germany) was used as a means to assess static balance [37,38]. Participants had the task to maintain balance to their best ability for 30 s with their hands on the hips, eyes open, and looking straight. The first and second trial was performed with a closed-feet and a semi-tandem stance, respectively. Postural sway values were divided by height in centimeters [39].

3.7. Trunk strength assessment

Isokinetic concentric trunk flexion and extension strength were measured with the Isomed 2000 (Isomed 2000 ®, D&R Ferstl GmbH, Hemau, Germany). The Isomed 2000 showed high reliability in isokinetic and isometric peak torque trunk measurements [40]. An angular velocity of 60° per second was used for all assessments. To minimize the involvement of hip musculature, the lower limbs were fixed by an adjustable pad and foot platform of the Isomed 2000 system. Additionally, the pelvis was fixed with a belt. The attachment to exert force against was adjusted to the trunk/torso length and placed approximately at the scapula level at the dorsal side and at the upper chest area at the ventral side. This attachment also provided handles for the participants to place their hands on during the assessment. Additionally, the Isomed system zeroized the weight of the trunk/torso to eliminate the influence of torso weight on muscle torques. The pivot point of trunk muscles (anterior superior iliac spine) and of the device were arranged accordingly. After preparatory measures have been completed, the full range of motion was examined and adjusted when needed. Prior to testing the maximum back extension and trunk flexion strength, participants were familiarized with the movement and the dynamometer by performing the movements with submaximal effort. Two trials were used for the testing phase, with three maximal repetitions per trial. Between trials, 2 min of rest were provided. In each direction (flexion and extension), three repetitions were performed to ensure the best chance of capturing genuine maximal strength. In case of a high torque difference ($>5\%$) between two trials, an additional trial was performed to ensure valid maximum voluntary contraction. The highest torque result was selected for data analysis, and verbal encouragement from the tester was provided during each trial. Results were displayed as newton meters and were subsequently divided by body weight for further relative analysis.

3.8. *Trunk muscle quality assessment*

Trunk muscle quality defined as the force per unit of muscle mass [41] was calculated by dividing the sum of absolute trunk flexion and extension torque by the trunk lean tissue mass.

3.9. *Statistical analysis*

Statistical analyses were performed with the open-source statistical programing language R (version 4.3.1, R Core Team, 2023, Vienna, Austria). An independent *t*-test was used to compare mean values between men and women. Normality distribution was tested with the Shapiro-Wilk test and sphericity (equality of variances) was tested with the Brown-Forsythe test. In case normality (height, sit-to-stand time, timed up and go time and both postural sway values) or equality of variance (sit-to-stand time, and both postural sway values) was violated, the Mann-Whitney-U Test was used. Linear regression analysis including age and sex as additional covariates was performed to assess the predictive ability of trunk muscle parameters for physical functions. In Pearson's correlation analysis, relative trunk flexion and back extension strength were revealed as being more closely related to physical function parameters than absolute strength (Table 2, Table 3). Including both parameters for regression analysis would have violated collinearity requirements. Therefore, only relative strength and not absolute strength were included for the regression models. For all regression models, a careful goodness-of-fit analysis based on both residual and QQ-plots has been performed in order to check the adequacy of the Gaussian assumption for the error distribution (plots not shown here). For three out of six regression models, we found no violations in those plots and the Gaussian assumption seems suitable. For the models with "postural sway closed feet stance", "postural sway semi-tandem stance" and "timed up and go time (s)" as response variable, we found deviations from normality in the larger quantiles, which indicate some skewness in those variables. As we consider these deviations as still acceptable, we performed simple linear models also for these responses, but want to stress that those results should be interpreted with some caution.

Collinearity diagnostics were performed to assess variance inflations in the predictors. For the six included predictors, variance inflation factor and tolerance ranged from 1.33 to 8.58 and 0.12–0.75, respectively.

Finally, a least absolute shrinkage and selection operator (LASSO) regression model [42] was employed to identify the most important predictors. As among some of the predictors substantial correlations were found, LASSO regression is particularly beneficial as it is known to be able to better deal with multicollinearity among predictors. The technique is implemented in the package "glmnet" [43] in the open-source statistical programing language R (version 4.3.1, R Core Team, 2023, Vienna, Austria). The LASSO is based on the so-called penalty parameter λ, which is tuned based on the prediction of unseen test data, for example, via K-fold cross validation (CV). Note that for a proper usage of the LASSO penalization technique, all covariates have to be standardized to make the strength of the penalty comparable, and we have set $K = 10$ in the CVs.

4. Results

Table 1 presents anthropometrical and physical function parameters of seventy-four (38 men, 36 women) older subjects who met all inclusion criteria and completed the full testing session. Comparisons between sexes showed that men were significantly ($p < 0.001$) taller, heavier, leaner, had more skeletal muscle mass, had more trunk lean tissue mass, more absolute and bodyweight adjusted back extension and trunk flexion strength, and a higher trunk muscle quality than women. For physical function parameters, significant

Table 1

Anthropometrical and physical function characteristics of participants.

