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ORIGINAL ARTICLE

Age-related effects on maximal and rapid hamstrings/quadriceps strength capacities and vertical jump power in young and older females

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Abstract

Background and aims Declines in hamstrings and quadriceps maximal and rapid strength are commonly reported as a consequence of aging; however, few studies have investigated the influence of age on maximal and rapid hamstrings to quadriceps (*H/Q*) strength ratios. This study aimed to examine the effects of age on leg extension and flexion maximal and rapid torque production, *H/Q* strength ratios, and muscle power in healthy, young and old females.

Methods Fifteen young (21 ± 2 years) and 15 old (69 ± 7 years) females performed 3 isometric leg extension and flexion maximal voluntary contractions (MVCs), from which peak torque (PT), early (0–30 ms) and late (0–200 ms) phase rate of torque development (RTD), and PT and RTD *H/Q* strength ratios were extracted. Lower-body peak power output (P_{max}) was assessed through a vertical jump test.

Results P_{max}, PT, and early (RTD30) and late (RTD200) RTD variables of the leg extensors and flexors were lower ($P \leq 0.048$) and PT and RTD200 *H/Q* strength ratios were higher ($P \leq 0.030$) in the old compared to the younger females; however, no difference was observed for RTD30 *H/Q* ($P = 0.300$). There were also significant negative relationships in the older ($r = -0.616$ and -0.522; $P = 0.014$ and 0.046) but not the younger ($r = 0.295$ and -0.109; $P = 0.286$ and 0.698) females between P_{max} and RTD30 and RTD200 *H/Q* strength ratios.

Conclusion The higher RTD200 *H/Q* ratio for the older females may contribute to the muscle power deficits often observed in elderly populations. Practitioners may use these findings to help identify older adults with low muscle power capacities and possibly overall functional decline.

Keywords Isometric · Countermovement · *H/Q* ratio · Peak torque · Rate of torque development

Introduction

Muscle strength of the leg extensors and flexors is critical for fundamental activities of daily living including rising from a chair, walking, maintaining postural stability, and jumping [1, 2]. However, with advanced age, leg extension and flexion strength deficits have been suggested to reduce one's ability to perform these daily tasks [2]. This may lead to a deterioration in health and quality of life and an increased risk for mortality [3]. Government statistics have confirmed that older adults (≥ 65 years) in the United States are living longer than ever before [4]. Thus, the prospect of monitoring isometric strength characteristics, such as maximal and rapid torque or force production [i.e., peak torque (PT) and rate of torque development (RTD) or peak force (PF) and rate of force development (RFD)] of the leg extensors and flexors across the lifespan, may be imperative in the assessment and treatment of age-related functional performance deficits in elderly populations. Given the importance of this prospect, numerous research studies have investigated age-related differences in leg extension and flexion maximal and rapid strength, reporting significant

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reductions in these characteristics for both muscle groups [5–7].

Although age-related declines in maximal and rapid strength have been reported for these antagonist muscle groups, several studies have shown greater strength deficits in the leg extensors than the flexors [5, 8, 9]. Greater age-related deficits in leg extension strength, which may be partially due to greater age-related declines in quadriceps muscle size [10], have been suggested to be a significant contributor to the functional decline often observed in older individuals [11]. Such deficits may also adversely influence the net balance of muscle strength expression around the knee joint [12]. Strength balance around the knee has been suggested to be an effective indicator of muscle function [12] and knee joint stabilization [13], and is typically assessed using the hamstrings to quadriceps (H/Q) strength ratio [14]. Previous studies investigating the effects of aging on isometric maximal strength (PT or PF) H/Q or Q/H ratios have yielded conflicting results, with some research showing a higher H/Q ratio in old compared to younger adults [11] and others reporting a lack of differences between age groups [15, 16]. Because the H/Q strength ratios reported in several of these studies [15, 16] were derived from hamstrings and quadriceps strength values at knee joint angles ranging between 15° and 60°, it remains unclear whether age-related differences in H/Q strength ratios exist at knee positions closer to terminal flexion. Greater age-related deficits in leg extension strength, which would increase the H/Q strength ratio, have been suggested to occur at flexed (~75°–90°) compared to more extended (~30–60°) knee positions in older adults [17, 18]. Thus, it is possible that the H/Q strength ratio derived from quadriceps and hamstrings strength values at a flexed knee joint angle of 90° may be an effective parameter for identifying age-related changes in leg flexor–extensor strength balances; however, further research is needed to confirm this hypothesis.

