

Effects of age on human muscle torque, velocity, and power in two muscle groups

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Lanza, I. R., T. F. Towse, G. E. Caldwell, D. M. Wigmore, and J. A. Kent-Braun. Effects of age on human muscle torque, velocity, and power in two muscle groups. *J Appl Physiol* 95: 2361–2369, 2003. First published August 15, 2003; 10.1152/jappphysiol.00724.2002.—The purpose of this study was to test the hypotheses that, under isovelocity conditions, older compared with young humans would 1) be slower to reach target velocity and 2) exhibit a downward shift in the torque-velocity and power-velocity relationships in the ankle dorsiflexor and knee extensor muscles. We studied 12 young (26 ± 5 yr, 6 men/6 women) and 12 older (72 ± 6 yr, 6 men/6 women) healthy adults during maximal voluntary concentric contractions at preset target velocities (dorsiflexion: 0–240°/s; knee extension: 0–400°/s) using an isokinetic dynamometer. The time to target velocity was longer in older subjects in the dorsiflexors and knee extensors (both $P \leq 0.02$). Averaged across all velocities, older subjects produced ~26% less concentric torque and power in the dorsiflexors ($P < 0.01$) and ~32% less in the knee extensors ($P < 0.01$). The downward shift in the torque-velocity relationship persisted even when torque was expressed relative to each subject's maximum. In the knee extensors only, the age-related decrement in power increased with increasing velocities, suggesting that this muscle group may be more susceptible to age-related losses of function than the dorsiflexor muscles are. In support of our hypotheses, these results demonstrate an age-related impairment in the dynamic performance of two functionally distinct muscle groups in healthy older adults. With age, the impairment of dynamic performance appears to exceed the loss of isometric performance, particularly in the knee extensor muscles.

ankle dorsiflexors; knee extensors; sarcopenia; dynamic; isometric

IN HUMANS, MUSCLE MASS AND thus force-generating capacity typically decline with age (7, 22). This process, known as sarcopenia, results in a cascade of events: the reduction in muscle strength impairs physical function in older adults and increases their susceptibility to falls, which can result in injury and loss of independence (37). In addition to the decline of muscle mass and strength with age, the speed of contraction slows (26, 28), likely due to selective atrophy of type II fibers (3, 21). During dynamic contractions in older adults, loss of functional capacity resulting from decreased muscular strength may be compounded by this contractile slowing. For example, rapid torque production

is required to maintain balance after a postural disturbance (32).

The relationship between joint torque and angular velocity is often used to quantify dynamic strength, similar to the force-velocity relationship in isolated muscle (10, 36). The ability to perform a dynamic task often depends on both torque production and the speed of contraction, the product of which is power. Therefore, performance during dynamic muscle contractions can be examined by measuring torque and power production across a range of velocities.

It has been suggested that not all muscle groups are affected in the same way by the aging process (6). Indeed, the effect of age on the torque-angular velocity and torque-power relationships may depend on the muscle group studied. The human ankle dorsiflexors (DF) and knee extensors (KE) provide an interesting opportunity to investigate this phenomenon. The larger KE muscles are of mixed fiber-type composition [40% type I in young adults, 55% type I in older adults (21)] and are used in power activities that ordinarily may not be sustained across the lifespan. Age-related declines in KE muscle mass of ~21–25% have been reported (14, 27). In contrast, the DF are small, contain a high proportion of type I fibers [76% in young, 84% in older (13)], and are used mainly for locomotion, regardless of age. DF contractile mass declines ~16% in healthy older men and women (19). Based on the different types of movements frequently performed by old and young individuals and the possibility that muscle mass and function may change differently across muscle groups, it seems likely that the KE muscles of older adults may show a greater age-related functional decline compared with the ankle DF.

The purpose of this study was to test the hypotheses that, during constant-velocity contractions, older compared with young subjects would 1) require more time to reach a preset target velocity and 2) exhibit a downward shift in the torque-velocity and power-velocity relationships that would be more pronounced as the velocity of the contraction increased. Based on the shift in fiber types toward a slower muscle composition (20) and the reduction in maximal discharge rates that have been shown with aging (15), we expected that a reduction in power would be evident due to both the

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loss of muscle mass (resulting in decreased isometric torque) and slower muscle characteristics. To compare these relationships in functionally distinct muscle groups, the ankle DF and KE were studied in the same subjects. To minimize the effects of health and physical activity levels on our measures, we recruited healthy, minimally active adults.

METHODS

Subjects

Twenty-four subjects, aged 20–35 yr (6 men and 6 women) and 65–85 yr (6 men and 6 women), were recruited from the University community and area Councils on Aging. All subjects gave informed consent according to the procedures approved by the University of Massachusetts Human Subject Review Board. Before enrollment in the study, each subject completed a screening questionnaire, which inquired about health status, medications, past medical history, and habitual physical activity level. All subjects were healthy and ranged from sedentary to recreationally active. Subjects with any history of coronary artery disease, hypertension, or peripheral vascular disease were excluded. In addition, subjects were excluded if they had an ankle/brachial pulse pressure of <1.0, which would indicate the possibility of latent peripheral vascular disease (24). All subjects underwent static and dynamic testing of their left ankle DF and KE. Each muscle group was tested twice, on separate days, for a total of four laboratory visits per subject. Isometric and isovelocity measures were performed on each visit, with at least 24 h between visits and 1 h between measurement periods. The order of testing within and between days was randomized by using a random numbers generator.