Parameter	Total (n = 74)	Men (n = 38)	Women (n = 36)	p-value
	Mean | SD	Mean | SD	Mean | SD	
Age (y)	76.85 ± 4.67	77.00 ± 4 .61	76.69 ± 4.79	0.781
Height (cm)	167.22 ± 8.95	173.13 ± 6.52	160.97 ± 6.64	<.001
Weight (kg)	73.16 ± 11.65	77.57 ± 9.06	68.51 ± 12.37	<.001
BMI (kg/m^2)	26.21 ± 3.52	25.86 ± 2.51	26.58 ± 4.35	0.380
Skeletal muscle mass (kg)	26.60 ± 5.17	30.62 ± 3.42	22.35 ± 2.69	<.001
Body fat (kg)	24.21 ± 8.25	21.90 ± 6.23	26.64 ± 9.44	0.012
Body fat (%)	32.74 ± 8.17	27.78 ± 6.08	37.97 ± 6.73	<.001
Trunk lean tissue mass (kg)	21.96 ± 4.03	25.08 ± 2.45	18.66 ± 2.40	<.001
Trunk flexion strength (Nm)	106.91 ± 34.61	132.71 ± 25.43	79.67 ± 18.11	<.001
Back extension strength (Nm)	158.49 ± 59.03	196.84 ± 53.60	118.00 ± 30.78	<.001
Relative trunk flexion strength (Nm/kg)	1.46 ± 0.39	1.72 ± 0.33	1.18 ± 0.22	<.001
Relative back extension strength (Nm/kg)	2.16 ± 0.70	2.55 ± 0.67	1.76 ± 0.47	<.001
Trunk muscle quality (Nm/kg)	11.92 ± 2.57	13.13 ± 2.39	10.65 ± 2.12	<.001
Normal walking speed (m/s)	1.26 ± 0.21	1.27 ± 0.23	1.26 ± 0.18	0.950
Fast walking speed (m/s)	1.82 ± 0.31	1.90 ± 0.31	1.74 ± 0.29	0.031
Sit-to-stand time (s)	19.95 ± 8.65	19.20 ± 9.06	20.75 ± 8.24	0.443
Timed up and go time (s)	6.94 ± 1.30	6.84 ± 1.32	7.05 ± 1.29	0.503
Postural sway closed feet stance	4.36 ± 1.41	4.71 ± 1.53	3.99 ± 1.17	0.026
Postural sway semi-tandem stance	6.03 ± 2.23	6.45 ± 2.67	5.58 ± 1.54	0.090

Table 2
Comparison of Pearson's Correlations between relative and absolute trunk muscle strength and physical functions tests in women (TFS = trunk flexion strength, BES = back extension strength).

Women	Normal walking speed		Fast walking speed		Sit-to-stand time	
	Pearson's r	p-value	Pearson's r	p-value	Pearson's r	p-value
Relative TFS	0.582	<.001	0.443	0.007	−0.448	0.006
Relative BES	0.501	0.002	0.487	0.003	−0.560	<.001
Absolute TFS	0.175	0.307	0.120	0.487	−0.062	0.719
Absolute BES	0.235	0.167	0.290	0.086	−0.343	0.041
	Timed up and go time		Postural sway closed feet stance		Postural sway semi-tandem stance	
Relative TFS	−0.500	0.002	−0.113	0.511	−0.233	0.171
Relative BES	−0.471	0.004	−0.112	0.516	−0.093	0.589
Absolute TFS	−0.094	0.584	0.041	0.813	−0.056	0.747
Absolute BES	−0.206	0.227	−0.019	0.911	−0.005	0.976

Table 3
Comparison of Pearson's Correlations between relative and absolute trunk muscle strength and physical functions tests in men (TFS = trunk flexion strength, BES = back extension strength).

Men	Normal walking speed		Fast walking speed		Sit-to-stand time	
	Pearson's r	p-value	Pearson's r	p-value	Pearson's r	p-value
Relative TFS	0.329	0.044	0.310	0.058	−0.284	0.084
Relative BES	0.507	0.001	0.606	<.001	−0.558	<.001
Absolute TFS	0.223	0.179	0.194	0.243	−0.201	0.227
Absolute BES	0.389	0.016	0.467	0.003	−0.475	0.003
	Timed up and go time		Postural sway closed feet stance		Postural sway semi-tandem stance	
Relative TFS	−0.404	0.012	−0.249	0.131	−0.227	0.170
Relative BES	−0.637	<.001	−0.235	0.156	−0.315	0.054
Absolute TFS	−0.225	0.174	−0.205	0.217	−0.218	0.189
Absolute BES	−0.463	0.003	−0.184	0.269	−0.296	0.071

differences were apparent in fast walking speed (p = 0.031) and closed feet postural sway (p = 0.025) with men exhibiting faster walking speeds but more postural sway.

