ORIGINAL ARTICLE

Effect of acceleration on the rate of power development and neural activity of the leg extensors across the adult life span

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Abstract

Purpose The rate of power development (RPD) represents the capacity to rapidly generate power during a dynamic muscle contraction. As RPD is highly susceptible to aging, its decline can have important functional consequences. However, the effect of age on RPD in response to rapid changes in movement velocity (cfr. fall incidence) is not yet clear. Therefore, the present study aimed to examine the effect of age on RPD and neural drive in response to different accelerations.

Methods Three maximal isokinetic leg extensor tests at 540°/s with different initial acceleration phases at 3200, 5700 and 7200°/s^2 were performed. RPD, which is the slope of the power-time curve during the acceleration phase, was calculated for 83 subjects aged between 20 and 69 years. Mean electromyography signal amplitude was determined for rectus femoris (RF), vastus lateralis (VL) and biceps femoris muscles.

Results The average annual age-related decline rate of RPD at highest acceleration was −2.93% and was −1.52% and −1.82% higher compared to lower acceleration rates ($p < 0.001$). This deficit can probably be explained by an age-related impairment in neural drive during the first 75 ms of the acceleration phase, as evidenced by a reduced RF and VL neuromuscular activity of −0.30% and −0.36% at highest versus lowest acceleration ($p < 0.05$).

Conclusion These findings highlight the inability of aged individuals to quickly respond to abrupt changes in movement velocity, which requires more focus in training and prevention programs.

Keywords Sarcopenia · Aging · Fall prevention · Explosive power

Abbreviations

BF	Biceps femoris
EMG	Electromyography
mA	Mean EMG amplitude
RF	Rectus femoris
RPD	Rate of power development
VL	Vastus lateralis

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Introduction

Aging is associated with a decrease in functional capacity leading to a reduced quality of life (Rolland et al. 2008). More specifically, an important consequence of the aging process is the higher risk of falls. About 24–40% of community-dwelling people aged 65 or older fall at least once a year and frequency of falls increases with age (Milat et al. 2011). Balance recovery after abrupt perturbations requires explosive muscle actions that correspond to short response times (< 200 ms) (Maffiuletti et al. 2016). A better understanding of age-related changes in neuromuscular function in response to abrupt perturbations could give valuable insights with regard to fall prevention in the aged.

The majority of research investigating age-related changes in dynamic neuromuscular function have been focused on changes in maximal muscle power (Lanza et al. 2003; Skelton et al. 1994). However, maximal power measures are limited to represent daily life functional capacity, because they do not take into account the time needed to reach peak power. Recently, we have shown that

the age-related decline in the rate of power development (RPD) exceeds the decline in peak power because of the additional decline in the time needed to reach peak power (Van Driessche et al. 2018a; Van Roie et al. 2018). This age-related decline is even more pronounced in multi-joint actions, as shown by our previous work (Van Driessche et al. 2018b). The latter reports indicate that aging has a detrimental effect on the initial acceleration phase of a contraction.

Many daily life activities such as fast walking, stair climbing, chair rising and balance recovery after tripping involve fast dynamic actions. These actions include a velocity component that is characterized by an acceleration phase, which requires a fast response of muscle action. Next to fiber type content, neural activity has been shown to have a predominant influence on neuromuscular function during fast actions (Folland et al. 2014; Maffiuletti et al. 2016). In addition, a fast concentric muscle action is shown to induce higher forces than fast isometric contractions, which has been attributed to higher neural activity (Tillin et al. 2012). Moreover, fast development of force is influenced by contractile acceleration in a way that fast concentric contractions elicit higher force development through higher neural activation than slower contractions in young adults (Hahn et al. 2017; Tillin et al. 2013b). However, it has been shown that aging has a detrimental effect on neural activation of skeletal muscles in terms of electromyographic (EMG) activity and motor unit firing rates (Clark et al. 2010; Klass et al. 2008) due to changes in the nervous system (Manini et al. 2013). Elevated levels of antagonist coactivation have been observed in older adults (Izquierdo et al. 1999a; Macaluso et al. 2002), whereas the neural drive to agonist muscles is shown to be reduced (Harridge et al. 1999; Stevens et al. 2003). In this regard, age-related impairment in neural activation may induce larger declines in RPD at fast accelerative actions. Although a link between the age-related decline in neuromuscular function and neural activity in fast actions has been suggested in the literature, the effect of age on neural activity and neuromuscular function in response to different accelerations remains unclear.