The majority of previous studies investigating the effects of aging on H/Q or Q/H strength outcomes between young and older adults have exclusively made such comparisons using maximal strength (PT or PF) ratios as the outcome measure [11, 15, 16]. However, to our knowledge, no previous studies have investigated the influence of age on rapid strength (RTD or RFD) H/Q ratios. Because many functional-related tasks (i.e., running, jumping, accelerating) involve movement durations of less than 250 ms [19], the rapid strength H/Q ratio derived from RTD values assessed over short time periods (i.e., 30–200 ms) has been suggested to be a more functionally relevant measure of muscle balance and knee joint stabilization than the maximal strength H/Q ratio [14], which often requires more than 300 ms to be achieved [20]. Previous authors investigating rapid strength H/Q ratios in younger adults have proposed

that a higher RTD H/Q may indicate better muscle balance and knee joint stabilization [13, 14], whereas other authors investigating older adults have suggested that higher H/Q strength ratios may be detrimental to functional performance abilities [11, 12], including the ability to generate muscle power [21]. Despite these claims, however, we are unaware of any studies that have evaluated the relationships between muscle power as assessed during a vertical jump test and rapid strength H/Q ratios. Similar to isometric strength, vertical jump muscle power has also been shown to be lower in old versus younger adults [22] and thus may be an important parameter for identifying age-related declines in functional performance abilities. Thus, given the potential influence of H/Q strength balance on muscle power and because of the paucity of research investigating the effects of aging on RTD H/Q, further research is warranted examining the effects of using maximal and rapid H/Q strength ratios and vertical jump power to characterize age-related changes in neuromuscular function of a healthy, active female population. Therefore, the purpose of the present study was to examine the influence of age on maximal and rapid H/Q strength ratios in healthy, physically active young and older females. A secondary aim of this study was to compare vertical jump power between the two groups and to examine the relationships between muscle power and maximal and rapid H/Q muscle strength.

Methods

Participants

Fifteen young (mean ± SD; age = 21 ± 2 years; height = 165 ± 7 cm; mass = 67 ± 10 kg; body mass index [BMI] = 24 ± 4 kg/m^2) and 15 old (age = 69 ± 7 years; height = 162 ± 5 cm; mass = 72 ± 13 kg; BMI = 27 ± 5 kg/m^2) females volunteered to participate in this investigation. Each participant completed a self-administered questionnaire prior to testing to assess their health history and volume of physical activity. None of the participants reported any current or ongoing neuromuscular diseases or musculoskeletal injuries specific to the ankle, knee, or hip joints. Participants were considered as being recreationally active based on their self-reported levels of exercise behaviors (young = 8.7 ± 7.5 h/week, old = 5.0 ± 3.3 h/week) [23]. This study was approved by the university's institutional review board for human subject's research, and each participant read and signed an informed consent document.

Procedures

Each participant visited the laboratory on two occasions separated by 2–7 days. During the first visit, participants

were familiarized with the testing procedures by performing several vertical jump and isometric strength assessment trials. During the second visit, participants completed 3 countermovement vertical jumps (CMJ) followed by 3 isometric strength assessments of the leg extensors and flexors.