Table 4 shows the results of the linear regression analysis, both for conventional linear models as well as for LASSO regression. Relative back extension strength was the most frequently significant predictor of all trunk muscle parameters for physical function parameters (p = 0.004–0.040). Relative trunk flexion strength was only related to habitual WS (p = 0.024). Trunk lean tissue mass was a significant predictor for timed up and go performance (p = 0.024). No trunk muscle parameter was a significant predictor for either postural sway conditions, and only age was a significant predictor for postural sway in semi tandem stance. Sex was not a significant predictor for any physical function in any model. The explained variance between independent and dependent variables in significant models (4 out of 5) ranged from (R^2 = 0.176–0.433, p=<0.001–0.037).

For some of the LASSO models, some of the variables sex, trunk muscle quality and relative trunk flexion were excluded from the model, while all other covariates were always selected. Hence, the results from the conventional linear regression models could mostly be confirmed. For example, for the response variable normal walking speed we show the corresponding 10-fold CV deviance prediction error together with the corresponding coefficient path plot in Fig. 2. It can be seen that at the optimal tuning parameter $\lambda_{opt} \approx 0.028$, which is indicated by the red, vertical dashed line, the paths of all coefficients have already quite evolved, except for trunk muscle quality, whose coefficient is still zero.

Hence, trunk muscle quality is excluded from the model. Moreover, it becomes noticeable that compared to the unpenalized maximum likelihood estimator (i.e., $\lambda = 0$ at the very left side of the graph), all other coefficients have received a substantial amount of shrinkage due to the LASSO penalty. The corresponding graphs for the other five response variables look quite similar, but are not shown.

5. Discussion

The goal of this study was to examine which trunk musculature parameter has the highest predictive ability for physical function. Further, the role of sex as an influencing factor on the trunk–function relationship was assessed. The regression analysis revealed back extension strength adjusted for the subject's body weight as the most consistent significant predictor for all physical function tests except for postural sway as a measure of static balance. Relative trunk flexion strength was not a prominent predictor for the tested physical function parameters since it was only related to normal walking speed. In comparison to all covariates, sex did not reach level of significance for any physical function tests, indicating that especially trunk muscle strength, and to some extent age, plays a superior role for physical function.

Table 4

Linear regression analysis between trunk muscle parameters and functional tests (LTM = lean tissue mass, TFS = trunk flexion strength, BES = back extension strength, TMQ = trunk muscle quality); all regression coefficients correspond to both standardized responses and coefficients.

Parameter	Normal walking speed						Maximum walking speed						Sit-to-stand time					
	β	SE	p-value	Partial Eta^2	R^2 (p-value) AIC	LASSO coefficients	β	SE	p-value	Partial Eta^2	R^2 (p-value) AIC	LASSO coefficients	β	SE	p-value	Partial Eta^2	R^2 (p-value) AIC	LASSO coefficients
LTM	−0.108	0.01	0.561	0.005	**0.332** **(<.001)** 195.189	−0.123	−0.343	0.013	0.051	0.056	**0.423** **(<.001)** 184.262	−0.163	0.294	0.391	0.111	0.038	**0.355** **(<.001)** 192.543	0.249
Relative TFS	0.459	0.105	**0.024**	0.074		0.225	0.103	0.145	0.581	0.005		0.096	−0.093	4.291	0.636	0.003		0.000
Relative TES	0.804	0.079	**0.004**	0.118		0.441	0.592	0.110	**0.020**	0.078		0.536	−0.553	3.245	**0.040**	0.062		−0.451
TMQ	−0.409	0.024	0.167	0.028		0.000	−0.047	0.033	0.864	<0.001		0.000	−0.045	0.968	0.877	<0.001		−0.125
Age	−0.074	0.005	0.525	0.006		−0.082	−0.228	0.007	**0.037**	0.063		−0.156	0.125	0.210	0.274	0.018		0.103
Sex	−0.478	0.101	0.055	0.054		−0.269	0.151	0.140	0.511	0.006		0.000	0.068	4.141	0.780	0.001		0.000

Parameter	Timed up and go time						Postural sway closed feet stance						Postural sway semi-tandem stance					
	β	SE	p-value	Partial Eta^2	R^2 (p-value) AIC	LASSO coefficients	β	SE	p-value	Partial Eta^2	R^2 (p-value) AIC	LASSO coefficients	β	SE	p-value	Partial Eta^2	R^2 (p-value) AIC	LASSO coefficients
LTM	0.393	0.055	**0.024**	0.073	**0.433** **(<.001)** 182.951	0.396	0.04	0.072	0.847	<0.001	0.165 (0.053) 211.635	0.053	0.042	0.114	0.838	<0.001	**0.176** **(0.037)** 210.637	0.044
Relative TFS	−0.284	0.605	0.126	0.035		−0.178	−0.264	0.793	0.239	0.021		−0.059	−0.128	1.248	0.565	0.005		−0.080
Relative TES	−0.679	0.457	**0.008**	0.101		−0.520	−0.419	0.600	0.168	0.028		−0.103	−0.252	0.944	0.402	0.011		−0.191
TMQ	0.177	0.136	0.514	0.006		0.000	0.355	0.179	0.281	0.017		0.000	0.061	0.281	0.852	<0.001		0.000
Age	0.210	0.030	0.052	0.055		0.212	0.184	0.039	0.157	0.0296		0.191	0.261	0.061	**0.045**	0.058		0.261
Sex	0.094	0.584	0.679	0.003		0.000	0.468	0.765	0.093	0.041		0.284	0.355	1.204	0.197	0.025		0.307