Therefore, this cross-sectional study investigated the effect of different preprogrammed accelerations on power production and neural drive in multi-joint leg extensor tests across the adult life span. We hypothesized that age-related declines in RPD are greater at higher accelerations compared to lower accelerations, which corresponds to an age by acceleration interaction effect. In addition, we hypothesized that this age-related change in neuromuscular function can be attributed to declines in neural activity as evidenced by Pearson's correlation coefficients and average annual age-related declines.

Methods

Subjects

Ninety-six healthy subjects (♂ 49, ♀ 47) aged between 20 and 69 years volunteered after recruitment ($n = 8$–10 ♂ and 8–10 ♀ per decade) through advertisements and oral communications. Subjects completed a short medical history and physical activity questionnaire and were excluded in case of a cardiovascular disease or acute thrombosis, recent surgery, neuromuscular disease, infection or fever, diabetes or pregnancy and systematic participation in strength or endurance training (i.e., progressive increases in volume and/or intensity) in the prior 6 months. Occasional engagement in physical activity, such as cycling, walking and running was allowed. After thorough examination of all EMG signals and exclusion of incomplete test samples because of measurement failure of 1 or more tests, complete data of 83 healthy subjects (♂ 43, ♀ 40) were used for further analyses. All subjects provided written informed consent. The study was approved by the University's Human Ethics Committee in accordance with the declaration of Helsinki.

Power measurements

Power measurements and signal analysis procedures have been previously described (Van Driessche et al. 2018b). Briefly, a multi-joint isokinetic machine was developed to measure multi-joint neuromuscular function of the leg extensors at a sampling frequency of 1000 Hz. The seat and lever arm were adjustable to allow for standard range of motion (i.e., knee joint angle of 90° to 160° and hip joint angle of 70° to 115°) (Fig. 1).

Measurements were performed unilaterally on the right side. The right foot was fully supported and fixed to the foot plate using a solid strap with the lateral malleolus aligned with the point of force application, provoking a heel thrust to minimize the influence of lower leg muscles and ankle movement. Movement of the lever arm was initiated by surpassing a cut-off torque of 20% of maximal isometric single-joint strength inducing a low-level of pretension (i.e., 20–70 N m) as previously recommended (Tillin et al. 2013a).

Subjects performed two test sessions separated by a rest day to avoid fatigue. In the first session, familiarization with the protocol was performed as well as isometric and isokinetic knee-extension tests (data not included). The second session was performed at the same time of day as session one and led by the same investigator. Participants started with a warming-up on a bike ergometer

Fig. 1 Start and end position of the multi-joint leg-press movement

at a self-determined submaximal resistance for 10 min. For the leg extensor tests, lever arm angular acceleration was preprogrammed using a real-time control program (Simulink, The Mathworks Inc., Natick, United States) at 5700°/s^2 (medium), 3200°/s^2 (low) and 7200°/s^2 (high acceleration) respectively until a fixed isokinetic velocity of 540°/s was reached. The terms medium, low and high acceleration are chosen for readability, although it should be noted that all accelerations used in the present study are high to extremely high. These lever arm angular accelerations correspond to knee angular accelerations of ~ 3627°/s^2, 2036°/s^2 and 4582°/s^2 respectively (calculated based on the knee joint's range of motion and the time of the particular tests). Each condition was performed three times with 30-s rest periods in between. During each test, the subjects were clearly instructed by the test leader to push as fast and as hard as possible.

Electromyography measurements

The EMG activity of rectus femoris (RF), vastus lateralis (VL) and biceps femoris (BF) were collected during the multi-joint leg extensor tests. Surface electrodes were positioned following the European Recommendations for Surface Electromyography (SENIAM) after careful preparation of the skin (i.e., shaving and cleaning with alcohol) to keep skin impedance low. EMG signals were recorded using wireless EMG electrodes (KINE®, KINE Ltd., Hafnarfjördur, Iceland) with an input impedance of 10 GΩ, a common mode rejection ratio of 110 dB, a signal-to-noise ratio of 60 dB, a differential detection mode and a built in A/D converter of 10 bit with a range of 4 mV, resulting in a sensitivity of 4 μV (Martens et al. 2015). EMG signals were sampled at 1600 Hz. An extra electrode unit was used to catch a trigger pulse from the real-time control program at the start of each leg extensor test to enable synchronization of the EMG signals and the power output.

