

Age-Related Changes in Maximal Hip Strength and Movement Speed

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Background. We quantified age-related decreases in the ability of female participants to generate whole leg movements about the hip.

Methods. We measured maximum hip strength and hip velocity in 12 young and 12 older healthy women. Both capabilities could help fall prevention by contributing to fast leg movements. We also measured maximum velocities as a function of isotonic load.

Results. Young participants produced 107.6 ± 25.4 N-m (mean \pm SD) isometric torque in flexion and 109.3 ± 22.3 N-m in extension. Older participants produced 22% and 31% lower torques, respectively ($p < .001$). Young participants generated maximum velocities of 362.8 ± 51.5 %/s in flexion and 371.5 ± 54.2 %/s in extension. Older participants produced 16% lower velocities in both directions ($p < .001$). Older participants also produced lower velocities as a function of load ($p < .001$), and lower maximum power ($p < .001$).

Conclusion. Both maximum strength and velocity contribute to reduced ability to move the leg quickly with age.

ELDERLY individuals experience physiological changes in muscle capabilities and functional impairments in mobility with age (1). Declines in isometric muscle strength have been reported for the knee (2) and hip (3–5), and these declines are correlated with impaired functional mobility in older adults (6,7). Strength, however, is one of several muscle characteristics that change with age. Maximum muscle contraction velocity also decreases, as measured for example in knee extensions (2). Strength and velocity both contribute to maximum muscle power, which decreases with age to a greater extent than either muscle strength or maximum velocity alone (8). Muscle power has been proposed as a better indicator of functional status (9). In a vertical jumping task, age-related decline in maximal power has been attributed more to a decrease in maximum velocity than to a loss of strength (10). Because the relative importance of maximal power versus strength depends on the task, it is important to evaluate these parameters in a context that is closely related to the desired task. In functional mobility, the task of avoiding a fall generally involves movement of the whole leg. Previous studies (2–4,8) have characterized knee strength, speed, and power, isometric hip strength, and isokinetic hip strength with the knee flexed. It would be helpful to augment these studies with additional data from a task more closely resembling what is needed to prevent falling.

Fall prevention is a critical issue among elderly people, but the reason for the increased rate of falls in an older population is not completely understood. The most common causes of falls in elderly persons are trips and slips (11), while the ability to move the entire leg could potentially be an important aspect of preventing such a fall. Recovery

could be limited by the ability to produce a large torque (acceleration), by the maximum attainable speed of movement, or by the available maximum power. Thelen and colleagues (12) suggested that the ability to recover from a fall in the forward direction depends on the maximum lower extremity velocity that can be developed in a forward step. The speed at which the leg can be moved therefore seems to be an important factor in everyday function and mobility. Successful functional task performance may thus depend on the ability to generate sufficient speed, and this speed must be generated against a specific load. Alternatively, Grabiner and colleagues (13) cited lower extremity muscle power as important in recovery from a trip. The hip joint is vital in producing whole leg movements, and would be expected to be important in fall prevention (14,15). While the ability to quickly move the leg forward or backward depends on the functional capacities of multiple joints, age-related changes have been less well characterized for the hip than the knee.

In this study, we will evaluate torque and speed for a situation that roughly approximates what is theoretically needed for fall prevention: whole leg movement about the hip. In contrast to previous studies, we will measure hip power and strength in a context closer to fall prevention, by placing the participant in a standing position, and measuring movement of the leg with the knee relatively straight. We will examine the effect of age on the velocity and torque developed during maximal voluntary hip flexion and extension contractions. Comparisons will be made in which strength dominates, maximal speed dominates, and several intermediate conditions where combinations of high torque and velocity are both required.

Table 1. Anthropometric Data (Means \pm Standard Deviations)

| Group | Height (m) | Hip Height (m) | Mass (kg) |
|--------------------|-----------------|-----------------|-----------------|
| Young ($n = 12$) | 1.63 \pm 0.05 | 0.86 \pm 0.04 | 62.2 \pm 10.9 |
| Old ($n = 12$) | 1.59 \pm 0.05 | 0.83 \pm 0.03 | 64.3 \pm 7.8 |

METHODS

We recruited 24 adult female participants, referred to as Young and Old age groups, to participate in this study. The Young age group consisted of 12 participants with mean age 23.2 years (± 2.2 SD [standard deviation]), range 21–28 years; the Old age group consisted of 12 participants with mean age 74.8 years (± 3.5 SD), range 69–82 years. None of these individuals were regular participants in competitive athletics, and the Young and Old participant pools were matched to avoid any significant differences in height, hip height (defined as distance from the floor to the greater trochanter), or weight (Table 1). All of the participants tested were identified as right leg dominant based on the preferred leg for kicking, and none reported a history of neurological or musculoskeletal impairment. The Old were screened by a nurse practitioner, and were found to have no significant abnormal impairments. Written consent was obtained in accordance with the Institutional Review Board for Human Subject Research at the University of Michigan Medical School.