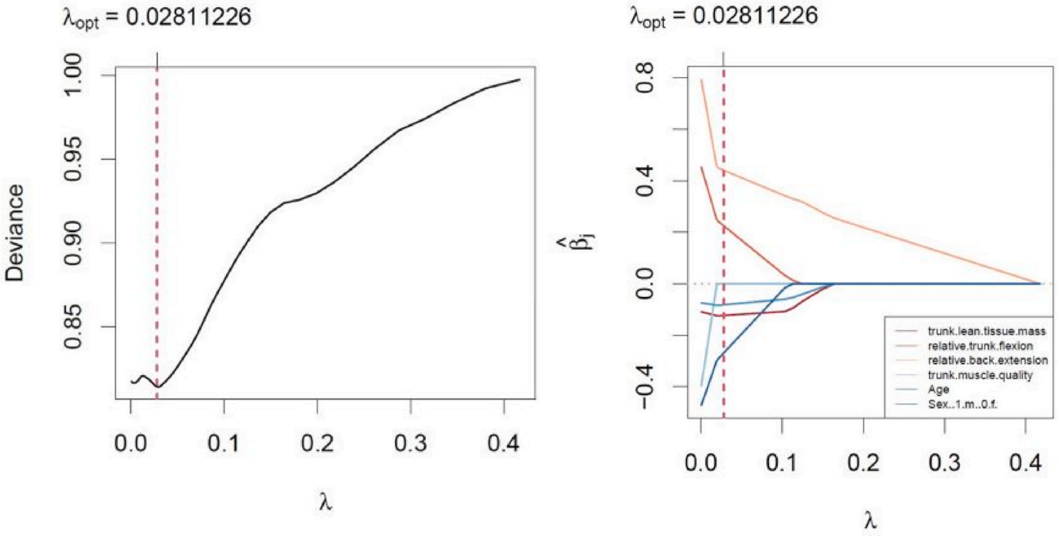

Fig. 2. Deviance prediction error of 10-fold CV (left) together with the corresponding coefficient path plot example (right) for normal walking speed (λ_{opt} = optimal turning parameter, $\widehat{\beta}_j$ = regression coefficient estimate).

Previous studies have primarily examined only either muscle morphology or strength with their association to physical function. To our knowledge, only Shahtahmassebi et al. [24] examined multiple trunk muscle parameters and compared their role for physical function in older adults. Their findings corroborate our results, demonstrating that while composite trunk strength was associated with four out of five functional tasks, composite trunk muscle size was not associated with any functional outcomes. In this context, it should be noted that other measures of trunk muscle morphology like ventral and dorsal trunk muscle thickness or cross-sectional area might be closer related to physical function than trunk lean tissue mass, however, the relationship between trunk muscle morphology and function seems to be less consistent than the relationships between trunk muscle strength and function [24]. Further, in accordance with our results, back extension strength was more closely related to functional tasks than trunk flexion strength. Our study extended this comparison by including trunk muscle quality and indicated that back extension strength adjusted to the subject's body weight is a superior predictor for physical function. To our knowledge, no other study has compared these trunk muscle parameters with each other. Our results are, however, generally consistent with findings from the lower limbs which indicate that relative muscle strength is a better predictor of physical function than muscle mass and muscle quality [28].

Of the available studies that examined the relationship between trunk muscle strength ($n = 7$, [18–20,23–25,44]) or trunk muscle morphology ($n = 4$, [21,22,26,27]) with physical function ($n = 2$, [18,24]), focused on walking speed ($n = 2$, [21,24]), on sit-to-stand transfer ($n = 8$, [18–20,23,25–27,44]), on static balance, and ($n = 3$, [20,23,24]) on other balance metrics. Four studies [20–22,26] used physical performance batteries that included walking speed, chair rise tests, and balance tasks but they did not report separate values and only presented the composite score making it not possible to compare results. Summarized together, there is a significant small to medium relationship between trunk muscle parameters and physical function as previously described by Granacher et al. [17]. However, the strength of this association depends highly on the tested population, strength testing modalities, and choice of functional test.