Signal processing

All signals were processed off-line using a commercial software package (Matlab R2016b, The MathWorks Inc., Natick, United States). Torque signals were filtered using a fourth-order low-pass Butterworth filter with a 20 Hz cut-off frequency. Instantaneous power (watt) was calculated as the product of torque (N m) and velocity (rad/s). As acceleration is defined as a change in velocity over time, we examined the ability to produce power in the acceleration phase of our three test conditions in two different manners: either at a fixed time interval (i.e., 75 ms) till different velocities between the three tests, or till a fixed velocity (i.e., 540°/s) at different time intervals. This approach allows us to examine the impact of both time and velocity in the effect of acceleration on power production during aging. In this way, the rate of power development (RPD, W/s) was calculated as the linear slope of the power-time curve from the start of the movement till 75 ms (RPD$_{0–75 ms}$) and till isokinetic speed (RPD$_{0–540°/s}$) was reached. The start of the movement was determined as the point where the cut-off torque was reached.

Raw EMG signals were band-pass filtered (20–500 Hz), full-wave rectified and smoothed using a second order low-pass Butterworth filter with a cut-off frequency of 6 Hz. Mean EMG amplitude was determined from the onset of activation (i.e., > 3 SD of baseline signal) till the start of the movement (electromechanical delay + pretension), till 75 ms and till the end of the acceleration phase (Fig. 2). EMG signals were normalized to the test at lowest acceleration to
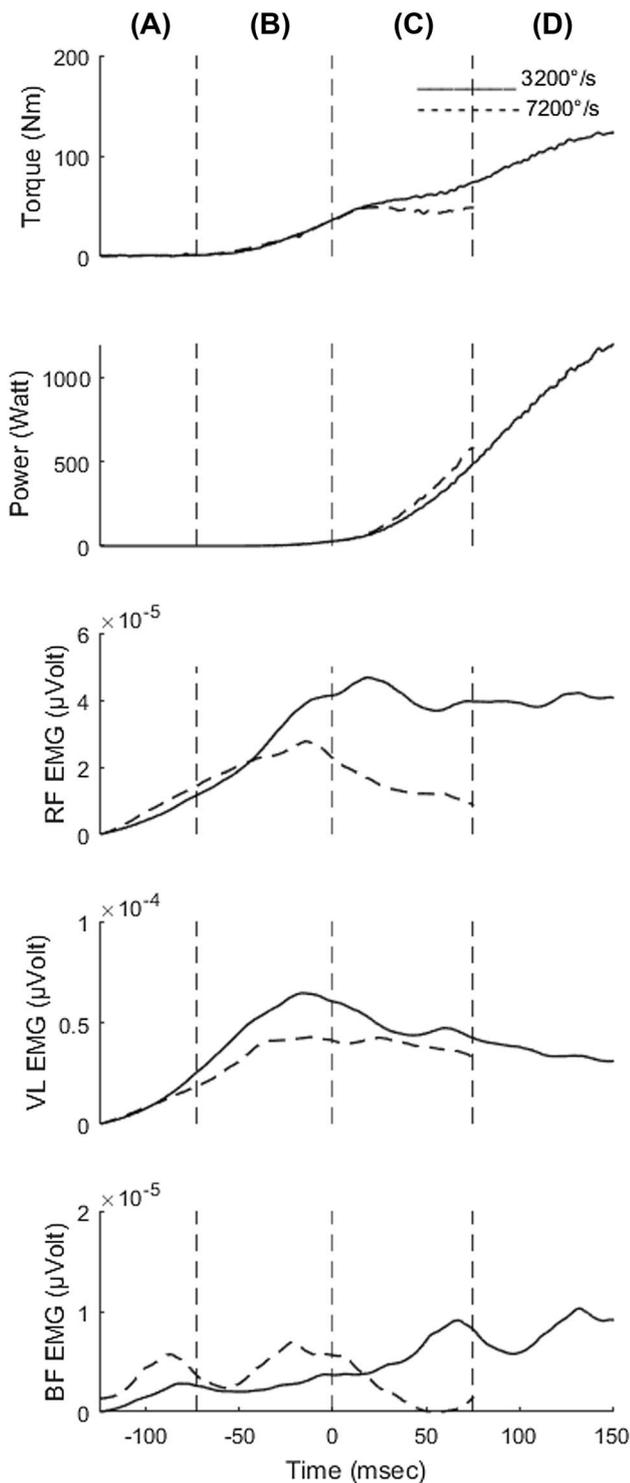
Fig. 2 Representation of torque, power and muscle activity signals at lower ($3200°/s^2$, solid line) and higher ($7200°/s^2$, dashed line) acceleration rate of a young male subject. Tests can be divided in three phases: **a** a phase of electromechanical delay, **b** a phase of pretension till 20% of maximal isometric knee-extension strength is reached and **c** the acceleration phase which can be calculated over a fixed time period (75 ms) or **d** until a fixed velocity (540°/s)

