One-repetition maximum strength test represents a valid means to assess leg strength in vivo in humans.

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One-repetition maximum strength test represents a valid means to assess leg strength *in vivo* in humans

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Abstract

Skeletal muscle strength is often determined to evaluate the adaptive response to an exercise intervention programme. Although dynamometry is considered the "gold standard" for the assessment of muscle strength *in vivo*, one-repetition maximum (1-RM) testing performed on training-specific equipment is more commonly applied. We assessed the validity of specific knee extension 1-RM testing by comparison with dynamometry in a heterogeneous population ($n = 55$). All participants performed 1-RM tests on regular leg extension and leg press machines. Additionally, isometric (at seven different knee angles) and isokinetic (at four different velocities) knee extension peak torques were determined. Pearson's r was calculated for the relationship between 1-RM data and peak torques for the entire population and for subgroups defined by age and gender. One-repetition maximum strength correlated strongly with the dynamometer results. One-repetition maximum leg extension correlated more strongly with peak torques than did 1-RM leg press ($0.78 \leq r \leq 0.88$ vs. $0.72 \leq r \leq 0.77$; $P < 0.001$). Similar correlations were observed in all subgroups. We conclude that 1-RM testing represents a valid means to assess leg muscle strength *in vivo* in young and elderly men and women. Considering the importance of training specificity in strength assessment, we argue that 1-RM testing can be applied to assess changes in leg muscle strength following an exercise intervention.

Keywords: *Leg muscle strength, one-repetition maximum test, dynamometry, validity, resistance training*

Introduction

Skeletal muscle strength is an important determinant of the functional capacity of an individual. Whereas in young adults muscle strength has been related to athletic performance, in the elderly greater strength is generally associated with better health and a higher level of independent living, both of which contribute to a higher quality of life. In the elderly, strong correlations have been reported between leg muscle strength and functional performance in activities of daily living, such as stair climbing (Jette & Jette, 1997), the ability to rise from a chair (Alexander, Schultz, Ashton-Miller, Gross, & Giordani, 1997; Bernardi et al., 2004), and balance recovery tasks (Schultz, Ashton-Miller, & Alexander, 1997). The age-associated decline in skeletal muscle mass and strength can have detrimental effects, including increased incidences of falls and bone fractures and the general loss of independence (Daley & Spinks, 2000; Prince, Corriveau, Hébert, & Winter, 1997; Rantanen et al., 2002; Wolfson, Judge, Whipple, & King, 1995). The importance of muscle strength for daily function requires the development of reliable and valid procedures to quantify muscle strength. The latter are needed to compare muscle strength on both an individual and population level, to evaluate muscle strength loss following disease or disability, and to evaluate the benefits of intervention programmes.

In general, two forms of strength assessment are frequently used: one-repetition maximum (1-RM) testing and dynamometry. One-repetition maximum testing requires an isoinertial contraction – that is, a constant weight is lifted at a voluntary speed. Dynamometry requires either an isometric or isokinetic contraction. When appropriate standardization is applied – for example, familiarization with the exercise, positioning and stabilization of the participant, and instruction and encouragement of the participant – dynamometry has been shown to provide highly reliable test results

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(Abernethy, Wilson, & Logan, 1995). Because of the high reliability and objectivity, isometric and isokinetic peak torque measurements performed on a dynamometer (e.g. Cybex) are considered the "gold standard" for the *in vivo* assessment of skeletal muscle strength in humans (Abernethy et al., 1995; Knapik, Wright, Mawdsley, & Braun, 1983; Ly & Handelsman, 2002). Consequently, dynamometry is generally applied to validate other strength assessment procedures (Dolny, Collins, Wilson, Germann, & Davis, 2001; Holm, Hammer, Larsen, Nordsletten, & Steen, 1995; Surburg, Suomi, & Poppy, 1992). However, a major disadvantage of dynamometry is that the contraction patterns used generally do not resemble the patterns that are performed in exercise intervention programmes (Abernethy et al., 1995). Evaluating the effects of training in a training specific context is considered to provide a more sensitive measure and thus represents a more accurate evaluation of strength gain (Abernethy & Jurimae, 1996; Abernethy et al., 1995). Therefore, in most exercise intervention studies, strength is determined by 1RM testing, using the equipment used in the training regimen (Hagerman et al., 2000; Kostek et al., 2005; McCall, Byrnes, Dickinson, Pattany, & Fleck, 1996; Williamson, Godard, Porter, Costill, & Trappe, 2000).