For gait performance, our results are in agreement with Shahtahmassebi et al. [24] who also showed a significant medium association of gait performance with back extension. However, they used the 6-min walking test while we examined walking speed over 4 m. Contrarily, Sakari-Rantala et al. [18] reported no association between walking speed over 10 m and trunk strength. For the sit-to-stand test, our results are also conflicting with those of Shahtahmassebi et al. [24] who found no relationship between sagittal plane trunk strength with sit-to-stand transfer which was apparent in our results. However, their composite strength score was related to sit-to-stand transfer time. Similarly, they reported no connection between trunk strength and TUG time while we found a significant connection. Again, strength modalities may have influenced the results. While we measured isokinetic trunk strength in a sitting position, the other authors measured isometric trunk strength in a standing position [24]. Lastly, static balance is the most frequent measured functional parameter among the aforementioned studies due to functional role of the trunk muscles primarily as stabilizers. This is of particular importance given that this age group often suffers from flexed (i.e., kyphotic) posture which is associated with significantly higher multisegmental spinal loads and demands of back extensor due to changes in erector spinae lever arm lengths [45–48]. Although mostly small effects between trunk strength or morphology with static balance are reported in the literature, they appear to be consistent. However, our results oppose those findings and show no connection between trunk parameters and postural sway. Similar postural sway measurements were carried out across studies and the main difference to our study is the application of isometric strength measures, while we used isokinetic strength measures. Torque of isometric measurements is highly dependent on the tested joint angle and varies between individuals [49]. Therefore, we opted for an isokinetic approach which is not dependent on the testing position. Further research is necessary to examine if isometric trunk strength testing may be closer related to postural sway than isokinetic testing, which would explain if there is a contraction type specific association between strength and function of the trunk muscles in general. It is plausible that there are functional tasks that are more dependent on a specific contraction type which would be valuable for intervention programs to improve the optimal type of strength ability.

In light of the current evidence, it seems that sufficient trunk muscle strength especially in the back extensor muscles is important for execution of basic physical functions and to live an independent life for older adults. This relationship can be used to design intervention programs for people with physical incapacities or those at risk of imminent physical incapacities. A positive aspect in this context is that trunk musculature, due to its function as a stabilizer, is involved in most compound movements of the human body so that it is possible to train multiple muscle groups (e.g., hip, knee and back extensors) with a limited number of exercises [50,51]. Further research in necessary to establish efficient training modalities that are easy to implement and facilitate adherence, particularly in an elderly population.

5.1. Limitations

Although the study provided new insights into the relationship between trunk muscle strength and physical function, two limitations need to be addressed. The available Isomed 2000 system used in this study has no lateral trunk flexor torque adjustment therefore it was not possible to include lateral flexion strength in our analysis. Lateral flexion strength has been reported to be related to physical function, although the association depends on the functional task [24].

We did not measure and include trunk muscle power in our analysis which would be a potential indicator for neuromuscular capabilities of the trunk musculature. In a review of Byrne et al. [52] it has been reported that muscle power is a marginally better indicator for physical function that muscle strength, and therefore we assume that trunk muscle power would be associated to physical function. However further research is necessary to examine this connection. Lastly, we did not assess trunk muscle strength endurance. Reduced trunk muscle strength endurance has been demonstrated to be related to poorer spinal posture and could be an important and unique predictor for other aspects of physical function in older adults [53,54].

6. Conclusion

The trunk musculature plays an important role for physical function in older adults. Of all trunk muscle parameters, back extension relative to the subject's body weight was the most consistent significant predictor for all physical function parameters (besides postural sway), and may therefore hold the highest utility for both researchers and practitioners. Further, this association does not appear to be mediated by sex. Further research should examine if this relationship can be used in interventions programs to enhance physical function through trunk muscle training.

Ethics declarations

This study was reviewed and approved by the Friedrich-Schiller-University Jena ethics committee, with the approval number: FSV 18/49. All participants/patients provided informed consent to participate in the study.

Author contribution statement

Conceived and designed the experiments: Andreas Stotz, Joel Mason and Astrid Zech.
Performed the experiments: Andreas Stotz.
Analyzed and interpreted the data: Andreas Stotz, Andreas Groll.
Contributed reagents, materials, analysis tools or data: Astrid Zech.
Wrote the paper: Andreas Stotz, Joel Mason, Andreas Groll and Astrid Zech.

Data availability statement

Data included in article/supplementary material/referenced in article.

Funding statement

We acknowledge support by the German Research Foundation Projekt-Nr. 512648189 and the Open Access Publication Fund of the Thueringer Universitaets- und Landesbibliothek Jena.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] R. Hasegawa, M.M. Islam, S.C. Lee, D. Koizumi, M.E. Rogers, N. Takeshima, Threshold of lower body muscular strength necessary to perform ADL independently in community-dwelling older adults, Clin. Rehabil. 22 (2008) 902–910, https://doi.org/10.1177/0269215508094713.

[2] W.K. Mitchell, J. Williams, P. Atherton, M. Larvin, J. Lund, M. Narici, Sarcopenia, dynapenia, and the impact of advancing age on human skeletal muscle size and strength; a quantitative review, Front. Physiol. 3 (2012) 260, https://doi.org/10.3389/fphys.2012.00260.

[3] J.D. Moreland, J.A. Richardson, C.H. Goldsmith, C.M. Clase, Muscle weakness and falls in older adults: a systematic review and meta-analysis, J. Am. Geriatr. Soc. 52 (2004) 1121–1129, https://doi.org/10.1111/j.1532-5415.2004.52310.x.

[4] H.P. Hirschfeld, R. Kinsella, G. Duque, Osteosarcopenia: where bone, muscle, and fat collide, Osteoporos. Int. 28 (2017) 2781–2790, https://doi.org/10.1007/s00198-017-4151-8.