enable comparison of age-related changes between acceleration rates.

For both RPD and EMG, the mean of the three trials was used for further analyses. Reliability of the multi-joint RPD measurements was assessed in 16 older adults, who returned for a third session to repeat the multi-joint tests [ICC 0.95–0.98; SEM (%) 7.3–24.5].

Statistical analyses

All statistical analyses were performed using R software, version 1.0.153 (R Core Team 2017). To study the effect of acceleration on RPD and muscle activation across the adult life span, we built linear mixed models for RPD and parameters of muscle activation using the function lmer provided by the R-package lme4 (Bates et al. 2015). The response variables were log-transformed to make relative comparison of the age-related declines between accelerations possible in all models (Törnqvist et al. 1985). Age, acceleration, sex and body mass were entered as fixed effects into the model. The variable age was used as continuous variable. In addition to the fixed-effects terms, the models included subject as a random effect to correct for the repeated measures design. An iterative model fitting procedure was conducted to analyze the effects of all factors (Van Driessche et al. 2018b). p values were obtained using the R-package lmertest (Kuznetsova et al. 2016). The R-function 'relevel' was used for comparison between acceleration phases. Statistical significance was set at $p < 0.05$ for all analyses.

Pearson's correlation coefficients were calculated to examine the association between muscle activity and the age-related decline in power output at high versus low acceleration rate, for which power data were also set relative to the test at lowest acceleration.

Results

RPD

All participants succeeded in performing the high accelerative knee extensor tests. Across participants, absolute mean ($\pm$ SD) RPD scores were as follows: low till 75 ms—3069 (1450) N m/s^2; low till 540°/s—4253 (1617) N m/s^2; medium till 75 ms—3375 (1819) N m/s^2; medium till 540°/s—4204 (1919) N m/s^2; high—3071 (2121) N m/s^2. The mixed effects model for RPD demonstrated a main age effect and an age × acceleration interaction effect. The average annual decline rate of $RPD_{0-540°/s}$ across the study sample was − 1.11% at low, − 1.43% at medium and − 2.93% at high acceleration with the decline rate at high acceleration significantly steeper than at low and medium acceleration ($p < 0.01$) (Fig. 3). Similar results
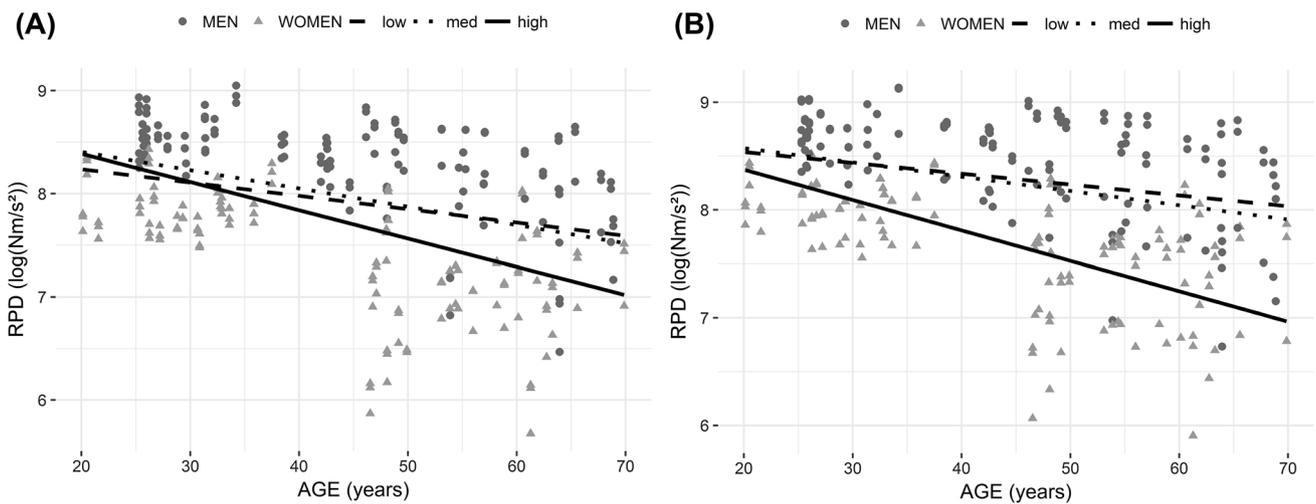
Fig. 3 Age-related decline of leg extensor rate of power development (RPD) across 83 subjects (♂ 43, ♀ 40, aged 20–69 years) at low (3200°/s², dashed line), medium (5700°/s², dotted line) and high (7200°/s², solid line) acceleration till fixed time point of 75 ms (**a**) and till fixed velocity of 540°/s (**b**)