Similar criteria apply to dynamometry and 1-RM testing when the aim is to establish reliable test results. Prediction equations for 1-RM testing facilitate the assessment of valid 1-RM measurements within four consecutive attempts, thereby preventing fatigue as a potential confounder (Abernethy et al., 1995). Thus, when applied in a standardized manner, 1-RM testing has been proposed to represent a reliable method for the assessment of muscle strength in both the young and elderly (Phillips, Batterham, Valenzuela, & Burkett, 2004; Ploutz-Snyder & Giamis, 2001). In addition, several studies have compared 1-RM testing with dynamometry. Whereas training-induced changes measured with these two procedures seem to be unrelated, the correlations between 1-RM testing and dynamometry are generally high (Abernethy & Jurimae, 1996; Baker, Wilson, & Carlyon, 1994; Murphy & Wilson, 1996), implying the validity of 1-RM testing for strength assessment. However, most research has investigated arm strength and only small groups of young participants have been studied (Abernethy & Jurimae, 1996; Baker et al., 1994; Murphy & Wilson, 1996). Hence, although leg strength is probably the most important factor affecting mobility in the elderly (Bernardi et al., 2004; Fiatarone et al., 1990; Jette & Jette, 1997) and numerous studies have included leg extension and leg press exercises for training of the upper legs (Hagerman et al., 2000; Kostek et al., 2005; Olsen et al., 2006), these specific 1-RM testing procedures have yet to be validated with dynamometry. The latter might be even more important in different subpopulations. Qualitative changes in muscle mass and muscle function with ageing (Bottinelli & Reggiani, 2000; Doherty, 2003) and gender-based differences in muscle characteristics (Lindle et al., 1997) may differentially affect muscle strength as measured with different assessment procedures. Therefore, the validity of 1-RM testing should be assessed in different age and gender subgroups.

In the present study, we wished to determine whether 1-RM testing is a good means of evaluating leg muscle strength when compared with the gold standard method of dynamometry. Therefore, we compared the results of 1-RM testing (leg extension and leg press) with isometric and isokinetic knee extension peak torque measurements in a large heterogeneous population, as well as in more homogeneous subgroups based on age and/or gender.

Methods

Participants

A total of 55 adults volunteered to participate in this study (Table I). All participants were healthy volunteers; individuals with any pathology or disorder known to compromise their ability to perform maximal strength exercises were excluded. To validate 1-RM testing for large heterogeneous populations and to correlate levels of muscle strength with age, both men and women over a large age range were selected. For validation in more homogeneous populations, subgroups were defined based on either gender or age (young: age < 60 years; old: age ≥ 60 years). Age cut-off points were based on the finding that an age-related decline in muscle mass and function generally becomes more significant after the age of 60 (Doherty, 2003; Savelberg & Meijer, 2004). All trials were performed on 2 days separated by no less than 3 days, and performed at the same time of day. Participants were instructed to refrain from intense physical activity in the 2 days prior to the test days. After explaining all procedures in detail, informed consent was obtained from all participants. The study was approved by the local medical ethics committee.

Test procedures

At the first visit, 1-RM for the leg press and leg extension was estimated using the multiple-repetition test procedure and regular fitness

Table I. Participant characteristics (mean ± s_x).

	Total ($N = 55$)	Female ($n = 26$)	Male ($n = 29$)	Elderly ($n = 22$)	Young ($n = 33$)
Age (years)	47 ± 3	45 ± 4	49 ± 4	69 ± 1*	33 ± 2
Height (m)	1.72 ± 0.01	1.65 ± 0.01#	1.79 ± 0.02	1.68 ± 0.02*	1.75 ± 0.02
Body mass (kg)	73.8 ± 1.4	68.5 ± 1.9#	78.6 ± 1.5	77.0 ± 2.1	71.7 ± 1.7
Body mass index ($\text{kg} \cdot \text{m}^{-2}$)	25.0 ± 0.5	25.1 ± 0.8	24.8 ± 0.7	27.3 ± 0.8*	23.4 ± 0.5
Leg volume (litres)	8.6 ± 0.2	8.1 ± 0.2#	9.1 ± 0.2	8.1 ± 0.2*	9.0 ± 0.2
PT isometric ($\text{N} \cdot \text{m}$)	155 ± 6	131 ± 6#	177 ± 8	135 ± 7*	168 ± 8
PT isokinetic 2.09 ($\text{N} \cdot \text{m}$)	105 ± 4	88 ± 3#	119 ± 4	92 ± 4*	114 ± 5
PT isokinetic 3.14 ($\text{N} \cdot \text{m}$)	86 ± 3	72 ± 3#	98 ± 4	74 ± 3*	95 ± 4
PT isokinetic 4.19 ($\text{N} \cdot \text{m}$)	72 ± 3	59 ± 2#	83 ± 4	63 ± 3*	78 ± 4
PT isokinetic 5.24 ($\text{N} \cdot \text{m}$)	63 ± 3	50 ± 2#	73 ± 3	54 ± 3*	69 ± 3
1-RM leg extension (kg)	81 ± 3	67 ± 3#	93 ± 4	70 ± 4*	88 ± 4
1-RM leg press (kg)	167 ± 6	137 ± 5#	193 ± 8	148 ± 9*	179 ± 8

Notes: PT = peak torque (isokinetic values in $\text{rad} \cdot \text{s}^{-1}$).