[5] D. Legrand, B. Vaes, C. Matheï, W. Adriaensen, G. van Pottelbergh, J.-M. Degryse, Muscle strength and physical performance as predictors of mortality, hospitalization, and disability in the oldest old, J. Am. Geriatr. Soc. 62 (2014) 1030–1038, https://doi.org/10.1111/jgs.12840.

[6] T. Rantanen, K. Masaki, Q. He, G.W. Ross, B.J. Willcox, L. White, Midlife muscle strength and human longevity up to age 100 years: a 44-year prospective study among a decedent cohort, Age (Dordr) 34 (2012) 563–570, https://doi.org/10.1007/s11357-011-9256-y.

[7] J. Wearing, M. Stokes, ED de Bruin, Quadriceps muscle strength is a discriminant predictor of dependence in daily activities in nursing home residents, PLoS One 14 (2019), e0223016, https://doi.org/10.1371/journal.pone.0223016.

[8] M. McLeod, L. Breen, D.L. Hamilton, A. Philp, Live strong and prosper: the importance of skeletal muscle strength for healthy ageing, Biogerontology 17 (2016) 497–510, https://doi.org/10.1007/s10522-015-9631-7.

[9] F. Buckinx, J.L. Croisier, J.Y. Reginster, J. Petermans, E. Goffart, O. Bruyère, Relationship between isometric strength of six lower limb muscle groups and motor skills among nursing home residents, J Frailty Aging 4 (2015) 184–187, https://doi.org/10.14283/jfa.2015.70.

[10] U. Granacher, T. Muehlbauer, L. Zahner, A. Gollhofer, R.W. Kressig, Comparison of traditional and recent approaches in the promotion of balance and strength in older adults, Sports Med. 41 (2011) 377–400, https://doi.org/10.2165/11539920-000000000-00000.

[11] F. Galbusera, M. van Rijsbergen, K. Ito, J.M. Huyghe, M. Brayda-Bruno, H.-J. Wilke, Ageing and degenerative changes of the intervertebral disc and their impact on spinal flexibility, Eur. Spine J. 23 (Suppl 3) (2014) S324–S332, https://doi.org/10.1007/s00586-014-3203-4.

[12] A. Mika, V.B. Unnithan, P. Mika, Differences in thoracic kyphosis and in back muscle strength in women with bone loss due to osteoporosis, Spine 30 (2005) 241–246, https://doi.org/10.1097/01.brs.0000150521.10071.df.

[13] L. Balzini, L. Vannucchi, F. Benvenuti, M. Benucci, M. Monni, A. Cappozzo, S.J. Stanhope, Clinical characteristics of flexed posture in elderly women, J. Am. Geriatr. Soc. 51 (2003) 1419–1426, https://doi.org/10.1046/j.1532-5415.2003.51460.x.

[14] J. Miyazaki, S. Murata, J. Horie, A. Uematsu, T. Hortobágyi, S. Suzuki, Lumbar lordosis angle (LLA) and leg strength predict walking ability in elderly males, Arch. Gerontol. Geriatr. 56 (2013) 141–147, https://doi.org/10.1016/j.archger.2012.09.004.

[15] W. Elsayed, A. Farrag, Q. Muaidi, N. Almulhim, Relationship between sagittal spinal curves geometry and isokinetic trunk muscle strength in adults, Eur. Spine J. 27 (2018) 2014–2022, https://doi.org/10.1007/s00586-017-5454-3.

[16] J.C.E. van der Burg, M. Pijnappels, J.H. van Dieën, Out-of-plane trunk movements and trunk muscle activity after a trip during walking, Exp. Brain Res. 165 (2005) 407–412, https://doi.org/10.1007/s00221-005-2312-z.

[17] U. Granacher, A. Gollhofer, T. Hortobágyi, R.W. Kressig, T. Muehlbauer, The importance of trunk muscle strength for balance, functional performance, and fall prevention in seniors: a systematic review, Sports Med. 43 (2013) 627–641, https://doi.org/10.1007/s40279-013-0041-1.

[18] R. Sakari-Rantala, P. Era, T. Rantanen, E. Heikkinen, Associations of sensory-motor functions with poor mobility in 75- and 80-year-old people, Scand. J. Rehabil. Med. 30 (1998) 121–127, https://doi.org/10.1080/003655098444237.

[19] M. Pfeifer, B. Begerow, H.W. Minne, T. Schlotthauer, M. Pospeschill, M. Scholz, et al., Vitamin D status, trunk muscle strength, body sway, falls, and fractures among 237 postmenopausal women with osteoporosis, Exp. Clin. Endocrinol. Diabetes 109 (2001) 87–92, https://doi.org/10.1055/s-2001-14831.

[20] P. Suri, D.K. Kiely, S.G. Leveille, W.R. Frontera, J.F. Bean, Trunk muscle attributes are associated with balance and mobility in older adults: a pilot study, Pharm. Manag. PM R 1 (2009) 916–924, https://doi.org/10.1016/j.pmrj.2009.09.009.