were found for RPD$_{0-75\,\text{ms}}$ with -1.37% at low, -1.85% at medium and -2.85% at high acceleration. No age × sex or age × body mass interaction effect was found. Therefore, these factors were excluded from the model.

To visualize the impact of both time and velocity on the age-related decline in RPD, we interpolated the results of the age-related decline rates of RPD at every time point

across the three acceleration tests and plotted them against both time and velocity (Fig. 4).

EMG

All EMG parameters from the onset of muscle activation till the start of the movement (i.e., electromechanical delay and small pretension phase) were the same across acceleration
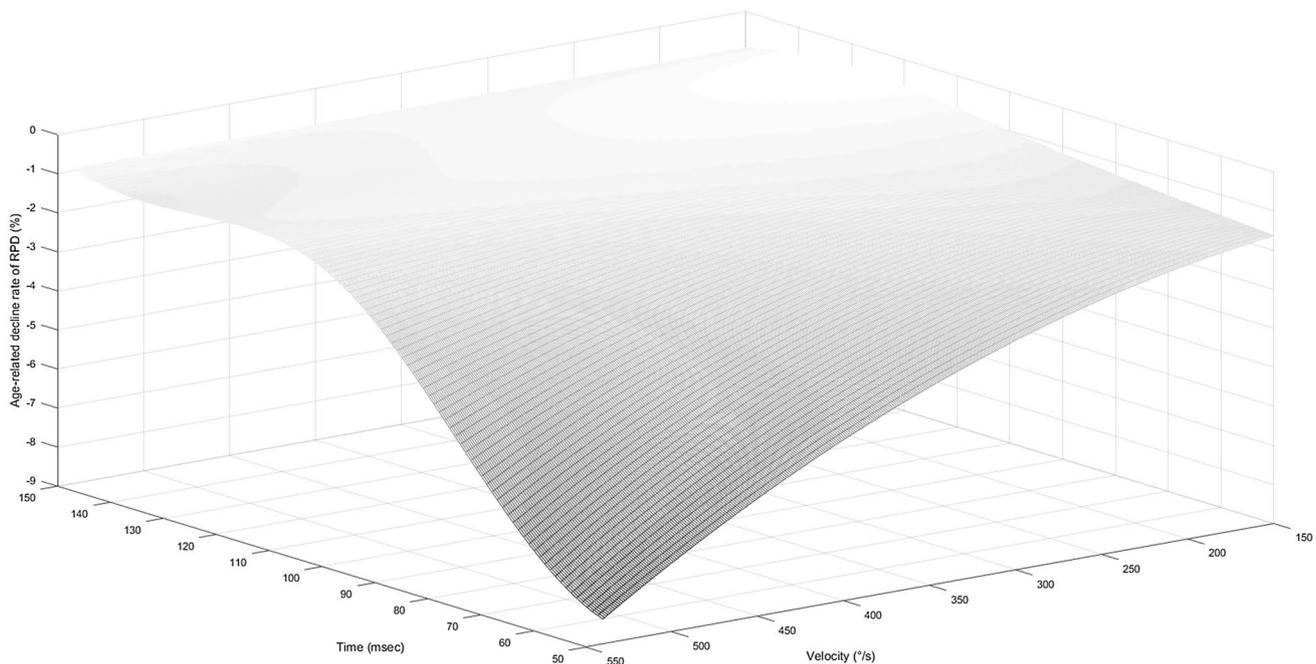