We devised an apparatus to allow participants to perform straight-legged hip flexion and extension against a dynamometer from a standing position. This configuration was used because many falls occur from a relatively upright position with the knee extended, while there are already some data regarding hip strength with the knee in the flexed position. The straight-legged configuration is conservative in that the leg presents the highest possible moment of inertia, thereby demanding greater strength to accelerate at the same rate as for bent-legged configurations. Each participant stood inside a custom-built steel frame adjacent to a Biodex Multi-Joint System 2 AP dynamometer (Biodex Medical Systems, New York, NY) used to measure hip torque and velocity. The frame supported each participant with a short platform under her left foot, padded armrests under her flexed forearms, and a padded backrest. Participants were secured in place within the frame using straps attached to a belt just above the hips and wrapped around the outside of the frame holding the pelvis in place, and straps over each shoulder to keep the torso upright (Figure 1). All participants were comfortably able to support themselves in this manner for short periods of time. The right leg was enclosed in a splint to keep it in a fully extended position, and attached to the radial arm of the dynamometer by a padded strap just below the knee, with the axis of the right hip joint aligned with the dynamometer axis. The arm of the dynamometer had a mass of 2.6 kg, and an estimated moment of inertia of 0.13 kg/m². In between tests, a block was placed under the participant's right foot to allow rest and prevent postural fatigue. The lowest cushioning setting on the Biodex, which controls the rate of deceleration near the end of the range of motion, was used to minimize the mechanical effect of the dynamometer

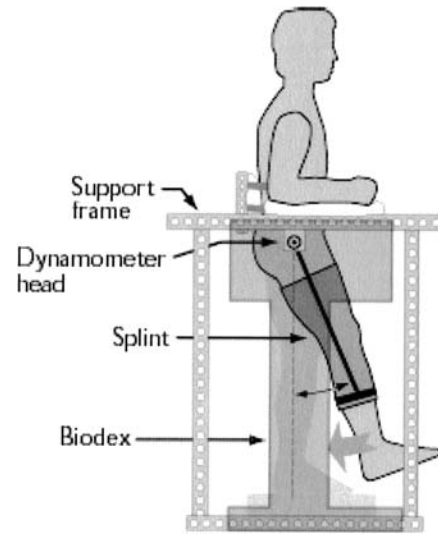


Figure 1. Experimental apparatus for measuring maximum torque and velocity about the hip from a standing position. Participants stood on one leg in a support frame, strapped securely to the frame about the waist and with forearms placed on armrests. The other leg was attached to a Biodex dynamometer through a splint. Measurements of maximum torque and velocity were made for movement of the straight leg about the hip, approximating a fast leg movement to prevent falling.

on the data (16). Participants were asked to stand comfortably erect and distribute their body weight equally between their feet (referred to as “neutral posture”). The allowable range of motion was set at limits of 15° of extension and 60° of flexion.

Hip torque-velocity profiles were evaluated using a series of three different settings on the Biodex hardware. We first measured each participant's maximum isometric hip flexion and extension torques using the isometric dynamometer setting. We next measured the maximum hip flexion and extension speeds under minimal load, using an isokinetic setting designed to provide no resistance. The isokinetic condition is normally meant to provide variable resistance to limit movement speed, but we set this limit to be higher than participants were capable of achieving, so that, effectively, the dynamometer provided minimal resistance. Finally, we measured the maximum attainable hip flexion and extension angular velocities over a range of loads, using a series of isotonic settings. Each isotonic setting provided a nearly constant load against which participants moved their legs as quickly as possible. To become familiar with the procedure, participants were given one nonmaximal practice contraction under each of the above conditions.