Dynamometer Positioning and Initial Range of Motion Measurements

Torque, velocity, and joint angle were measured by using a Biodex System 3 dynamometer (Biodex Medical Systems, Shirley, NY) at a sampling frequency of 100 Hz. The dynamometer's internal goniometer was calibrated by using a manual goniometer. Thereafter, all joint angle measurements were obtained from the internal dynamometer.

Ankle dorsiflexion. The left foot was secured to the footplate by using Velcro straps and a thermoplastic mold to stabilize the foot. Subjects were seated with the hip flexed to 90° (full hip extension = 180°) and the left knee fixed at 175° of flexion (full knee extension = 180°), which was maintained by a knee brace. The subjects were secured to the seat by using straps across the hips and thigh. The axis of the dynamometer was aligned with the axis of rotation of the ankle joint. For ankle dorsiflexion, the total range of motion (ROM) for each subject was manually determined by the investigator. The ROM for the contractions was mechanically limited to 30°, based on pilot work that indicated that young and older subjects could be passively moved through a ROM of 40° and, therefore, could comfortably generate torque through 30°. This 30° range was determined by finding the midpoint of each subject's total ROM and mechanically limiting the dynamometer to 15° on either side of the midpoint.

Knee extension. The hip was fixed at 90° of flexion and stabilized by using straps across the hips and upper thigh. The dynamometer arm was secured to the lower leg 2 cm proximal to the medial malleolus of the ankle by using a Velcro strap. The axis of the dynamometer was aligned with the axis of rotation of the knee joint. Total ROM at the knee

was determined passively by the investigator. The ROM for the contractions was then mechanically limited to 70° (from 90° of extension to 160° of flexion) for all subjects.

Isometric Measurements

For both muscle groups, maximal isometric strength was measured at incremental angles throughout the ROM to be used during the concentric exercise sessions. In this way, an isometric torque-angle curve was generated for both muscle groups in each subject. To become familiar with the equipment and procedures before the measurements, each subject performed several submaximal trials for isometric DF and KE. Each subject then performed a 3- to 4-s maximal voluntary isometric contraction at increments throughout the defined ROM for each muscle group. During DF, the isometric trials were performed at 5° increments throughout the 30° ROM. For KE, 10° increments throughout the 70° ROM were used. The order of test angles was randomized. During all trials, subjects were verbally encouraged to give a maximal effort. These measures were repeated after at least 24 h of recovery.

Isovelocity Measurements

Each subject also performed a series of maximal concentric isovelocity contractions of each muscle group at a range of angular velocities. The order of testing speeds was randomized, and all trials were repeated with at least 24 h between sessions. The subjects were positioned on the dynamometer, as described above.

Ankle dorsiflexion. Each subject performed one submaximal and two maximal contractions at each velocity (from 30 to 240°/s, incremented by 30°/s). Seven seconds of rest were given between the three contractions at each velocity, and 30 s were allowed between velocities to avoid fatiguing the muscle. At each session, the first and last trials were performed at a velocity of 90°/s, although all other speeds were randomized. In this way, we were able to determine whether fatigue had occurred during the session, which would be reflected by a decrease in torque from the first to the second 90°/s contraction. Furthermore, we used these data to assess the reliability of dynamic torque production at 90°/s within and across days.

Knee extension. The ROM for knee extension was 70°, and the test velocities were 60, 120, 210, 240, 270, 300, 330, 360, and 400°/s. The angular velocity of the first and last trials was set at 120°/s to assess fatigue and the reliability of dynamic KE torque production. The order of the remaining velocities was randomized.

When torque-angular velocity relationships are examined, torque is often measured at a single angle (31). Such analyses do not consider that measured joint velocity may not be the same as the contractile component (CC) velocity. The two-component Hill model describes muscle as an active CC and a passive series elastic component (SEC) (10). During contraction, the instantaneous total muscle velocity is the sum of the CC and SEC velocities. When SEC velocity is zero, such as the instant of peak torque production, total muscle velocity is the CC velocity. We, therefore, used peak isovelocity torque rather than angle-specific torque to evaluate our torque-angular velocity relationships (2).

We also sought to examine the effects of age on the torque-velocity relationship, independent of the effects of age-related changes in muscle mass and strength. To account for intersubject differences in muscle mass, we scaled each subject's peak isovelocity torques to the isometric torques produced at that angle (2). This analysis also accounts for any