Fig. 4 Age-related decline of leg extensor rate of power development (RPD). Data across 83 subjects (♂ 43, ♀ 40, aged 20 to 69 years) at low (3200°/s²), medium (5700°/s²) and high (7200°/s²) acceleration were interpolated and visualized in terms of time and velocity

rates. Therefore, potential differences between the tests can only be attributed to differences in the acceleration phase and EMG parameters further on in the manuscript will represent neuromuscular activation from the onset of muscle activation till the end of the acceleration phase.

In line with the results of $RBD_{0-540°/s}$, neuromuscular activation of RF and VL declined more at high compared to low acceleration with advancing age (Table 1; Fig. 5). No interaction effect with age was found for BF neuromuscular activation.

Correlation

For high acceleration relative to low acceleration, the age-related changes in RF and VL activation were associated with the age-related decline in RPD across the sample, except for the association between $RPD_{0-75 ms}$ and RF

activation. A non-significant and very weak association ($r < -0.08$) was found between BF neuromuscular activation and age-related changes in RPD.

Discussion

This study demonstrates that the rate of power development is significantly more affected by aging at high compared to lower acceleration rate and that this phenomenon is significantly associated with impaired quadriceps neuromuscular activation. These results indicate that reduced neural activity during healthy aging likely limits the capacity to rapidly develop power in very fast dynamic actions.

The primary finding of the current study is the highly impaired leg extensor RPD (-2.93%/year) at advancing age in response to a high acceleration rate. This average annual

Table 1 Relative decline rates and associations with RPD

Test target	Parameter	Decline rate medium versus low (%)	Decline rate high versus medium (%)	Decline rate high versus low (%)	Association with RPD high relative to low (r value)
540°/s	RPD	− 0.32	− 1.52***	− 1.82***	1
	RF mA	− 0.17	− 0.12	− 0.30*	0.26*
	VL mA	− 0.15	− 0.22	− 0.36**	0.30**
75 ms	RPD	− 0.48	− 1.01**	− 1.49***	1
	RF mA	− 0.08	− 0.10	− 0.19	0.19
	VL mA	0.01	− 0.21	− 0.20	0.24*

Data represent differences in age-related decline rates and associations of the rate of power development (RPD), rectus femoris (RF) and vastus lateralis (VL) mean EMG amplitude (mA) between low (i.e., 3200°/s^2), medium (i.e., 5700°/s^2) and high (i.e., 7200°/s^2) acceleration ($n=83$).
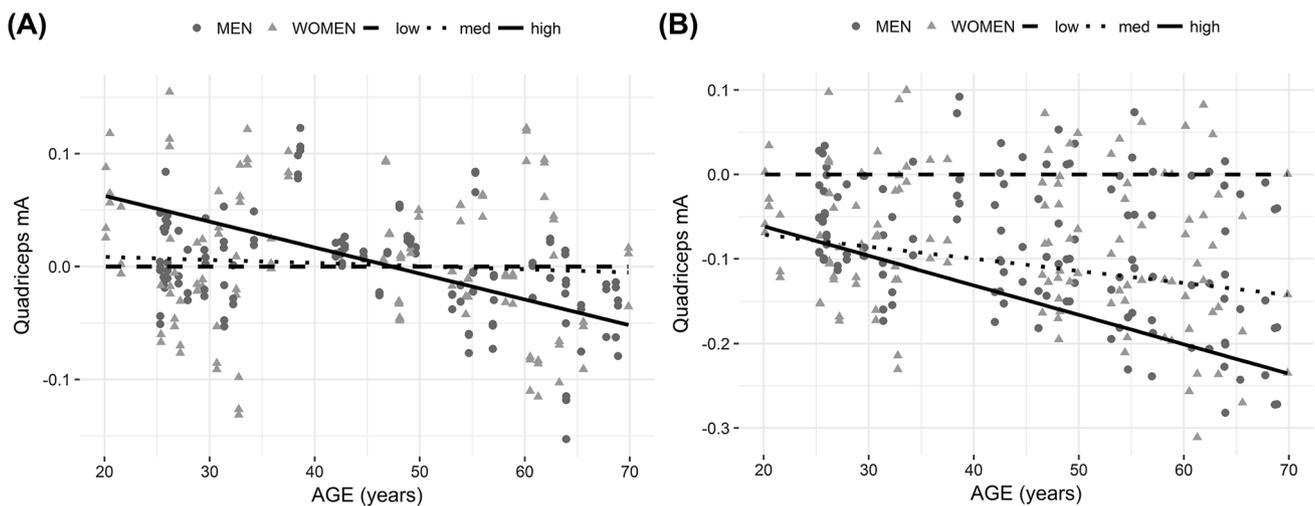
*$p<0.05$, **$p<0.01$, ***$p<0.001$