#Significantly different compared with males. *Significantly different compared with the young. No age × gender interactions were observed.

machines (Technogym, Rotterdam). After a 5-min warm-up on a cycle ergometer and demonstration of the lifting technique, familiarization trials were performed to ensure proper execution of the exercise protocol. The maximum amount of repetitions (reps) measured for a certain load was used to estimate the 1-RM: $\text{1-RM} = \text{load}/(1.0278 - 0.0278 * \text{reps})$ (Mayhew et al., 1995). This estimate was used at the second visit to determine the initial load for the actual 1-RM test. Body mass (digital balance scale; accuracy 0.01 kg) and height (wall-mounted stadiometer; accuracy 0.001 m) were measured with participants standing barefoot and dressed lightly. Leg volume was assessed according to the method described by Jones and Pearson as an estimate of leg muscle mass (Buckley et al., 1987; Jones & Pearson, 1969). Since muscle mass is one of the major factors affecting muscle strength, we also wished to determine whether leg volume represents a valid (indirect) marker for muscle strength.

At the second visit, 1-RM leg press and 1-RM leg extension were measured following the protocol described by Kraemer and Fry (1995). In short, the load was set at 90% of the estimated 1-RM (Mayhew et al., 1995) and was increased by 2.5–5.0% after each successful lift until failure. Resting periods of 2 min duration were allowed between successive attempts. Although Mayhew et al., (1995) developed their prediction equation in young adults performing a bench press exercise, 1-RM leg extension and leg press in the present study was typically reached within 3–4 attempts in all subgroups. Moreover, no significant differences were observed between predicted and measured 1-RM in any of the subgroups. After 30 min of rest, dynamometer testing took place on a Cybex-II dynamometer. Participants were in a seated position, with the hip joint at 80° of flexion (0° corresponding to the upper leg in line with the trunk). The lateral femoral epicondyle was aligned with the axis of rotation of the Cybex dynamometer and the upper leg and pelvis were stabilized with Velcro straps to restrict compensatory movement. The lever arm was attached just proximal to the ankle joint. Familiarization trials at low intensity were performed before each measurement. All trials were separated by 2 min of rest to reduce fatigue. Since instantaneous muscle strength depends on muscle length, isometric contractions were randomly performed at seven different knee joint angles (20, 35, 50, 65, 80, 95, and 110°, with 0° representing a fully extended knee joint). Participants were instructed to provide maximal voluntary contractions for 2–3 s. To study the effect of different contractile velocities, isokinetic knee extension torque was randomly measured at four different speeds (2.09, 3.14, 4.19, and 5.24 $\text{rad} \cdot \text{s}^{-1}$). The hip joint angle and fixation to the chair were the same as in the isometric condition. A cyclic protocol was used, in that three consecutive extension/flexion movements were performed for each speed. All dynamometer data were sampled at 1000 Hz and were digitized with a 12-bit analog-to-digital converter. All anthropometric and dynamometer measurements were performed on the right leg and all test procedures were performed by the same investigator. Although test–retest reliability was not explicitly determined in the present study, all necessary measures were taken to ensure reliable test results for both 1-RM and dynamometry testing by adhering to a standardization routine (Abernethy et al., 1995).

Data analysis

After correction for gravitational forces (Herzog, 1988), isometric peak torque was determined as the absolute maximum of all the torque data for knee extension. The knee joint angle at which isometric peak torque was obtained averaged 79 ± 2°, with no differences between age or gender subgroups. The latter is in agreement with optimum knee joint angles reported previously (Bobbert & Harlaar, 1993; Lanza, Towse, Caldwell, Wigmore, & Kent-Braun, 2003; Savelberg & Meijer, 2004). Isokinetic data were first filtered with a fourth-order low-pass Butterworth filter with a cut-off frequency of 5 Hz. Then, isokinetic knee extension peak torque was determined as the highest of the three consecutive attempts for each speed. Thus, a total of seven strength indices were determined for all participants: 1-RM leg extension, 1-RM leg press, isometric peak torque, and isokinetic peak torque at 2.09, 3.14, 4.19, and 5.24 rad $\cdot$ s^{-1}.

Statistics

To determine between-group differences in anthropometric variables and muscle strength (all seven strength indices), a two-way analysis of variance (ANOVA) was performed with age and gender as factors. To compare the outcome of the 1-RM testing with the dynamometer testing, bivariate Pearson correlation coefficients (r) were calculated for the primary outcome measures; 1-RM leg extension and 1-RM leg press were correlated with isometric peak torque and with all isokinetic peak torques. This was done for the group as a whole, as well as for the young and elderly and for males and females separately. As a measure of reliability for the comparisons between the different methods of strength assessment, 95% confidence intervals (95% CI) were computed for the correlation coefficients (Hinkle, Wiersma, & Jurs, 1998). Also, standard errors of the estimates (SEE) were calculated as an indication of the magnitude of error involved in the comparisons. Differences between the correlation coefficients calculated for leg extension and leg press were tested statistically (Hinkle et al., 1998). Bonferroni corrections were used for multiple testing.

The relation between age and all seven strength indices was investigated by calculating Pearson correlation coefficients for the entire group and for the male and female subgroups separately. In addition, the correlation between leg volume (as an estimate of muscle mass/volume) and all seven strength indices was determined. All statistical procedures were performed with SPSS v. 13.0. Statistical significance was set at $P < 0.05$.