Assessment of lower-body power output

Lower-body power output was measured during the CMJs using a linear velocity transducer (Tendo Sports Machines, Slovak Republic) that was attached to the posterior portion of a belt fastened around the participants' waistline [24]. During the CMJs, participants stood on the floor with feet shoulder width apart and hands positioned on the hips. Participants were not allowed to take any steps prior to performing the CMJ and a quick descending quarter-squat countermovement was allowed before the ascending takeoff phase. The participants were instructed to jump as explosively as possible with both feet at the same time and land on the floor in the starting position. To calculate power output in watts (W), each participants' body mass was measured with a stadium scale (Detecto, Webb City, MO) and entered into the linear velocity transducer microcomputer (Tendo weightlifting analyzer V-207). Following the completion of each jump, estimated peak power output (P_{max}, W) was calculated and displayed by the microcomputer. A total of three jumps were performed with 1 min of rest between trials, and the trial with the highest P_{max} was used for all subsequent data analyses. Previous reliability statistics for these procedures from our laboratory have revealed an intraclass correlation coefficient (ICC) of 0.89 and a standard error of measurement (SEM) value expressed as a percentage of the mean of 4.88% [25].

Isometric strength testing

These leg extension and flexion isometric strength testing procedures have been described previously [26]; however, they will be briefly discussed below. A manual isometric strength assessment technique was used to quantify the maximal and rapid isometric torque characteristics. This technique consisted of the participant extending or flexing the leg against a load cell (LCHD-250, Omega Engineering, Inc., Bridgeport NJ) attached to a steel frame, which was anchored to a 15-cm-high platform placed underneath the participant's feet (Fig. 1). For each isometric strength assessment, participants sat in an upright position with restraining straps placed over the trunk, waist, and thigh. The ankle was immobilized in a neutral 90° position (between foot and leg) with a custom-made cast that was fixed around the foot and held with straps above the ankle and over the toes and metatarsals. All assessments

Fig. 1 Illustration of the manual isometric strength assessment technique used to quantify maximal and rapid torque characteristics. This technique consisted of the participant extending or flexing the leg against a load cell attached to a steel frame, which was anchored to a 15-cm-high platform placed underneath the participant's feet

were performed on the right leg at a knee joint angle of 90° below the horizontal plane, which was consistent with the knee joint angle for the isometric leg extensor and flexor strength assessments previously reported by Bohannon [27]. Prior to the maximal isometric strength testing, participants performed 3 submaximal isometric leg extension and flexion muscle actions at approximately 75% of their perceived maximal effort. Following the submaximal contractions, each participant performed 3 isometric maximal voluntary contractions (MVCs) of the leg extensors and flexors with 1 min of recovery between each contraction and 3 min of recovery between muscle groups [6]. The order of the leg extensor and flexor testing was randomized to control for any potential effects of fatigue [19]. For all isometric MVCs, participants were verbally instructed to "push" or "pull" "as hard and fast as possible" for a total of 3–4 s, and strong verbal encouragement was given throughout the duration of the MVC [26].

Data analyses

During each isometric strength assessment, the force (N) signal was sampled from the load cell at 1 kHz (MP150WSW; Biopac Systems, Inc, Santa Barbara, CA),

stored on a personal computer (Dell Inspiron 8200; Dell, Inc, Round Rock, TX), and processed off-line using custom-written software (LabVIEW, Version 11.0; National Instruments, Austin, TX). The scaled force signal was low-pass filtered, with a 10-Hz cutoff (zero-phase lag, fourth-order Butterworth filter). A torque (Nm) signal was subsequently derived off-line by multiplying the force (N) signal from the load cell by the limb length (m) for each participant [28]. Limb length was measured as the distance from the lateral knee joint to the heel (positioned over the load cell), and was measured once, prior to the strength assessment testing. The passive baseline torque value was considered the limb weight and subtracted from the signal so that the new baseline value was 0 Nm. All subsequent analyses were conducted on the scaled, filtered, and gravity-corrected torque signal.