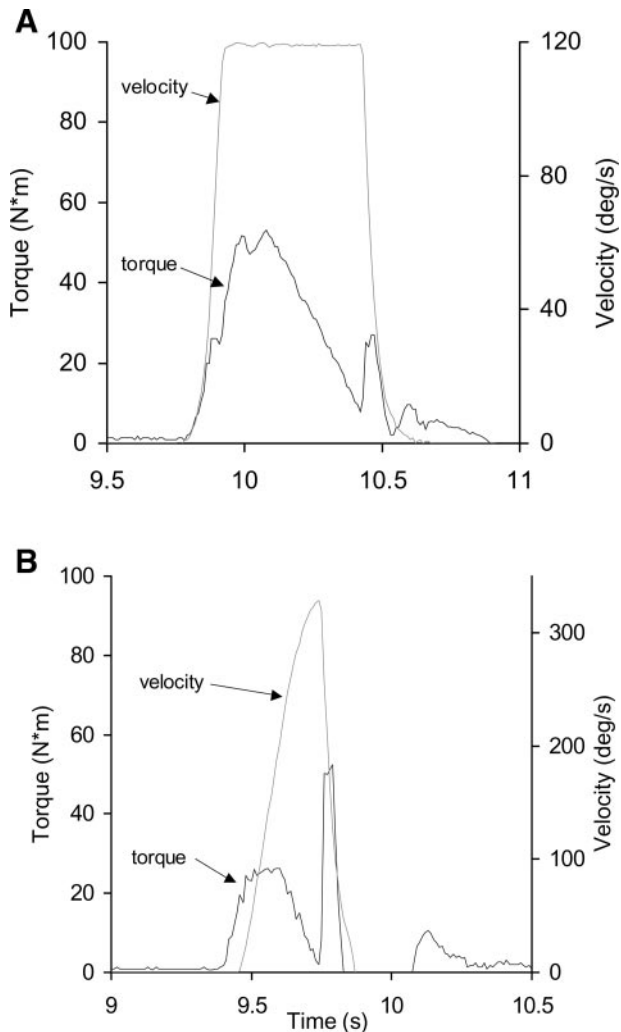


Fig. 1. Representative torque and angular velocity traces during knee extension. Data illustrate conditions under which an 80-yr-old subject was able (A) and unable (B) to reach target velocity. A: peak torque was generated while velocity was constant at 120°/s. B: the target velocity of 400°/s was not attained. The artifact resulting from the rapid increase in (isometric) torque at the end of contraction is visible in both traces.

intersubject differences in moment arms or force-length relationships and the occurrence of peak torque at different angular positions (1).

Data Analysis

The data were downloaded to a personal computer for analysis in a spreadsheet.

Isometric measures. After the torque-time trace was smoothed with a three- (DF) or five-point (KE) moving average to minimize any false peaks due to noise, the peak isometric torque produced at each angle was used to generate torque-angle relationships for each muscle group in each subject. Individual torque-angle curves were generated by plotting peak isometric torque vs. joint angular position for both muscle groups. A second-order polynomial regression was fit to each subject's curve to estimate maximal isometric torque production at any angle. In all cases, the r^2 value for each regression was at least 0.9.

Isovelocity measures. During each isovelocity contraction, the subjects were considered to have reached the target

velocity if they were able to maintain a constant velocity for at least 30 ms (3 data points) in ankle dorsiflexion and 50 ms (5 data points) during knee extension. Figure 1A shows a typical force tracing during knee extension at 120°/s for an 80-yr-old subject who achieved the target velocity. Figure 1B shows a force trace from the same subject at a target velocity of 400°/s, which was not achieved. For all contractions during which a subject was able to achieve the target velocity, peak torque and the angle at which it was generated were recorded, along with the time required to reach the target velocity. For all contractions, peak power was calculated from the product of absolute peak torque and the actual velocity at which it was measured.

With the use of the regression equation of torque-angle curves generated from the isometric contractions, each peak isovelocity torque was expressed as a percentage of the isometric torque produced at the same joint position. Absolute (N·m) and scaled (%peak isometric torque) torque-velocity curves were generated for each subject in both muscle groups.

Statistical Analyses

For isometric trials, three-factor (age, gender, joint angle) repeated-measures ANOVA was used to compare isometric strength across joint angles between age groups and genders. For dynamic trials, three-factor (age, gender, velocity) repeated-measures ANOVA was used to compare groups for absolute torque, scaled torque, time-to-target velocity, and power for both muscle groups. Statistical analyses included only the velocities that all subjects in all groups could achieve, i.e., the "highest common velocity." Gender differences are reported where detected. Because the focus of this study was age and because the groups were balanced with regard to gender distribution, all data are presented by age group. Significance was established at $P \leq 0.05$. Intraclass correlation (ICC) and ANOVA were used to assess the reliability of DF and KE dynamic torque production within and across days in young and older subjects.

RESULTS

Subjects

The physical characteristics of the subjects are provided in Table 1. The young and older subjects were similar in height and mass.

Reliability of Dynamic Torque Production

During ankle dorsiflexion at an angular velocity of 90°/s, the young subjects showed no effect of day or trial on the amount of torque produced, as assessed by ANOVA. The within-day reliability of this measure was ICC $r = 0.98$, and the across-days reliability was ICC $r = 0.97$. Similar to the young subjects, the older

Table 1. Subject characteristics

	Young	Older
<i>n</i>	12	12
Age, yr	26.3 ± 4.8	72.2 ± 6.4
Height, cm	171.6 ± 7.7	167.8 ± 8.3
Mass, kg	80.1 ± 19.1	77.2 ± 13

Values are means ± SD; *n*, no. of subjects. Groups were similar in height and mass.

group demonstrated high reliability within days ($r = 0.99$). However, there was a main effect of day on DF torque production ($P < 0.01$), such that torque was higher on *day 2*. Day-to-day reliability was ICC $r = 0.72$. To account for this day-to-day variability, the higher value for each measure from the 2 days was included in the statistical analyses. The lack of effect of trial on the $90^\circ/s$ contraction suggests that no appreciable fatigue developed during the testing sessions in either group.