Results

A total of 55 participants aged 19–84 years were examined in this study (Table I). For leg muscle strength, significant age and gender effects were observed for the group as a whole, with no age × gender interactions. Males were significantly stronger than females on all seven strength indices ($P < 0.001$). Young adults were significantly stronger than the elderly, with leg extension and leg press strength and all isokinetic and isometric peak torques being higher in the young than in the elderly ($P < 0.01$). These age and gender effects were evident in both the male and female and in the young and elderly subgroups, respectively ($P < 0.05$).

The correlations between 1-RM and isometric/isokinetic peak torques were stronger for leg extension than for leg press (Figure 1 and Table II), with r-values ranging from 0.78 to 0.88 (SEE = 0.06–0.09) and from 0.72 to 0.77 (SEE = 0.08–0.09), respectively ($P < 0.001$). The strongest correlation was found between 1-RM leg extension and isometric peak torque ($r = 0.88$; SEE = 0.06, 95% CI = 0.81–0.93). The correlations between 1-RM and isometric peak torque and between 1-RM and isokinetic peak torque at 3.14 rad $\cdot$ s^{-1} were markedly larger for leg extension than leg press ($P < 0.05$). In general, stronger correlations were observed between 1-RM leg extension and peak torque values than between 1-RM leg press and peak torque values in the different age and gender subgroups, except in the female subgroup. In all subgroups separately, the strongest correlation was between 1-RM leg extension and isometric peak torque, with r ranging from 0.83 (SEE = 0.11, 95% CI = 0.67–0.92) to 0.93 (SEE = 0.08, 95% CI = 0.83–0.97; $P < 0.001$). Statistically significant differences between leg extension and leg press ($P < 0.05$) were observed for the relationship between 1-RM and isometric peak torque (male, elderly, and young subgroups), and for that relation between 1-RM and isokinetic peak torque at 2.09 and 3.14 rad $\cdot$ s^{-1} (male subgroup) and at 5.24 rad $\cdot$ s^{-1} (elderly subgroup). For the study population as a whole and for the subgroups, the correlations between 1-RM (both leg extension and leg press) and isokinetic peak torques tended to decrease with an increase in angular velocity. Correlations between 1-RM and peak torque values were at all times moderate to strong with only 6 of the 50 r-values being below 0.60 and 35 of the r-values being 0.71 and higher (Table II).

Leg volume was significantly correlated with all strength indices, with r ranging from 0.64 to 0.72 ($P < 0.001$). The strongest correlations were between leg volume and 1-RM measures (Figure 2, Table III). Correlations were shown to be similar in the male, young and elderly subgroups, although the absolute r-values tended to be lower in the elderly subgroup (range 0.46–0.66). In the female subgroup,