Isometric MVC PT (Nm) was determined as the highest mean 500 ms epoch during the entire 3–4 s MVC plateau. Isometric RTD (Nm s^{-1}) was calculated as the linear slope of the torque–time curve (Δtorque/Δtime) at time intervals of 0–30 (RTD30) and 0–200 (RTD200) ms [29]. These time intervals were chosen for analysis because they represent rapid torque characteristics in the early (0–30 ms) and late (0–200 ms) phases of muscle contraction [30], and have been previously shown to effectively differentiate among strength-related performances [31]. The onset of contraction was determined as the point when the torque signal reached a threshold of 7.5 Nm for the leg extensors or 4 Nm for the leg flexors [6]. Test–retest reliability for these procedures from our laboratory has been reported previously [26]. The ICC and SEM as a percentage of the mean values for all the variables and muscles reported in this study ranged from 0.88 to 0.96 and 8.56 to 22.16%, respectively.

Maximal and rapid isometric H/Q strength ratios were determined by taking the quotients between leg flexor and extensor PT $\left(PT\,H/Q; \frac{\text{Leg Flexor PT}}{\text{Leg Extensor PT}} \right)$ and RTD values at RTD30 $\left(RTD\,30\,H/Q; \frac{\text{Leg Flexor RTD 30}}{\text{Leg Extensor RTD 30}} \right)$ and RTD200

$\left(RTD\,200\,H/Q; \frac{\text{Leg Flexor RTD 200}}{\text{Leg Extensor RTD 200}} \right)$ [14]. Reliability analysis for these variables revealed ICCs ranging from 0.71 to 0.83 and SEM values ranging from 20.95 to 27.78%.

Statistical analyses

Independent samples t tests were used to analyze differences in demographic characteristics, P_{max}, and maximal and rapid H/Q strength ratios between the young and old females. Three separate two-way mixed factorial analyses of variance (ANOVAs) [group (young vs. old) × muscle (leg extensors vs. leg flexors)] were used to analyze the PT and RTD variables. When appropriate, follow-up analyses included independent and dependent samples t tests. In addition, Cohen's d effect sizes were calculated for each between-group comparison in which values of 0.20, 0.50, and 0.80 corresponded to small, medium, and large effect sizes, respectively. Pearson product-moment correlation coefficients (r) and coefficients of determination (r^2) were calculated separately for the young and old females to examine the relationships between P_{max} and the maximal and rapid torque variables and H/Q strength ratios. In addition, multiple regression analysis (stepwise model) of the young and old females was used to determine the best predictors of P_{max} in each group. Statistical analyses were performed using IBM SPSS Statistics v. 22.0 (SPSS Inc., Chicago, IL, USA), and an alpha level of $P \leq 0.050$ was used to determine statistical significance.

Results

There were no differences between the young and old females for body mass ($P = 0.245$), height ($P = 0.171$), BMI ($P = 0.092$), or volume of physical activity ($P = 0.097$). Table 1 shows the means, standard deviations, and Cohen's d effect sizes for PT and the RTD variables for the leg extensors and flexors. For PT and RTD200, there were

Table 1 Means (standard deviations) and Cohen's d effect sizes for peak torque (PT) and rate of torque development (RTD) at time intervals of 0–30 (RTD30) and 0–200 (RTD200) ms

Variable	Leg extensors			Leg flexors		
	Young ($n = 15$)	Old ($n = 15$)	Cohen's d	Young ($n = 15$)	Old ($n = 15$)	Cohen's d
PT (Nm)[a]	131.46 (37.76)	77.12 (31.57)	1.24	69.27 (19.64)	48.47 (7.71)	1.15
RTD30 (Nm s^{-1})[b]	497.62 (281.51)	317.61 (182.09)	0.72	315.57 (197.48)	211.41 (134.85)	0.60
RTD200 (Nm s^{-1})[a]	409.61 (214.37)	175.86 (79.80)	1.18	228.29 (101.45)	135.39 (43.50)	1.03

[a] Indicates significant interactions (group × muscle) such that PT and RTD200 were lower in the old compared to the young females for the leg flexors and extensors and were higher for the leg extensors than for the leg flexors in both the young and old groups