During knee extension at an angular velocity of $120^\circ/s$, the young subjects showed no effect of day or trial on the amount of torque produced, as assessed by ANOVA. The within-day reliability of this measure was ICC $r = 0.99$, and the across-days reliability was ICC $r = 0.99$. Similar to the young subjects, the older group demonstrated high reliability within days ($r = 0.99$), with no effect of day or trial on torque production assessed by ANOVA. Day-to-day reliability was ICC $r = 0.88$. As with the DF, the lack of effect of trial on the $120^\circ/s$ contraction indicates that fatigue did not develop in either group during the testing sessions.

Isometric Torque-Angle Relationships

During isometric ankle dorsiflexion, men produced more torque than women ($P < 0.01$), and young subjects produced more torque than older subjects for each angle tested ($P < 0.01$, Fig. 2), with the largest torques occurring when the ankle was positioned $5\text{--}10^\circ$ plantarflexed from the midpoint of the ROM. Although the angles are expressed relative to the midpoint of the ROM (0°), the older and young groups differed by $<1^\circ$ in the absolute midpoints of their ROM. During isometric knee extension, men were stronger than women ($P < 0.01$), and young were stronger than older ($P < 0.01$, Fig. 2), with the greatest torque generated with the knee positioned at 90° . Overall, the older group produced an average of 21% less isometric torque in the DF and 20% less isometric torque in the KE compared with the young group. Only in the KE did the effect of age appear to be angle specific, with a negligible age difference in torque at 90° but a 52% difference in torque at 140° (Fig. 2).

Time to Target Velocity

In some cases, particularly at the highest test velocities, subjects failed to attain target velocity (Fig. 3). Above $120^\circ/s$ in the ankle DF, some older subjects were unable to reach the target velocity, whereas most young subjects attained target velocities up to $210^\circ/s$. Similarly, some older subjects were unable to achieve target velocities beyond $270^\circ/s$ in the KE, whereas most young subjects could achieve all knee extension target velocities. Overall, men were faster than women during DF ($P < 0.01$) and KE ($P = 0.04$), and young were faster than older subjects during DF ($P < 0.01$) and KE ($P = 0.02$). Figure 4 illustrates the mean time to attainment of target velocity for each age group, up to the velocity achieved by all subjects in the group. The torque and power data from only those velocities

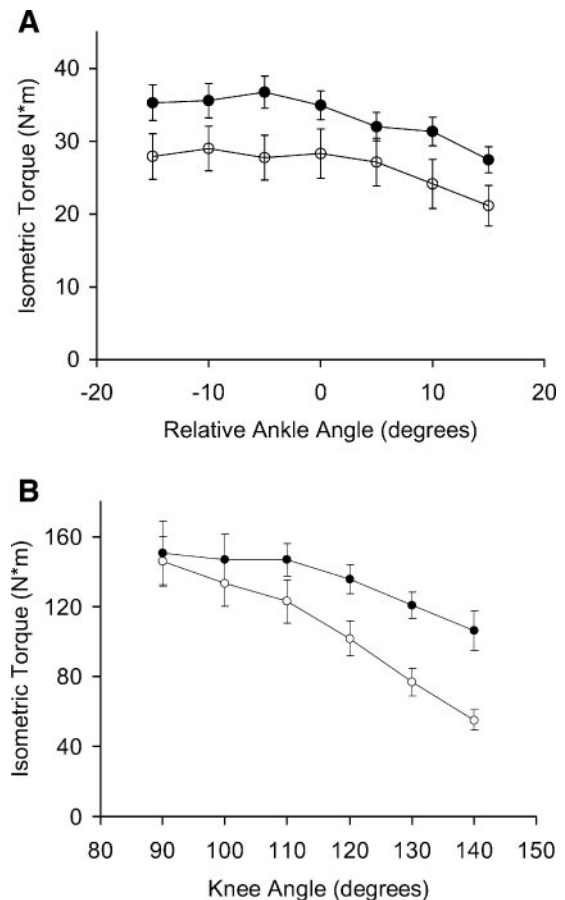


Fig. 2. Isometric torque throughout the range of motion. A: older subjects (\circ) produced less isometric torque than young subjects (\bullet) during ankle dorsiflexion at all angles throughout the 30° range of motion ($P < 0.01$). B: during knee extension, older subjects produced less torque overall ($P < 0.01$), and they exhibited a progressive deficit in isometric torque as the angle increased. Values are means \pm SE for 12 young and 12 older subjects.

achieved by all subjects were included in the subsequent statistical analyses.

Torque-Velocity Relationships

In both muscle groups, men produced more torque than women ($P < 0.01$), and young produced higher peak torques than older subjects ($P < 0.01$). The magnitude of these differences in absolute torque was similar at all velocities (i.e., there was no significant interaction). Across all velocities combined, the older group averaged 26% less DF torque and 30% less KE torque compared with the young group (data not shown).