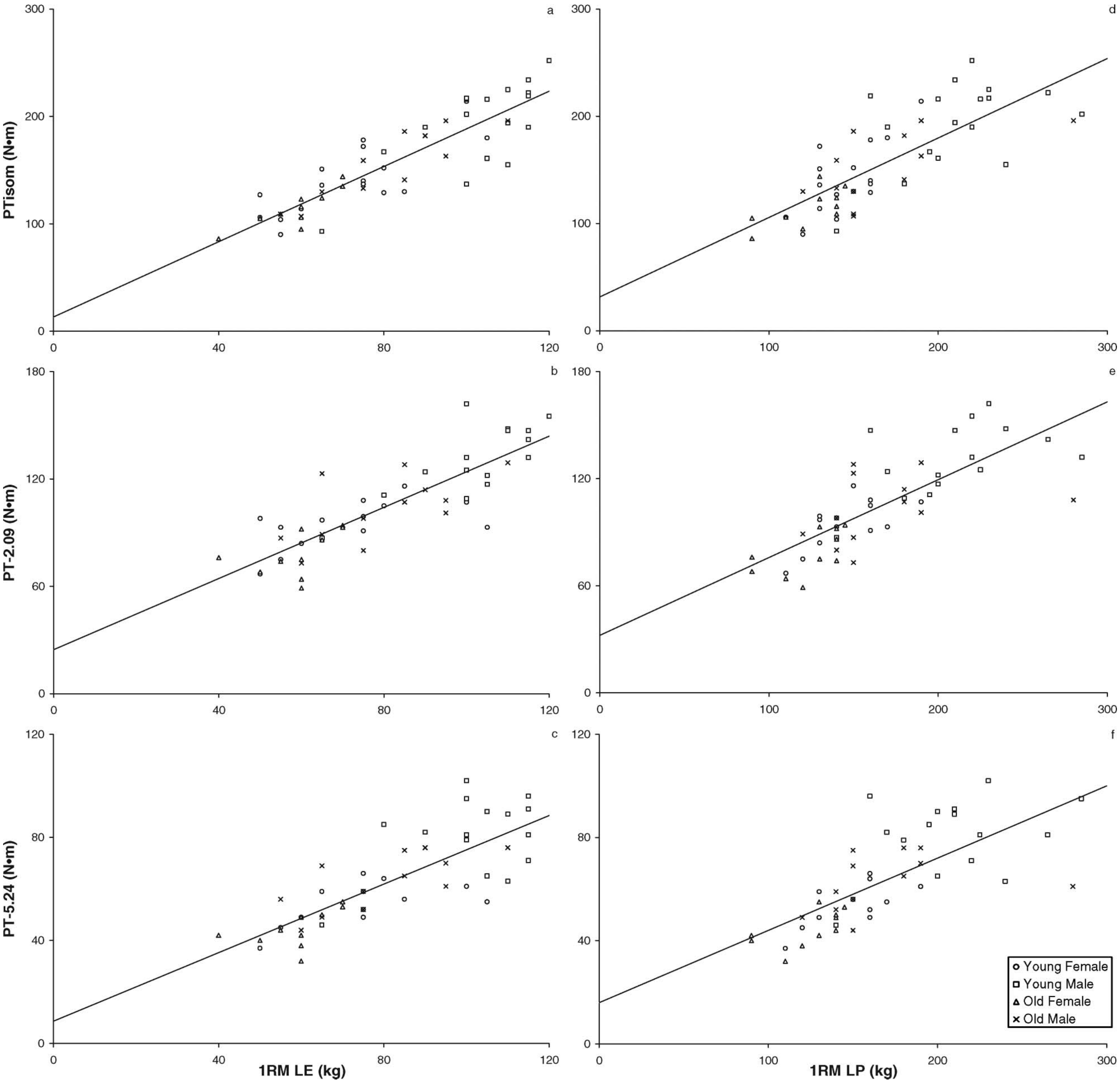

Figure 1. Scatterplots of the relationships between one-repetition maximum and peak torque data. Subgroups are indicated by different symbols: ○, young females; □, young males; Δ, elderly females; ×, elderly males. (a, b, c) 1-RM leg extension (1-RM LE) vs. isometric (PTisom), isokinetic 2.09 rad · s^{-1} (PT − 2.09), and isokinetic 5.24 rad · s^{-1} (PT − 5.24) peak torques, respectively. (d, e, f) 1-RM leg press (1RM LP) vs. PTisom, PT − 2.09, and PT − 5.24, respectively. Lines represent the fitted regression.

the correlation between leg volume and strength was relatively weak and r only reached significance for the correlation between leg volume and 1-RM leg extension, 1-RM leg press, isometric peak torque, and isokinetic peak torque at 2.09 rad · s^{-1}, with r-values of 0.56, 0.49, 0.40, and 0.41, respectively.

Age correlated negatively with all strength indices, with r ranging from -0.30 to -0.43 (Table III). In the gender subgroups, the correlations tended to be even stronger, with r ranging from -0.32 to -0.61 and from -0.50 to -0.64 in the female and male subgroups, respectively ($P < 0.05$).

Discussion

The aim of the present study was to determine whether 1-RM testing is a valid means to assess muscle strength of the knee extensors. A strong correlation was observed between strength measured with 1-RM testing and knee extension peak torque as obtained using dynamometry. Furthermore, the strong correlation was shown to be independent of age and/or gender.

One-repetition maximum testing and isometric/isokinetic dynamometry are the main methods of strength assessment in scientific research

Table II. Correlations between different strength indices.