[b] Indicates significant main effects such that RTD30 was lower in the old compared to the young females when collapsed across muscle and was higher for the leg extensors than for the leg flexors when collapsed across group

significant group×muscle interactions ($P=0.006$ and 0.002, respectively); however, these interactions were not evident during the post hoc tests. PT and RTD200 were lower ($P \leq 0.001$–0.004) for the old compared to the young females for the leg extensors and flexors, and they were greater ($P \leq 0.001$–0.022) for the leg extensors than for the leg flexors in both the young and old groups. For RTD30, there was no interaction ($P=0.226$), but there were main effects for group ($P=0.048$) and muscle ($P<0.001$). The marginal mean for RTD30 collapsed across muscle was lower for the old compared to the young females, and collapsed across group was greater for the leg extensors than for the leg flexors. For measures of muscle power and maximal and rapid strength H/Q ratios, the P_{max} values were lower ($P<0.001$) and PT and RTD200 H/Q were higher ($P=0.030$ and 0.008) in the old compared to the young females; however, there was no difference between the young and old females for RTD30 H/Q ($P=0.300$) (Table 2).

Table 3 summarizes the relationships between P_{max} and the maximal and rapid torque variables and H/Q strength ratios. Significant positive relationships were observed in the young and old females between P_{max} and RTD30 ($P=0.020$) and RTD200 ($P=0.049$ and 0.009) for the leg extensors and P_{max} and RTD200 ($P=0.045$ and 0.048) for the leg flexors. Significant negative relationships were also observed between P_{max} and RTD30 and RTD200 H/Q (Fig. 2) ratios in the older females ($P=0.014$ and 0.046) but not in the younger females ($P=0.286$ and 0.698). No relationships were observed in the young and older females between P_{max} and PT for the leg extensors or flexors ($P=0.081$–0.897) or P_{max} and PT H/Q ($P=0.918$ and 0.182; Fig. 2). Regarding the multiple regression analysis, only RTD30 of the leg flexors entered the model for the younger females. For the older females, regression analysis revealed that RTD200 of the leg extensors explained 41.9% of the variance in P_{max}. Additionally, with the inclusion of the RTD30 H/Q ratio, the model explained 62.3% of the

Table 2 Means (standard deviations) and Cohen's d effect sizes for vertical jump peak power output (P_{max}) and hamstrings to quadriceps (H/Q) strength ratios for peak torque (PT H/Q) and rate of torque development (RTD) at RTD30 (RTD30 H/Q) and RTD200 (RTD200 H/Q)

Variable	Young ($n=15$)	Old ($n=15$)	Cohen's d
P_{max} (W)	3131.07 (1426.22)	1075.87 (376.78)[a]	1.40
PT H/Q	0.54 (0.13)	0.71 (0.24)[a]	0.81
RTD30 H/Q	0.65 (0.23)	0.78 (0.43)	0.38
RTD200 H/Q	0.61 (0.22)	0.85 (0.25)[a]	0.92

[a] Significantly lower P_{max} and higher PT and RTD200 H/Q ratios in the old compared to the young females ($P \leq 0.050$)

Table 3 Pearson correlation coefficients (r) and coefficients of determination (r^2) between vertical jump peak power output (P_{max}) and peak torque (PT) and rate of torque development (RTD) of the leg extensors and flexors and hamstrings to quadriceps (H/Q) strength ratios

	Young		Old	
	r	r^2	r	r^2
Leg extensors				
PT	0.439	0.193	0.370	0.137
RTD30	0.593*	0.352	0.592*	0.350
RTD200	0.515*	0.265	0.647*	0.419
Leg flexors				
PT	0.465	0.216	0.037	0.001
RTD30	0.742*	0.551	0.088	0.008
RTD200	0.524*	0.275	0.518*	0.268
H/Q ratios				
PT H/Q	0.029	0.001	−0.364	0.132
RTD30 H/Q	0.295	0.087	−0.616*	0.379
RTD200 H/Q	−0.109	0.012	−0.522*	0.272