During concentric contractions, there was no effect of age on the angle at which peak torque was achieved in either muscle group. However, there was an effect of velocity ($P < 0.001$), such that peak torque was generated farther along in the ROM as the angular velocity increased.

To examine the torque-velocity relationship while accounting for differences in maximal strength across individuals, as well as velocity-dependent changes in the angle of peak torque production, torque was also

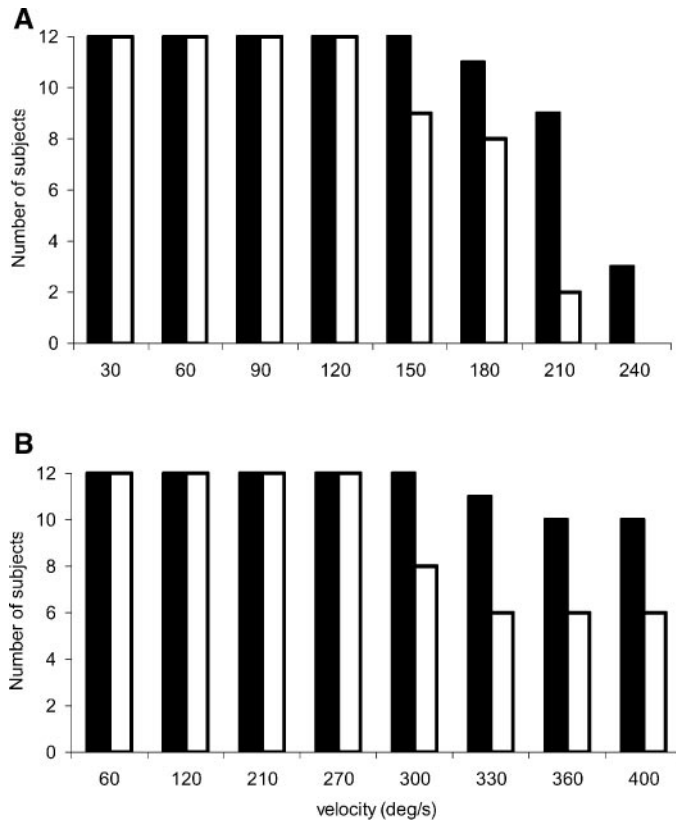


Fig. 3. Number of subjects who achieved each target velocity. *A*: during ankle dorsiflexion, some older subjects (open bars) failed to reach the target velocities $>120^\circ/\text{s}$, whereas the young subjects (solid bars) were all able to reach angular velocities through $150^\circ/\text{s}$. *B*: during knee extension, some older subjects failed to reach angular velocities $>270^\circ/\text{s}$, whereas some young subjects fell short $>300^\circ/\text{s}$.

expressed relative to each subject's angle-appropriate peak isometric torque. This scaled torque was similar across genders in the KE ($P = 0.36$), but lower in women in the DF ($P = 0.05$). As shown in Fig. 5, scaled torque was higher in young compared with older subjects at all velocities for both DF and KE (both $P < 0.01$). Interestingly, at the highest velocity achieved by all subjects, the older subjects produced 16% less relative torque in the DF ($120^\circ/\text{s}$) and 36% less relative torque in the KE ($270^\circ/\text{s}$) compared with the young, suggesting that there was a relatively greater impairment at high velocities in the KE.

Power-Velocity Relationships

Peak power was lower for women compared with men and older compared with young subjects across all velocities in both DF ($P < 0.01$) and KE ($P < 0.01$, Fig. 6). The average loss of power across all velocities was 26% in the DF and 33% in the KE. In the KE, there was a significant age-by-speed interaction ($P < 0.01$) for peak power, such that older subjects were progressively more impaired in power production as the velocity of contraction increased. This interaction was not apparent in the ankle DF. Similar to the torque-velocity comparisons, at the highest velocity achieved by all subjects, the older subjects produced 28% less power in

the DF ($120^\circ/\text{s}$) and 41% less power in the KE ($270^\circ/\text{s}$) compared with the young.

DISCUSSION

The results of this study provide support for our hypotheses in that healthy older men and women 1) required more time to reach target velocities and were less able to attain high velocities and 2) demonstrated downward shifts in the torque-velocity and power-velocity relationships compared with young adults. Isometric torque was lower in older compared with young adults at all angles in the DF and at angles $>90^\circ$ in the KE. In the KE muscles only, the older adults showed progressive impairment of the power-velocity relationship as velocity increased. These data provide new evidence, in two very different muscle groups, of impairments in muscle dynamic function that exceed the loss of isometric strength in healthy older adults. An important mechanism of the loss of dynamic torque and power with age appears to be the slowing of voluntary contractile speed. Furthermore, we provide evidence of muscle-specific impairments in the older volunteers compared with their younger counterparts.