Fig. 5 Age-related decline of quadriceps muscle activity across 83 subjects (♂ 43, ♀ 40, aged 20–69 years) during leg extensor tests at low (3200°/s^2, dashed line), medium (5700°/s^2, dotted line) and high (7200°/s^2, solid line) acceleration till fixed time point of 75 ms (**a**) and till fixed velocity of 540°/s (**b**). Quadriceps mean EMG amplitude (mA) was calculated as the sum of rectus femoris (RF) and vastus lateralis (VL) mA for visualization

decline rate is much higher than the decline rates of -0.6 to -1.9%, reported for peak power and RPD in isokinetic and isotonic single- and multi-joint leg extension tests (Allison et al. 2013; Edwen et al. 2014; Kostka 2005; Macaluso and De Vito 2003; Van Driessche et al. 2018a, b; Yamauchi et al. 2009) and reported in the current study for low and medium acceleration. To note, comparison between the previous studies is difficult because of differences in distinct age-groups and statistical analyses, yet the large age-related decline of RPD at high acceleration presented in this study is remarkable. Although this age-related decline was significantly greater at high compared to low and medium acceleration, we found no difference between low and medium acceleration. This finding suggests that rapid power production becomes increasingly difficult at advancing age at acceleration rates of more than $5700°/s^2$ lever arm displacement, which corresponds to knee angular accelerations of about $3627°/s^2$.

It should be noted that the combination of little time and high velocity, together expressed as high acceleration, leads to the largest age-related declines. To visualize this phenomenon, we interpolated the results of the age-related decline rates of RPD at every time point across the three acceleration tests and plotted them against both time and velocity (Fig. 4). On one hand, this figure shows that a test at for example high velocity ($>450°/s$ lever arm angular velocity) reached within longer time periods (>150 ms) or a test at low velocity ($<150°/s$ lever arm angular velocity) reached within short time periods (<75 ms) both result in age-related decline rates of RPD that are similar to previous reports (i.e., -0.9 to -1.1%). On the other hand, short time periods and high velocities, together expressed as high acceleration, seem to result in large decline rates of RPD. According to Thompson et al. (2014a), these findings suggest that not high velocity as such, but acceleration might be highly susceptible to aging, taking into account the time needed to reach those velocities.

The present results indicate that muscle action in response to extremely high accelerations (e.g., abrupt perturbations) is extremely vulnerable to the effect of aging. This may explain the lower probability to recover successfully after a trip at advancing age (Pijnappels et al. 2008). Although, the direct link with falling could not be made, the present findings are in accordance with previous reports about rapid torque development that has been shown to be more relevant for the performance in fast actions, like to prevent for a fall after stumbling (Maffiuletti et al. 2016; Pijnappels et al. 2005). Although the age-related decline in RPD was the largest for the highest acceleration, it should be noted that the low, medium and high accelerations used in this study were all high and that all participants succeeded to perform the tests and to produce additional torque. This suggests that muscular action in response to high accelerations could be trained

in the way we tested it. Although, it should be further investigated whether training can improve RPD at high acceleration rates and whether this could lead to a reduced risk of falling.