	PTisom	PTisok 2.09	PTisok 3.14	PTisok 4.19	PTisok 5.24
Total					
1-RM LE	$0.88^{\ddagger}$ (0.81–0.93)$^{\#}$	$0.85^{\ddagger}$ (0.75–0.91)	$0.84^{\ddagger}$ (0.74–0.91)$^{\#}$	$0.78^{\ddagger}$ (0.65–0.87)	$0.80^{\ddagger}$ (0.68–0.88)
1-RM LP	$0.77^{\ddagger}$ (0.63–0.86)	$0.77^{\ddagger}$ (0.63–0.86)	$0.74^{\ddagger}$ (0.59–0.84)	$0.74^{\ddagger}$ (0.59–0.84)	$0.72^{\ddagger}$ (0.57–0.83)
Female					
1-RM LE	$0.83^{\ddagger}$ (0.66–0.92)	$0.64^{\dagger}$ (0.33–0.82)	$0.73^{\ddagger}$ (0.47–0.87)	0.47^{*} (0.19–0.72)	$0.69^{\ddagger}$ (0.41–0.85)
1-RM LP	$0.75^{\ddagger}$ (0.51–0.88)	$0.72^{\ddagger}$ (0.47–0.87)	$0.73^{\ddagger}$ (0.48–0.87)	$0.61^{\dagger}$ (0.29–0.81)	$0.71^{\ddagger}$ (0.45–0.86)
Male					
1-RM LE	$0.83^{\ddagger}$ (0.67–0.92)$^{\#}$	$0.82^{\ddagger}$ (0.64–0.91)$^{\#}$	$0.79^{\ddagger}$ (0.59–0.90)$^{\#}$	$0.73^{\ddagger}$ (0.49–0.86)	$0.69^{\ddagger}$ (0.43–0.84)
1-RM LP	$0.64^{\ddagger}$ (0.36–0.81)	$0.59^{\dagger}$ (0.29–0.79)	$0.56^{\dagger}$ (0.25–0.77)	$0.56^{\dagger}$ (0.25–0.77)	$0.50^{\dagger}$ (0.17–0.73)
Elderly					
1-RM LE	$0.93^{\ddagger}$ (0.83–0.97)$^{\#}$	$0.75^{\ddagger}$ (0.49–0.89)	$0.77^{\ddagger}$ (0.52–0.90)	$0.76^{\ddagger}$ (0.49–0.89)	$0.81^{\ddagger}$ (0.59–0.92)$^{\#}$
1-RM LP	$0.76^{\ddagger}$ (0.49–0.89)	$0.60^{\dagger}$ (0.24–0.82)	$0.64^{\dagger}$ (0.30–0.84)	$0.58^{\dagger}$ (0.21–0.81)	$0.63^{\dagger}$ (0.28–0.83)
Young					
1-RM LE	$0.84^{\ddagger}$ (0.69–0.92)$^{\#}$	$0.84^{\ddagger}$ (0.70–0.92)	$0.82^{\ddagger}$ (0.67–0.91)	$0.73^{\ddagger}$ (0.52–0.86)	$0.72^{\ddagger}$ (0.51–0.85)
1-RM LP	$0.73^{\ddagger}$ (0.52–0.86)	$0.79^{\ddagger}$ (0.62–0.89)	$0.72^{\ddagger}$ (0.50–0.85)	$0.75^{\ddagger}$ (0.55–0.87)	$0.70^{\ddagger}$ (0.47–0.84)