Isometric Torque-Angle Relationships

During ankle dorsiflexion, the older subjects produced less isometric torque than the young subjects at

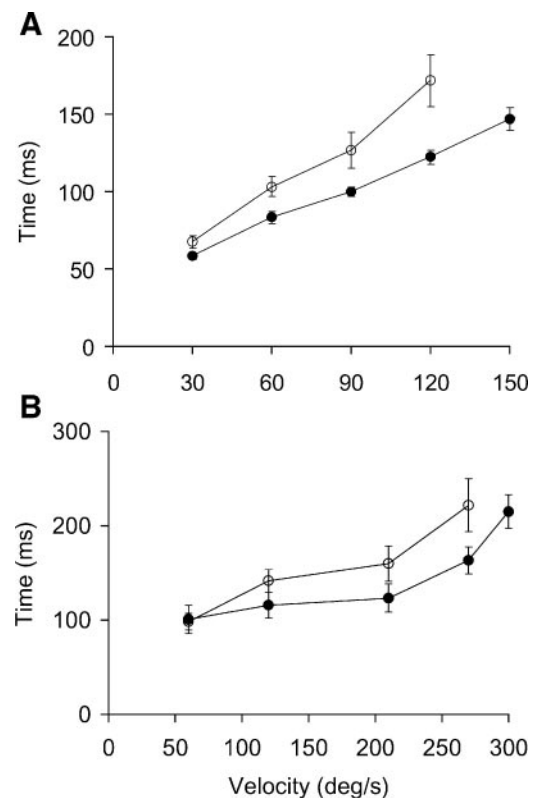


Fig. 4. Time to target velocity during dynamic contractions. Older subjects (\circ) required more time to reach target velocities during ankle dorsiflexion (*A*; $P < 0.01$) and knee extension (*B*; $P = 0.02$). Values (means \pm SE) for 12 young (\bullet) and 12 older subjects are shown for those velocities that all subjects in the group achieved.

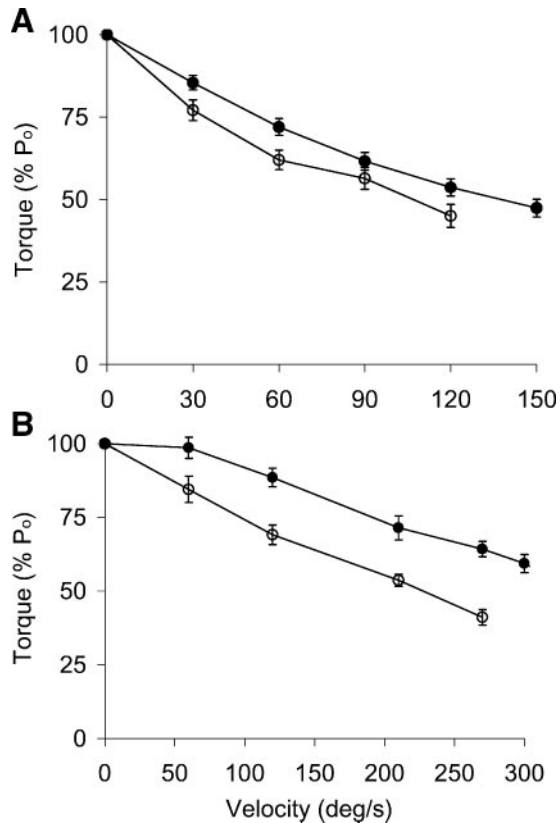


Fig. 5. Relative torque-velocity relationships in dorsiflexor (A) and knee extensor (B) muscles. When torque was scaled to peak (isometric) torque, older subjects (\circ) produced less torque than young subjects (\bullet) during ankle dorsiflexion (A) and knee extension (B) (both $P < 0.01$). Values (means \pm SE) for 12 young and 12 older subjects are shown for those velocities that all subjects in the group achieved.

all angles tested (Fig. 2). These results are in agreement with those of others who found decrements in maximal isometric strength with age (34, 35) and are consistent with the age-related decline in muscle mass. In the KE, the age-related decrement in isometric strength was dependent on the knee angle (Fig. 2). At a knee angle of 90° , the young and older groups produced similar amounts of KE torque. As the knee was moved to progressively more extended positions, the differences in torque between young and older subjects became more apparent. This angle-dependent decrement in torque may be the result of a decreased functional ROM in older adults. For example, some activities that older adults continue to perform daily, such as rising from a chair, require the greatest torque production when the knee is in a flexed (near 90°) position. In contrast, activities that load the KE throughout the more extended portion of the ROM (e.g., stair climb and descent) may be engaged in less frequently as we age, particularly if there is a fear of falling. Decreased flexibility in the antagonist muscles or reduced tolerance for compressive force at the joint are other possible factors in this angle-specific deficit in the older subjects.

Time to Target Velocity

In the DF muscles, the older adults demonstrated a significant increase in the time required to attain target velocity (Fig. 4). In both muscle groups, the older subjects were less able to attain higher target velocities, with failure beginning $>120^\circ/\text{s}$ for dorsiflexion and $270^\circ/\text{s}$ for knee extension (Fig. 3). This age-related slowing of contraction speed may be due to a number of changes in muscle morphology and function with age, including a selective loss of type II muscle fiber area (23), increased proportion of type I fibers (20), and an impaired ability to generate high motor unit discharge rates (4, 15). In support of the importance of maximal firing rates on DF muscle contractile speed, Van Cutsem et al. (33) observed increases in motor unit firing rates in conjunction with increases in the speed of voluntary muscle contraction in response to 12 wk of dynamic exercise training. Our laboratory has previously reported slowed contractile speeds in older adults during electrically stimulated isometric contractions in the DF muscles (26). Of note, the slowing of the maximal rate of voluntary force production in older subjects during rapid, isometric contractions in the DF muscles was nullified when this rate was scaled to the