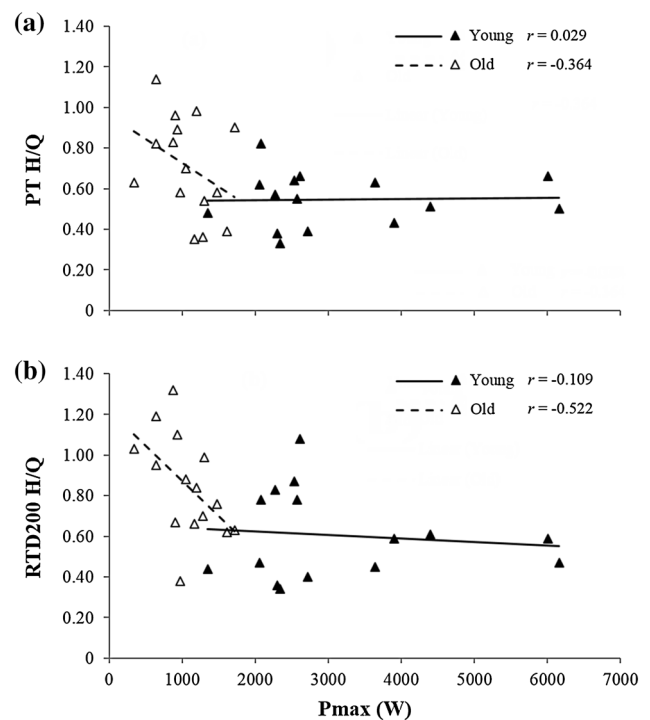*Significant correlation ($P \leq 0.050$)

Fig. 2 Relationships between vertical jump peak power output (P_{max}) and the hamstrings to quadriceps (H/Q) strength ratios for peak torque (PT H/Q) (**a**) and rate of torque development at RTD200 (RTD200 H/Q) (**b**) for the young and old females

Table 4 Stepwise multiple regression analysis for the prediction of vertical jump peak power output (P_{max}) in the older females

	B	SE_B	β
Step 1			
Constant	538.802	191.745	
Leg extension RTD200	3.054	0.999	0.647*
Step 2			
Constant	972.133	233.642	
Leg extension RTD200	2.428	0.872	0.514*
RTD30 H/Q ratio	−414.498	162.289	−0.472*

$R^2 = 0.419$ for Step 1; $R^2 = 0.623$ for Step 2

*$P \leq 0.050$

variance. Table 4 shows the stepwise regression analysis in the older female group.

Discussion

The primary findings of the present study revealed that PT and RTD200 H/Q strength ratios were significantly higher in the old compared to the young females, while no difference was observed for RTD30 H/Q (Table 2). Maximal and rapid torque characteristics (i.e., PT, RTD30, and RTD200) of the leg extensors and flexors were significantly lower in the older females (Table 1); however, greater age-related reductions in PT and RTD200 were observed for the extensors (41 and 57%, respectively) than the flexors (30 and 41%). The old females also exhibited lower P_{max} values than the young females (Table 2). In addition, there were significant positive relationships between P_{max} and RTD30 and RTD200 for the leg extensors and P_{max} and RTD200 for the leg flexors in both the young and old female groups (Table 3). There were also negative relationships between P_{max} and RTD30 and RTD200 H/Q strength ratios in the older females; however, there were no such relationships in the younger females nor were there any relationships between P_{max} and maximal strength nor PT H/Q for either age group (Fig. 2). Multiple regression analysis revealed that leg flexion RTD30 in the young females and leg extension RTD200 and RTD30 H/Q ratio in the old females were the best predictors of P_{max} (Table 4).

Age-related decreases in maximal and rapid torque or force characteristics of the leg extensors and flexors have been well documented in the literature [5–7]. In this study, we also revealed age-related declines in maximal and rapid torque production for these muscle groups, with greater reductions in PT and RTD200 for the leg extensors than the flexors. However, a key finding of the present study was the higher PT and RTD200 H/Q strength ratios in the old compared to the younger females. Because a greater decline