[21] G.E. Hicks, E.M. Simonsick, T.B. Harris, A.B. Newman, D.K. Weiner, M.A. Nevitt, F.A. Tylavsky, Cross-sectional associations between trunk muscle composition, back pain, and physical function in the health, aging and body composition study, J Gerontol A Biol Sci Med Sci 60 (2005) 882–887, https://doi.org/10.1093/gerona/60.7.882.

[22] G.E. Hicks, E.M. Simonsick, T.B. Harris, A.B. Newman, D.K. Weiner, M.A. Nevitt, F.A. Tylavsky, Trunk muscle composition as a predictor of reduced functional capacity in the health, aging and body composition study: the moderating role of back pain, J Gerontol A Biol Sci Med Sci 60 (2005) 1420–1424, https://doi.org/10.1093/gerona/60.11.1420.

[23] U. Granacher, A. Lacroix, K. Roettger, A. Gollhofer, T. Muehlbauer, Relationships between trunk muscle strength, spinal mobility, and balance performance in older adults, J. Aging Phys. Activ 22 (2014) 490–498, https://doi.org/10.1123/JAPA.2013-0108.

[24] B. Shahtahmassebi, J.J. Hebert, M.D. Hecimovich, T.J. Fairchild, Associations between trunk muscle morphology, strength and function in older adults, Sci. Rep. 7 (2017), 10907, https://doi.org/10.1038/s41598-017-11116-0.

[25] A. Golubić, N. Šarabon, G. Marković, Association between trunk muscle strength and static balance in older women, J. Women Aging 33 (2021) 288–297, https://doi.org/10.1080/08952841.2019.1692628.

[26] D.E. Anderson, E. Quinn, E. Parker, B.T. Allaire, J.W. Muir, C.T. Rubin, et al., Associations of computed tomography-based trunk muscle size and density with balance and falls in older adults, J Gerontol A Biol Sci Med Sci 71 (2016) 811–816, https://doi.org/10.1093/gerona/glv185.

[27] E. Acar, T. Çankaya, S. Öner, The relationship between trunk muscle thickness and static postural balance in older adults, J. Aging Phys. Activ 28 (2020) 269–275, https://doi.org/10.1123/japa.2019-0127.

[28] P. Francis, W. McCormack, C. Toomey, M. Lyons, P. Jakeman, Muscle strength can better differentiate between gradations of functional performance than muscle quality in healthy 50-70y women, Braz. J. Phys. Ther. 21 (2017) 457–464, https://doi.org/10.1016/j.bjpt.2017.06.013.

[29] E. Rowe, M.K. Beauchamp, J. Astephen Wilson, Age and sex differences in normative gait patterns, Gait Posture 88 (2021) 109–115, https://doi.org/10.1016/j.gaitpost.2021.05.014.

[30] Y. Kwon, J.-H. Heo, H.-M. Jeon, S.D. Min, J.-H. Jun, G.-R. Tack, et al., AGE–GENDER difference in the biomechanical features of sit-to-stand movement, J. Mech. Med. Biol. 16 (2016), 1640027, https://doi.org/10.1142/S0219519416400273.

[31] C.H.Y. Ling, AJM de Craen, P.E. Slagboom, D.A. Gunn, M.P.M. Stokkel, R.G.J. Westendorp, A.B. Maier, Accuracy of direct segmental multi-frequency bioimpedance analysis in the assessment of total body and segmental body composition in middle-aged adult population, Clin. Nutr. 30 (2011) 610–615, https://doi.org/10.1016/j.clnu.2011.04.001.

[32] H.-J. Kim, I. Park, H.J. Lee, O. Lee, The reliability and validity of gait speed with different walking pace and distances against general health, physical function, and chronic disease in aged adults, J Exerc Nutrition Biochem 20 (2016) 46–50, https://doi.org/10.20463/jenb.2016.09.20.3.7.

[33] A. Zech, S. Steib, D. Sportwiss, E. Freiberger, K. Pfeifer, Functional muscle power testing in young, middle-aged, and community-dwelling nonfrail and prefrail older adults, Arch. Phys. Med. Rehabil. 92 (2011) 967–971, https://doi.org/10.1016/j.apmr.2010.12.031.

[34] D. Podsiadlo, S. Richardson, The timed "Up & Go": a test of basic functional mobility for frail elderly persons, J. Am. Geriatr. Soc. 39 (1991) 142–148, https://doi.org/10.1111/j.1532-5415.1991.tb01616.x.

[35] D. Schoene, S.M.-S. Wu, A.S. Mikolaizak, J.C. Menant, S.T. Smith, K. Delbaere, S.R. Lord, Discriminative ability and predictive validity of the timed up and go test in identifying older people who fall: systematic review and meta-analysis, J. Am. Geriatr. Soc. 61 (2013) 202–208, https://doi.org/10.1111/jgs.12106.

[36] S.-P. Lee, J. Dufek, R. Hickman, S. Schuerman, Influence of procedural factors on the reliability and performance of the timed up-and-go test in older adults, Int. J. Gerontol. 10 (2016) 37–42, https://doi.org/10.1016/j.ijge.2015.10.003.