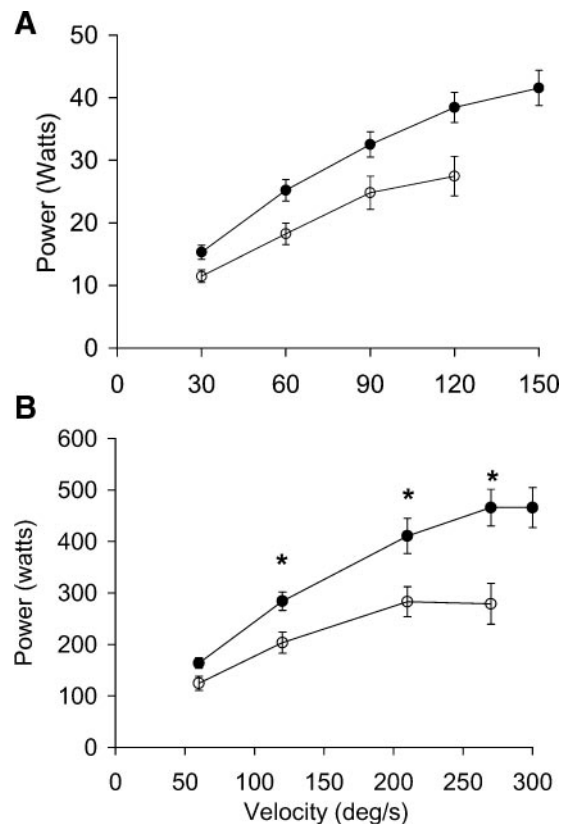


Fig. 6. Power-velocity relationship in dorsiflexor (A) and knee extensor (B) muscles. Older subjects (\circ) produced less power than young subjects (\bullet) during ankle dorsiflexion and knee extension (both $P < 0.01$). During knee extension, older adults produced progressively less power as the contraction velocity increased (interaction $*P < 0.01$). Values (means \pm SE) for 12 young and 12 older subjects are shown for those velocities that all subjects in the group achieved.

rate of force production during an electrically stimulated tetanus, suggesting that the cause of slowed voluntary contraction speed with age was due to factors beyond the point of stimulation (26). Furthermore, a recent study by Gür et al. (8) demonstrated a significant relationship between the ratio of torque produced at high-to-low velocities and the relative area of type II muscle fibers in young athletes, which provides evidence in humans that fiber type plays an important role in torque production at high speeds. Overall, it seems likely that much of the age-related slowing observed here during dynamic contractions may be a result of changes in the periphery.

An important result of this study was the inability of the subjects to achieve the higher target velocities, as set with the dynamometer. The isovelocity mode on the dynamometer provides an upper limit to the velocity that can be attained by the subject, but does not guarantee that the subject actually reaches the predetermined speed. It is, therefore, possible for subjects to complete contractions and generate torque without, in fact, achieving a constant velocity. In the present study, older subjects began to fail to reach target velocities $>120^\circ/\text{s}$, whereas young subjects began to fail at $180^\circ/\text{s}$. Similarly, during knee extension, older subjects began to fail at velocities $>270^\circ/\text{s}$, whereas all of the younger subjects were able to achieve a velocity of $300^\circ/\text{s}$, and most were able to achieve $400^\circ/\text{s}$. This observation, that not all subjects could achieve the target velocities, is not in agreement with some previous studies of the torque-velocity characteristics in a range of age groups (12). However, it is not clear whether the previous investigators measured the actual velocity achieved during contractions or assumed that the constant velocity target specified by the dynamometer was achieved because torque was produced. Our results point to an important limitation of isokinetic dynamometers that should be considered during studies involving "isovelocity" contractions, particularly in older subjects.

Torque-Velocity Relationships

In addition to the decrease in isometric torque in older adults, there were significant decrements in the torque-velocity curves for both the KE and DF muscles in the older group. This was the case whether torque was expressed in absolute terms ($\text{N}\cdot\text{m}$) or scaled to peak isometric torque (Fig. 5) and was not due to age-related differences in the angle at which peak torque occurred. Due to the well-documented loss of muscle mass with age, a decrease in absolute torque production in the older subjects was not unexpected. However, it is of interest that there remained differences in the torque-velocity relationships even after scaling torque to peak isometric values. By expressing peak dynamic torque relative to peak isometric torque at the same angle, we were able to account for individual differences in 1) muscle mass, because isometric torque is well-correlated to muscle cross-sectional area (16), 2) muscle moment arms, and 3) muscle force-

length relations. The latter two factors can alter the shapes of both the torque-angle and torque-velocity relationships. Overall then, there remains an age-related impairment of muscle function during dynamic contractions over a range of velocities that is due to factors beyond merely the loss of muscle mass. These results are consistent with those of Harries and Basse (9), who demonstrated a downward shift in the torque-velocity relationship (scaled to isometric torque) of the KE in older women. In contrast, Stanley and Taylor (29) reported no shift in the relative torque-velocity relationship in the KE or flexor muscles of older women, although these data were scaled to torque measured at a velocity of $60^\circ/\text{s}$, rather than peak isometric torque.