in leg extension strength causes a greater reduction in the magnitude of the H/Q denominator which would increase the H/Q ratio [13], it appears that the higher maximal and rapid strength H/Q ratios observed for the older females resulted from their greater strength deficits in the quadriceps versus hamstrings (i.e., leg extensors versus flexors). These findings are consistent with the reports of Hayes and Falconer [11] who showed that older adults exhibited an elevated maximal strength H/Q ratio, which was attributed to greater deficits in leg extension strength. Alternatively, however, other authors have reported a lack of age-related differences in isometric maximal strength H/Q or Q/H ratios between younger and older adults [15, 16, 32]. The discrepancies between these findings and those reported by the present study may be due to differences in the joint angles of testing, the strength assessment device used, and/ or the ages and physical activity levels of the participants that were tested [12]. The present study evaluated leg extensor and flexor strength and H/Q ratios at 90° of knee flexion using a manual strength assessment device in highly active young and older females (8.7 and 5.0 h/week of physical activity, respectively), whereas the previous authors calculated H/Q or Q/H ratios by determining leg extensor and flexor strength at more extended knee positions (15°–60° of knee flexion) [15, 16] and/or used a computer-controlled isokinetic dynamometer to measure these ratios in less active adults (≤4.8 h/week of physical activity) [32]. Greater age-related deficits in leg extension than leg flexion torque have been reported at flexed compared to extended knee positions [17, 18], and because a greater decrease in leg extension relative to leg flexion would increase the H/Q ratio in the elderly, it is possible that H/Q isometric strength ratios as measured with the knee flexed at a 90° joint angle may be a better measure than more extended-range H/Q ratios at identifying age-related differences in leg flexor–extensor strength balances.

Previous studies investigating age-related effects on H/Q strength performances between young and older adults have exclusively made such comparisons using maximal strength (PT or PF) ratios as the performance measure [11, 15, 16, 32]. A novel aspect of our study was the assessment of the rapid strength H/Q ratios, which to our knowledge is the first to examine the influence of age on these variables. Because leg flexor and extensor RTD assessed at short time periods (i.e., 30–200 ms) reflect the capacity of the hamstrings and quadriceps to generate force rapidly [6], previous authors have suggested that when these values are expressed as a ratio (RTD H/Q), they may be more functionally relevant than maximal strength H/Q ratios for assessing muscle balance and knee joint stabilization during explosive-type activities [13, 14]. In this study, greater age-related declines were observed in quadriceps versus hamstrings rapid strength (i.e., leg extension versus flexion

RTD200), which contributed to the higher RTD200 *H/Q* ratio for the old compared to the younger females. An elevated *H/Q* ratio resulting from large deficits in quadriceps RTD may indicate better muscle strength balance and increased knee joint stabilization [13]. However, because large quadriceps rapid strength deficits have been shown to negatively affect the performances of many locomotor-related tasks (i.e., walking, running, jumping, standing up from a chair) [26, 33–35], we suggest that having a higher RTD *H/Q* ratio may be detrimental to functional performance ability specifically in older populations. As such, lower-extremity muscle strengthening programs with an emphasis on explosive power training (particularly for the quadriceps muscles) may be warranted as a preventative measure for older adults who are at an increased risk for abrupt functional decline. Future research is needed to explore the efficacy of training programs targeted at decreasing the RTD *H/Q* ratio (by attenuating quadriceps strength declines) to a more optimal value (i.e., ~0.40–0.80) similar to that of younger adults, for the maintenance and/or restoration of locomotor function and independence in the elderly.

The reason for the increase in *H/Q* strength ratios with age is currently unknown, but could be due to a number of different factors including changes in muscle involvement during physical activity [36], fiber-type composition [12], and coactivation of antagonist muscles [22]. Another possible factor could be age-related changes in muscle size. Although age-related declines in muscle size have been reported for both the anterior and posterior thigh muscles, recent authors have revealed greater losses in the quadriceps than the hamstrings [10, 37]. Given the relationships reported by previous studies between muscle mass, strength, and RTD [38, 39], it is possible that these greater age-related declines in quadriceps muscle size may have played a role in the disproportionately lower leg extension torque and higher PT and RTD200 *H/Q* strength ratios observed for the older females in the present study. It should be noted, however, that the present findings revealed no difference in RTD30 *H/Q* between age groups. The smaller age-related difference in RTD30 compared to RTD200 *H/Q* may be due to discrepancies in the relationships between maximal strength and muscle mass and early versus later rapid torque characteristics. It has been suggested that early RTD values (<100 ms), which are primarily influenced by neural factors (motor unit firing rates, doublet counts, etc.) [29], have a smaller relationship with maximal strength and muscle mass than later RTD values (≥200 ms) [30, 40]. Thus, given the aforementioned greater declines in quadriceps versus hamstrings muscle size in older adults, it is possible that leg flexion and extension RTD30 values,