In the maximum isometric torque measurements, participants pushed or pulled their leg against the stationary radial arm of the Biodex for approximately 3 seconds, with verbal encouragement from the experimenter. Isometric flexion contractions were performed at neutral posture, while the extension contractions were performed at 15° of hip flexion. Participants completed a minimum of two contractions in each direction. If the measured maximum torque values were not within 10% of each other, third and possibly fourth contractions were performed until the torques were

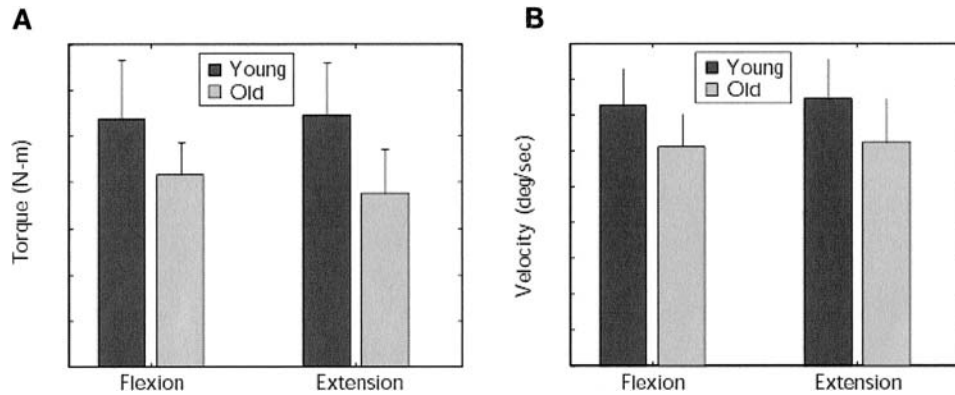


Figure 2. Maximum isometric torques and velocities generated about the hip for Young and Old participants. **A**, Maximum isometric hip torques in the Old were 22% lower than in the Young for hip flexion, and 31% lower for hip extension ($p < .001$). **B**, Maximum hip velocities with no load were 16% lower in Old compared to Young in both directions ($p < .001$).

consistent. The order of the direction of the contractions was randomized, and 2 minutes of rest were given between contractions.

We next measured each participant's maximum flexion and extension velocity using the isokinetic dynamometer mode of the Biodex. The isokinetic speed was set to 450 °/s, exceeding the maximum speed achievable by any of the participants, so the motion was essentially unresisted. Participants were asked to move the leg as quickly as possible through the entire range of motion. Again, a minimum of two contractions in each direction was required. If the values of the maximum velocities were not within 10% of each other, additional contractions were required until the velocities were consistent. We randomly selected either the flexion or extension direction to be performed first. One minute of rest was given between contractions.

Maximum velocities were also evaluated over a range of isotonic loads, applied in random order. The load settings were 5, 10, 20, 40, 60, 80, and 100 ft-lbs (in SI units, 6.8, 13.6, 27.1, 54.2, 81.4, 108.5, and 135.6 N-m, respectively). All of the contractions in one direction were performed consecutively, with either extension or flexion randomly chosen to be performed first. For each load, participants completed at least two contractions in each direction. More contractions were performed if the maximum velocities were not within 10% of each other. If a participant was unable to generate any velocity at a given load, no attempts were made at any higher loads. Participants rested 1 minute between tests.

In order to determine if fatigue affected performance from the beginning to the end of the test, we also performed additional isokinetic and isometric trials at the end of the protocol. These consisted of single maximum speed and maximum isometric torque evaluations, in both flexion and extension directions. We compared these with trials performed earlier in each test session, and found no decreases in strength of greater than 10%, our criteria for consistency.

We recorded the torque, velocity, and position of the Biodex's radial arm during each test. These data were recorded by Biodex Advantage Software 4.5 at a sampling

rate of 100 Hz, and exported for analysis. We identified the maximum torque in the isometric contractions from the measured torque trajectories, ignoring an initial transient maximum that occurred as participants began to exert force on the Biodex arm. For the remaining conditions, we identified maximum angular velocities in the direction of interest.

We performed a series of statistical comparisons between Old and Young. A two-way analysis of variance (ANOVA) was used to test for differences in maximum velocity with age and load setting. We also performed two-way ANOVAs to determine whether there were significant age group or direction differences between the Young and Old participants for maximum isometric torque, maximum unloaded velocity, and maximum instantaneous power at an intermediate load. An additional two-way ANOVA was performed to find the factors influencing the leg angle at which maximum velocity was reached.

RESULTS

Old participants generated significantly lower maximum isometric torques than Young participants ($p < .001$), while direction did not have a significant effect and there was no significant interaction. The mean (\pm SD) maximum flexion torque was 107.6 (\pm 25.4) N-m in the Young, and 83.4 (\pm 13.7) N-m in the Old, while the maximum mean extension torque was 109.3 (\pm 22.3) N-m in the Young, and 75.1 (\pm 18.9) N-m in the Old (Figure 2A). Old participants therefore produced 22% less flexion torque and 31% less extension torque than Young.