Power-Velocity Relationships

Older adults showed a decrease in power production in both muscle groups (Fig. 6). The age-related deficit in power increased with increasing velocities in the KE, but not the DF. These results depict a difference in the degree of impairment in two morphologically distinct muscle groups, both of which are involved in locomotion and are important to the prevention of falls in the elderly.

There are several possible explanations for our results, based on the physiological changes observed in aging skeletal muscle. One obvious physical change with age is a decline in total muscle mass (21–23), which would explain why older adults produced less absolute torque than young adults. Although we did not measure muscle mass in the present study, results from studies of men and women in comparable age groups as those used here suggest that maximal muscle cross-sectional area decreases by $\sim 16\%$ in the ankle DF (19) and $\sim 21\%$ in the KE (14) in healthy older adults. Interestingly, isometric torque, which is largely dependent on muscle cross-sectional area (16), was lower in the older subjects of this study by approximately the same degree ($\sim 20\%$) in both muscle groups. Thus the deficit in isometric torque with age is likely due to a loss of muscle mass. In contrast, the age-related deficits in dynamic torque and power, which depend on the ability to rapidly generate torque, averaged 26–33% in the older subjects. These deficits in dynamic performance appear to be in excess of those observed during isometric contractions. In fact, at the highest velocities achieved by all subjects, the age-related power deficit was 28% in the DF and 41% in the KE.

It is not surprising that the decline in muscle mass alone likely does not explain the age differences in scaled torque or power. In addition to the age-related shift toward a slower muscle (7), there are also changes within the central nervous system that likely affect how muscle force is generated. Researchers have often (4, 15), but not always (28), shown a decline in maximal motor unit discharge rates with age. As a result of this and the denervation-reinnervation process that occurs with aging (20), older adults may be less able to rapidly modulate their level of force production (5). Therefore,

the velocity-dependent decline in power with age may be the result of both slowed muscle contractile properties and an impaired ability to rapidly mount high-discharge rates.

Muscle Specificity

In this study, a direct comparison across muscle groups of the effects of age on torque and power production is difficult to make, due to the necessary differences in test velocities for the two muscle groups. However, comparison of the torque responses at the highest common velocity for each muscle group (Fig. 5) suggests a greater decrement with age for the KE (36% less torque for the older subjects at 270°/s) than the DF (16% less at 120°/s). This muscle-specific age effect was also apparent in peak power (KE 41% less for the older subjects, DF 28% less; Fig. 6). Thus there appears to be a greater alteration in the torque-velocity and power-velocity characteristics of the KE with aging. It is interesting to note that this muscle specificity is most apparent during dynamic contractions. Under isometric conditions, muscle torque is well-preserved at 90°, but not beyond, in the KE (Fig. 2), whereas the DF show a similar age-related torque deficit across all angles. It seems likely that the quantity and quality of muscular activation play a role in this observation.

In this project, we studied healthy, community-dwelling adults. Because the DF are used for locomotion and little else, it is logical to expect that function will be reasonably well preserved in this muscle group. In fact, we have found no impairment in DF muscle-specific strength (16), activation (16), oxidative capacity (17), or ability to resist fatigue (18) during isometric contractions in older compared with young adults. In contrast, the KE muscles are typically involved in more high-intensity activities (e.g., sprinting, jumping) that may be less frequently performed by older adults than by their younger counterparts. As a result, rapid and high-intensity contractions, such as those used here, may be more profoundly impacted by changes in the type of activities engaged in by aging adults.

Reliability of Dynamic Torque Production

An analysis of the reliability of the maximal isovelocity contractions revealed that the young subjects had no effect of day or trial on the amount of torque produced by either muscle group during these contractions. Additionally, the ICC demonstrated that our measures of dynamic torque were highly reliable across as well as within days. These data are consistent with other reports indicating that dynamic tests of ankle DF strength using a Biodex dynamometer are highly reliable in young adults (11).

Similar to the young subjects, the older subjects also showed no effect of trial on peak concentric torque and high reliability within days for both muscle groups. These results are in agreement with those of previous reports of the reliability of DF isokinetic strength in older adults, in which ICC coefficients ranged from 0.61 to 0.92 (25, 30). However, we observed a main

effect of day on DF torque production and lower reliability from day to day for this measure. For this reason, we used each individual's highest value for each measure, which generally occurred on *day 2*. In contrast, the within- and across-day reliabilities for the KE measures were excellent for the older subjects. Thus our analyses of two different muscle groups in both young and older subjects reveal differences by age and muscle group in the reliability of isovelocity testing. Overall, these data emphasize the need to provide adequate habituation to the testing protocol for all muscle groups to be studied, particularly when measures of muscle torque and power are performed in older adults.

Conclusions

We conclude that decreased torque production and slowing of contraction speed contribute to an age-related decrement in both the torque-velocity and power-velocity relationships of the ankle DF and KE muscles. Furthermore, our data suggest that the effects of age on these variables may be muscle specific, such that the KE and DF muscles are affected differently by age. It remains to be determined whether this difference is due to alterations in the pattern of muscle use or to intrinsic changes in muscle characteristics.

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