Notes: Data are Pearson's r, with 95% confidence intervals in parentheses. Standard errors of the estimates were between 0.06 and 0.09 for the group as a whole and between 0.08 and 0.17 for the subgroups. PTisom and PTisok = isometric and isokinetic peak torque, respectively (isokinetic values in rad $\cdot$ s^{-1}). LE = leg extension, LP = leg press.

$^{*}P < 0.05$; $^{\dagger}P < 0.01$; $^{\ddagger}P < 0.001$. $^{\#}$Significantly different from 1-RM LP ($P < 0.05$).

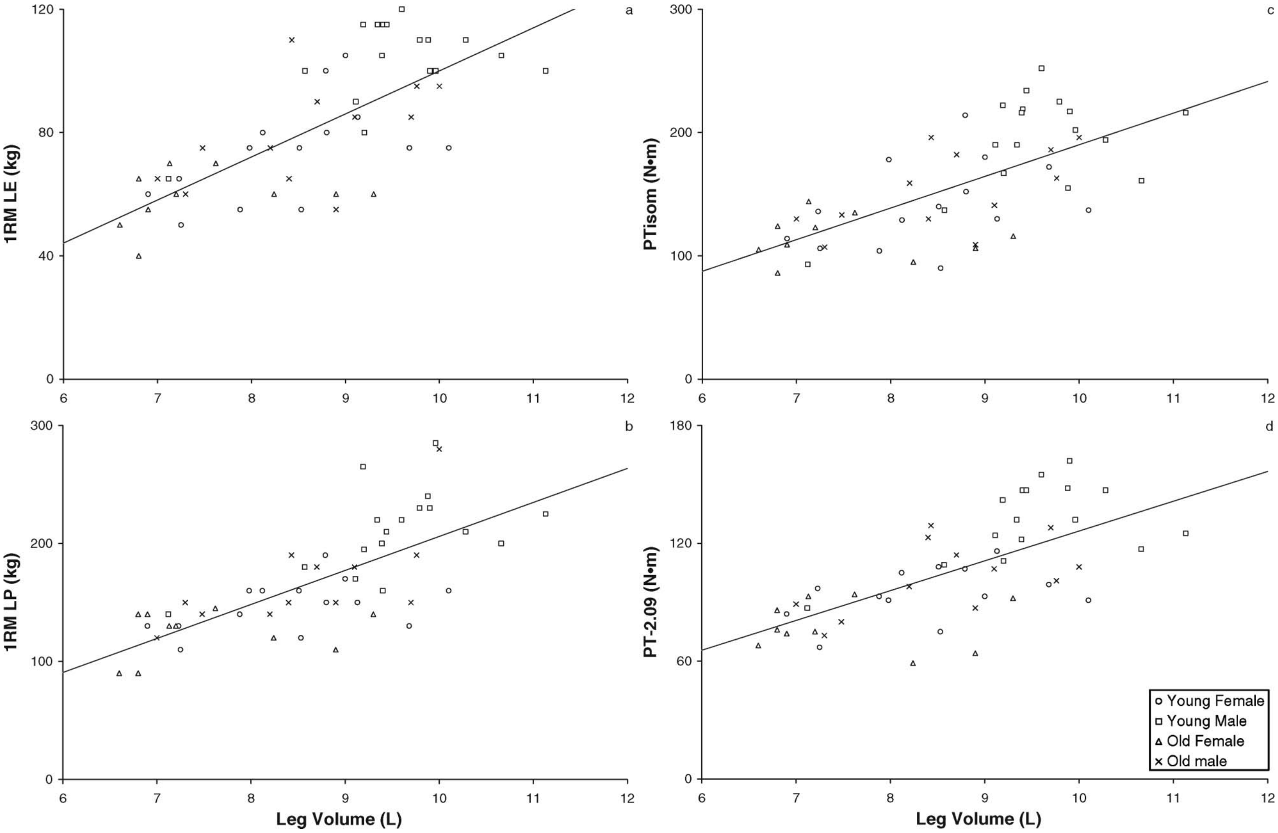

Figure 2. Scatterplots of the relationships between leg volume and different strength indices. Subgroups are indicated by different symbols: ○, young females; □, young males; Δ, elderly females; ×, elderly males. (a, b, c, d) Leg volume vs. 1-RM for leg extension (1-RM LE), 1-RM for leg press (1RM LP), isometric peak torque (PTisom), and isokinetic 2.09 rad $\cdot$ s^{-1} peak torque (PT − 2.09), respectively. Lines represent the fitted regression.

Table III. Correlations between strength, age, and leg volume.

	1-RM LE	1-RM LP	PTisom	PTisok 2.09	PTisok 3.14	PTisok 4.19	PTisok 5.24
Total							
age	$-0.40^{\dagger}$	$-0.34^{\star}$	$-0.36^{\dagger}$	$-0.39^{\dagger}$	$-0.43^{\dagger}$	$-0.30^{\star}$	$-0.37^{\dagger}$
legV	$0.72^{\ddagger}$	$0.72^{\ddagger}$	$0.67^{\ddagger}$	$0.68^{\ddagger}$	$0.65^{\ddagger}$	$0.64^{\ddagger}$	$0.67^{\ddagger}$
Female							
age	$-0.48^{\star}$	$-0.57^{\dagger}$	$-0.45^{\star}$	$-0.56^{\dagger}$	$-0.61^{\dagger}$	-0.32	$-0.54^{\star}$
legV	$0.56^{\dagger}$	$0.49^{\star}$	$0.40^{\star}$	$0.41^{\star}$	0.32	0.14	0.31
Male							
age	$-0.64^{\ddagger}$	$-0.50^{\dagger}$	$-0.50^{\dagger}$	$-0.57^{\dagger}$	$-0.56^{\dagger}$	$-0.51^{\dagger}$	$-0.55^{\dagger}$
legV	$0.66^{\ddagger}$	$0.70^{\ddagger}$	$0.65^{\ddagger}$	$0.65^{\ddagger}$	$0.65^{\ddagger}$	$0.68^{\ddagger}$	$0.69^{\ddagger}$
Elderly							
legV	$0.60^{\dagger}$	$0.66^{\dagger}$	$0.56^{\dagger}$	$0.54^{\star}$	$0.46^{\star}$	$0.46^{\star}$	$0.56^{\dagger}$
Young							
legV	$0.72^{\ddagger}$	$0.69^{\ddagger}$	$0.65^{\ddagger}$	$0.67^{\ddagger}$	$0.65^{\ddagger}$	$0.64^{\ddagger}$	$0.64^{\ddagger}$

Notes: LE = leg extension, LP = leg press, PTisom and PTisok = isometric and isokinetic peak torque, respectively (isokinetic values in rad $\cdot$ s^{-1}), legV = leg volume.
$^{\star}P < 0.05$; $^{\dagger}P < 0.01$; $^{\ddagger}P < 0.001$.

(Abernethy et al., 1995; Baker et al., 1994; Knapik et al., 1983). Because of superior reliability and high internal validity, dynamometry is considered the gold standard for strength assessment. In addition, the function of individual muscles can be studied more appropriately when using dynamometry (Herzog, Guimaraes, Anton, & Carter-Erdman, 1991; Savelberg & Meijer, 2003). However, in exercise intervention programmes, resistance training equipment is used instead of dynamometers. Therefore, 1-RM testing is generally performed on the same equipment used in the training to evaluate changes in muscle strength. The 1-RM strength testing procedure represents a training-specific assessment (e.g. activation- and coordination-related aspects). As such, 1-RM testing should provide the most sensitive measure of the training response (Abernethy et al., 1995). In accordance, greater increases have been reported in 1-RM strength when compared with isometric/isokinetic peak torques after a period of resistance training in both the young (Abernethy & Jurimae, 1996; Baker et al., 1994) and elderly (Ferri et al., 2003; Frontera, Meredith, O'Reilly, Knuttgen, & Evans, 1988; Tracy et al., 1999). Resistance training programmes in the elderly have often included leg press and leg extension exercises, since *quadriceps* muscle strength is strongly associated with mobility (Chrusch, Chilibeck, Chad, Davison, & Burke, 2001; Fiatarone et al., 1990; Hagerman et al., 2000; Kostek et al., 2005). Strength assessment procedures used in these training programmes should not only be sensitive to temporal changes, but should also allow discrimination between participants of different strength. Unfortunately, most validation studies comparing 1-RM testing with dynamometry have focused on arm strength in young participants (Abernethy & Jurimae, 1996; Baker et al., 1994; Murphy & Wilson, 1996). Therefore, in the present study, we evaluated the validity of 1-RM leg extension and 1-RM leg press for measuring maximal knee extension strength with knee extension dynamometry in a heterogeneous population, consisting of participants of various ages and both sexes.