[37] I. Amiridis, F. Arabatzi, P. Violaris, E. Stavropoulos, V. Hatzitaki, Static balance improvement in elderly after dorsiflexors electrostimulation training, Eur. J. Appl. Physiol. 94 (2005) 424–433, https://doi.org/10.1007/s00421-005-1326-3.

[38] A. Karlsson, G. Frykberg, Correlations between force plate measures for assessment of balance, Clin. Biomech. 15 (2000) 365–369, https://doi.org/10.1016/s0268-0033(99)00096-0.

[39] T. Cattagni, G. Scaglioni, D. Laroche, J. van Hoecke, V. Gremeaux, A. Martin, Ankle muscle strength discriminates fallers from non-fallers, Front. Aging Neurosci. 6 (2014) 336, https://doi.org/10.3389/fnagi.2014.00336.

[40] R. Roth, L. Donath, E. Kurz, L. Zahner, O. Faude, Absolute and relative reliability of isokinetic and isometric trunk strength testing using the IsoMed-2000 dynamometer, Phys. Ther. Sport 24 (2017) 26–31, https://doi.org/10.1016/j.ptsp.2016.11.005.

[41] R.A. McGregor, D. Cameron-Smith, S.D. Poppitt, It is not just muscle mass: a review of muscle quality, composition and metabolism during ageing as determinants of muscle function and mobility in later life, Longev. Heal. 3 (2014) 9, https://doi.org/10.1186/2046-2395-3-9.

[42] R. Tibshirani, Regression shrinkage and selection via the lasso, J. Roy. Stat. Soc. B 58 (1996) 267–288, https://doi.org/10.1111/j.2517-6161.1996.tb02080.x.

[43] J. Friedman, T. Hastie, R. Tibshirani, Regularization paths for generalized linear models via coordinate descent, J. Stat. Software 33 (2010) 1–22.

[44] Y. Kasukawa, N. Miyakoshi, M. Hongo, Y. Ishikawa, H. Noguchi, K. Kamo, et al., Relationships between falls, spinal curvature, spinal mobility and back extensor strength in elderly people, J. Bone Miner. Metabol. 28 (2010) 82–87, https://doi.org/10.1007/s00774-009-0107-1.

[45] T. Roghani, M.K. Zavieh, F.D. Manshadi, N. King, W. Katzman, Age-related hyperkyphosis: update of its potential causes and clinical impacts-narrative review, Aging Clin. Exp. Res. 29 (2017) 567–577, https://doi.org/10.1007/s40520-016-0617-3.

[46] A.M. Briggs, J.H. van Dieën, T.V. Wrigley, A.M. Greig, B. Phillips, S.K. Lo, K.L. Bennell, Thoracic kyphosis affects spinal loads and trunk muscle force, Phys. Ther. 87 (2007) 595–607, https://doi.org/10.2522/ptj.20060119.

[47] A.G. Bruno, D.E. Anderson, J. D'Agostino, M.L. Bouxsein, The effect of thoracic kyphosis and sagittal plane alignment on vertebral compressive loading, J. Bone Miner. Res. 27 (2012) 2144–2151, https://doi.org/10.1002/jbmr.1658.

[48] P. Tveit, K. Daggfeldt, S. Hetland, A. Thorstensson, Erector spinae lever arm length variations with changes in spinal curvature, Spine 19 (1994) 199–204, https://doi.org/10.1097/00007632-199401001-00015.

[49] A. Stotz, E. Maghames, J. Mason, A. Groll, A. Zech, Maximum isometric torque at individually-adjusted joint angles exceeds eccentric and concentric torque in lower extremity joint actions, BMC Sports Sci Med Rehabil 14 (2022) 13, https://doi.org/10.1186/s13102-022-00401-9.

[50] H.U. Yavuz, D. Erdağ, A.M. Amca, S. Aritan, Kinematic and EMG activities during front and back squat variations in maximum loads, J. Sports Sci. 33 (2015) 1058–1066, https://doi.org/10.1080/02640414.2014.984240.

[51] I. Martín-Fuentes, J.M. Oliva-Lozano, J.M. Muyor, Electromyographic activity in deadlift exercise and its variants. A systematic review, PLoS One 15 (2020), e0229507, https://doi.org/10.1371/journal.pone.0229507.

[52] C. Byrne, C. Faure, D.J. Keene, S.E. Lamb, Ageing, muscle power and physical function: a systematic review and implications for pragmatic training interventions, Sports Med. 46 (2016) 1311–1332, https://doi.org/10.1007/s40279-016-0489-x.

[53] P.B. O'Sullivan, T. Mitchell, P. Bulich, R. Waller, J. Holte, The relationship beween posture and back muscle endurance in industrial workers with flexion-related low back pain, Man. Ther. 11 (2006) 264–271, https://doi.org/10.1016/j.math.2005.04.004.

[54] T. Roghani, M. Khalkhali Zavieh, S. Talebian, A. Akbarzadeh Baghban, W. Katzman, Back muscle function in older women with age-related hyperkyphosis: a comparative study, J. Manip. Physiol. Ther. 42 (2019) 284–294, https://doi.org/10.1016/j.jmpt.2018.11.012.