due to their smaller relationship with muscle mass, may be less affected by these age-related muscle size changes, resulting in smaller *H/Q* differences than those observed at later time points. Although future research involving more invasive measures (i.e., ultrasound imaging) is needed to test these hypotheses, our findings of higher PT and RTD200 *H/Q* strength ratios in older adults suggest that maximal and later rapid torque differences between the hamstrings and quadriceps may become smaller with aging.

Vertical jump P_{max} values for the older females in this study were significantly lower than those for the younger females. Given the significant positive relationships ($r = 0.515$–0.742) observed in the young and older females between P_{max} and RTD30 and RTD200 (Table 3), it is possible that these findings may have been the result of the older females' lower rapid strength characteristics of the leg flexors and extensors. However, in light of the older females' higher PT and RTD200 *H/Q* strength ratios, it is possible that the reduced vertical jump power was also influenced by the balance between leg flexion and extension maximal and rapid strength in the old compared to the younger groups. Previous authors have suggested that greater hamstrings strength relative to the quadriceps muscles may be a limiting factor in the performances of functional-related activities [11, 12] and that higher *H/Q* strength ratios in older adults may lead to a decreased ability to generate muscle power [21]. Our findings would support these hypotheses given the significant negative relationships ($r = -0.616$ and -0.522) observed between RTD30 and RTD200 *H/Q* and P_{max} in the older females; however, it should be noted that we observed no such relationships in the younger females ($r = 0.295$ and -0.109). In addition, multiple regression analysis revealed that a large portion of the variance in P_{max} for the older group ($R^2 = 62.3\%$) could be explained by leg extension RTD200 and RTD30 *H/Q*. Thus, taken together, these findings provide support that leg extension rapid strength and RTD *H/Q* ratio may play an important role in jumping-related performances, especially in older populations. It is also noteworthy that the present findings did not support the relationships between P_{max} and maximal strength nor PT *H/Q* in this active older female group. Although the reason for this is uncertain, the lack of such relationships may be a function of the aforementioned limited functional relevance of these characteristics as they pertain to quick and forceful movement tasks, such as vertical jumping. Finally, we acknowledge that the generalizability of these findings is limited to a population of healthy, active females. Thus, future research is warranted to extend these research objectives to other populations, including males and diseased patients.

Conclusions

A key finding of this investigation was the higher PT and RTD200 *H/Q* strength ratios for the old compared to the younger females. These findings provide support that maximal and rapid strength differences between the leg flexors and extensors may become smaller with age. We also observed significant age-related declines in vertical jump muscle power. Given the negative relationships between vertical jump power and rapid strength *H/Q* ratios in the older females and the lack of such relationships in the younger females, the present findings suggest that these age-related increases in *H/Q* explosive strength may be an important characteristic relevant to vertical jump performances, especially in older populations. With respect to these findings, future researchers and practitioners may consider performing leg extension and flexion muscle strength assessments in older adults, with the intention of measuring rapid strength *H/Q* ratios to identify individuals with lower muscle power and possibly overall functional decline. Because the higher RTD200 *H/Q* ratio for the older females in this study resulted from greater age-related decreases in quadriceps rapid strength, our findings also highlight the need to implement training programs in the elderly which have a substantial focus on the leg extensor musculature.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Human and animal rights All procedures performed in this study were in accordance with the ethical standards of the university's institutional review board for human subject's research.

Informed Consent Each participant gave informed consent prior to the study.

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