Skeletal muscle strength is affected by the speed and mode of contraction, as well as by muscle length during contraction. Each of these factors is likely to influence the relationship between 1-RM testing and dynamometry. Nonetheless, in the present study we observed strong significant correlations between strength as assessed by 1-RM leg extension and dynamometry (Figure 1 a–c; $0.78 \leq r \leq 0.88$; SEE = 0.06–0.09). The latter clearly shows that there is excellent agreement between muscle strength as assessed by 1-RM leg extension and knee extension peak torques. This strong correlation is likely attributed to the similarity in joint positioning, the single-joint movement (isolating the *quadriceps*), and the open-chain of resistance that characterize both approaches. The differences in contraction velocity and the single-leg versus the two-legged nature of the exercises clearly do not seem to have a major effect on the relationship between 1-RM leg extension and dynamometry. Our findings are in line with those of other studies reporting strong correlations between upper extremity strength as assessed by 1-RM testing and isometric/isokinetic dynamometry in young males (Abernethy & Jurimae, 1996; Murphy & Wilson, 1996).

Although strong correlations were also observed between 1-RM leg press and knee extension peak torques, the observed correlations were generally lower than those between 1-RM leg extension and peak torques (Table II). Although not always statistically significant, this difference was evident for all peak torques separately and is likely explained by the different characteristics of the leg press exercise. Leg press consists of a closed-chain exercise including hip, knee, and ankle joint movement, representing whole limb extension strength rather than isolating the knee extensors, as is the case with leg extension and dynamometry. Several other studies have suggested that weaker correlations between different testing methods are the result of dissimilarities in the execution of the movement (Knapik et al., 1983; Murphy & Wilson, 1996).

For both leg extension and leg press, correlations tended to be stronger with isometric and low-velocity isokinetic peak torques than with high-velocity isokinetic peak torques. The stronger correlations are probably due to greater similarities in contraction velocity between the different methods, which has been reported previously (Knapik et al., 1983). This finding might be explained by the fact that a change in maximum force with a change in contraction velocity has a differential effect in participants: this effect depends on, for example, the different training backgrounds of the participants, the activation status of the muscle (Bobbert & Harlaar, 1993), and fibre type differences (i.e. percentage of type II fibres) between participants (Bottinelli & Reggiani, 2000). Because of the high load in 1-RM testing, the contraction velocity is relatively low. Since the strongest correlations were found between the 1-RM data and isometric peak torques, it could be argued that the contraction velocity during 1-RM testing is closest to the isometric condition. In addition, larger differences in the contraction velocity between the 1-RM testing and the high-velocity isokinetic testing could have caused the larger variability between these test modalities, thereby explaining the decrease in the respective correlations. In the present study, all correlations between 1-RM and dynamometer data were > 0.71. The latter implies that 1-RM testing is a valid means to evaluate maximal muscle strength.

In the present study, subgroups were defined to investigate the possible modulating effect of age and gender on the relationship between strength as assessed by 1-RM and dynamometry. Although the sample size of the individual groups was relatively small ($n = 22$), leading to somewhat larger standard errors of the estimates (see Table II), we observed good correlations between the 1-RM (especially leg extension) and dynamometer data within each of the subgroups, with the only exception being the relationship between 1-RM leg extension and peak torque at 4.19 rad $\cdot$ s^{-1} in the subgroup of females. Hence, we conclude that 1-RM testing can be applied in both the young and elderly, independent of gender, as a valid measure of knee extensor strength. In addition, the subtle differences we observed between the two 1-RM exercises and their correlation with dynamometry suggest that leg extension more accurately isolates knee extension strength and leg press represents not merely *quadriceps* strength but is related to both hip and knee extension strength.

In general, the measurement of strength in a large heterogeneous population inherently increases the likelihood of finding significant correlations between the different assessment methods. To limit the range over which strength was measured, we defined specific subgroups, to improve the usefulness of correlation analyses. It should be noted that correlation analysis as applied in the present study is accompanied by further limitations, such as the inability to detect non-linear relationships between the measured variables. However, since other methods of assessing validity, such as limits of agreement (Bland & Altman, 1986), cannot be used to compare data with different units of measurement, correlation analysis was regarded as the most appropriate way of assessing 1-RM validity in the present study (Dolny et al., 2001; Surburg et al., 1992).

Significant correlations were observed between leg volume and all seven strength indices, supporting the contention that leg volume can be indicative of leg muscle strength. Although the use of computed tomography and/or magnetic resonance imaging likely provides a much better estimate of leg muscle mass, we argue that non-invasive anthropometric leg volume measures may be helpful in future studies in which large cohorts are subjected to, for example, lifestyle intervention programmes, to determine whether increases in muscle mass and/or strength have occurred.

We conclude that 1-RM testing represents a valid means to evaluate leg muscle strength *in vivo* in both young and elderly men and women. Although dynamometry can reveal additional information about the underlying aspects of muscle strength, it is not essential. Considering the importance of training specificity in exercise intervention studies, we suggest that training-specific 1-RM strength assessment can be used to assess changes in muscle strength.

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