Interpretation of absolute age-related declines of surface EMG activity across the adult life span may be misleading because of differences in subcutaneous tissue thickness and in distribution and characteristics of motor units between young and older adults (Masakado et al. 1994). Therefore, surface EMG signals were normalized to the test at lowest acceleration. In line with our hypotheses, the higher age-related decline in mean EMG amplitude of RF and VL at high versus low acceleration demonstrates the inability of older adults to increase neuromuscular activation in response to high accelerations. This decline in neuromuscular activation at high versus low acceleration was weak but significantly associated with the age-related decline in RPD. Remarkably, Fig. 5 demonstrates that younger adults activated their quadriceps muscles more at high compared to low acceleration within the first 75 ms, whereas the older adults' quadriceps activation was less at high compared to low acceleration. The latter indicates that within the first 75 ms, higher movement velocity requires higher neural activation, in which the older adults fail. Although the age-related declines in neural activation between accelerations till 75 ms were not significantly different, these trends and the significantly higher age-related declines in neural activity at high acceleration (i.e., till $540°/s$ in 75 ms) compared to low acceleration (i.e., till $540°/s$ in 169 ms) suggest that older adults particularly have difficulties in fast activation of muscles in short time periods (≤ 75 ms), whereas longer time periods (i.e., >75 ms) may allow to compensate for the early phase deficits in neural activation. This is in line with previous reports, which suggested that neural input predetermines the first 75 ms (Folland et al. 2014; Maffiuletti et al. 2016). In addition, it has been shown via intramuscular EMG that the age-related decline in rapid torque development is predominantly influenced by neural characteristics, next to type II myofibre content (Klass et al. 2008). However, previous studies that investigated rapid muscle activation in fast single-joint isometric tests using surface EMG in healthy well-functioning adults failed to find any age-related decline in neural activation (Clark et al. 2010, 2011; Thompson et al. 2014b). Next to differences in test procedures, the tests in the latter studies might not have been challenging enough to reveal age-related changes in neural activation compared to the challenging high acceleration test used in the current study. Moreover, a significant decline in neural activity and a high association ($r = 0.73$) between power output and neural activity were previously reported when subjects with mobility limitations were included, for which the tests are expected to be even more challenging compared to for healthy and well-functioning subjects (Clark et al. 2011).

The results of the current study suggest that impairments in neuromuscular activation during aging may be a major physiologic mechanism contributing to the age-related deficit in rapid power development, especially within the first 75 ms of a fast movement. However, the significant, but relatively weak associations found between reduced neuromuscular activity and RPD at high versus low acceleration suggest that the increased age-related decline rate of RPD can only be partly explained by impaired quadriceps neuromuscular activation. These findings suggest that other factors may have an influence on the age-related impairment of RPD at high accelerations. Although no age-related differences were found between acceleration rates in biceps femoris neuromuscular activity in the present study, the coordination and activation of other synergist and antagonist muscles could have influenced neuromuscular function as it has been shown that the level of coactivation is increased with aging (Izquierdo et al. 1999b; Macaluso et al. 2002). However, in line with the current findings, it has been shown for the ankle dorsiflexors that age-related changes in coactivation were absent during fast contractions (Klass et al. 2008). In addition, other potential mechanisms like shortening velocity of the fascicles, musculotendinous stiffness and fibre type composition may have an influence on neuromuscular function during fast contractions (Maffiuletti et al. 2016).

Some limitations have to be considered. Surface EMG was only recorded in RF, VL and BF, whereas other muscles contribute to a leg extensor movement. Next, this study was limited to a cross-sectional design which does not allow for longitudinal interpretations of aging effects. Furthermore, only healthy well-functioning participants were measured in this study, making it difficult to find an association with mobility limitations or fall risk. However, excluding the latter allows us to refer the current findings predominantly to the effect of aging as such. The challenging test conditions of the present study revealed significant age-related declines in neuromuscular function that are relevant to a healthy and well-functioning population between 20 and 70 years of age. Yet, this may emphasize the problem for older and mobility limited people that are highly susceptible to falling. Moreover, the present findings underscore the importance of early detection of the age-related deterioration of neuromuscular function for prevention purposes.

To conclude, this study emphasizes the magnitude of the age-related decline in rapid leg extensor power development in response to abrupt changes in movement velocity across the adult life span and demonstrates that impairment in neuromuscular activity is associated with this age-related deficit. Future research should examine how these findings relate to fall risk at old age. As the power to accelerate strongly deteriorates with advancing age, practitioners should pay attention to improve rapid power development via training programs. Training intervention studies in older adults should examine the trainability to accelerate the lower limb in short time periods.

Compliance with ethical standards

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