Maximum unloaded hip angular velocities were significantly lower ($p < .001$) in the Old than the Young (Figure 2B), while there was no direction or interaction effect. The average maximum flexion and extension velocities in the Young group were 362.8 (\pm 51.5) °/s and 371.5 (\pm 54.2) °/s, respectively; while in the Old group these values were 305.0 (\pm 44.3) °/s and 311.1 (\pm 61.5) °/s (Figure 2B). Thus, the Old produced 16% slower hip flexion and extension than the Young.

Maximum hip angular velocities also decreased with increasing isotonic load. There were significant differences

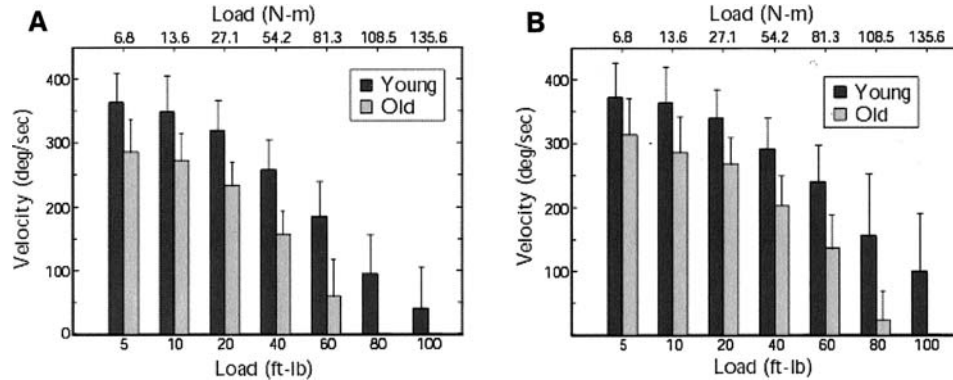


Figure 3. Maximum hip velocities as a function of load for isotonic contractions, in (A) flexion and (B) extension directions. Old participants produced lower maximum speeds at all loads compared to Young ($p < .001$).

associated with both age and load level ($p < .001$), as shown in Figure 3. There was also a significant interaction ($p < .01$) between age and load level for hip flexion, but not for hip extension. In addition, with higher loads an increasing number of participants were unable to generate any movement of the load.

In addition to reduced maximum isometric torque and maximum angular velocity in the Old, we found that these same participants produced lower maximum instantaneous power during isotonic contractions. This is shown in Figure 4, for an intermediate load of 40 ft-lbs (54.2 N-m). The Old group developed significantly less ($p < .001$) maximum power than the young. The power in the extension direction was significantly higher ($p < .01$) than in the flexion direction. No significant interaction was seen.

The generated load-velocity curves exhibited fairly linear relationships. Fitting the group data to a linear equation resulted in R^2 values of 0.78 for Young flexion, 0.75 for Old flexion, 0.69 for Young extension, and 0.68 for Old extension (Figure 5). The theoretical maximum isometric torque and maximum unloaded velocity of each participant could be calculated by extending the torque-velocity curve to the x- and y-axes.

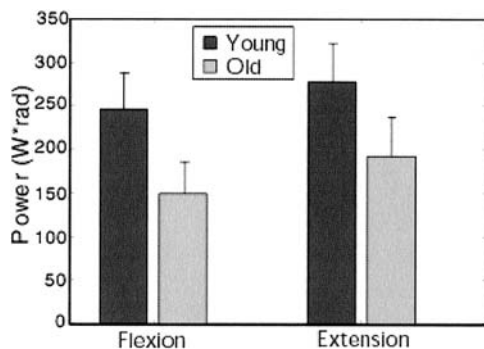


Figure 4. Maximum instantaneous power generated with a load of 40 ft-lbs (54.2 N-m), for flexion and extension. Old participants produced 39% less power for hip flexion, and 31% for hip extension, compared with Young participants ($p < .001$).

All the results above concern the maximum velocity found throughout the range of motion. However, this velocity did not always occur at the same point in the range of motion. In flexion, with higher loads, the maximum velocity occurred significantly closer to the neutral position ($p < .001$). In contrast, during extension, the maximum velocity occurred significantly further from the neutral position as the load increased ($p < .001$) (Figure 6). The Old group reached their maximum velocity significantly closer to the neutral position for both flexion ($p < .001$) and extension ($p < .05$). Therefore, the Old reached their maximum velocity at a significantly different angle than the Young as the load was increased. However, the time at which the maximum velocity was reached was not significantly different for the two groups. Interestingly, as load increased, the participants' maximum velocities occurred closer to the position at which isometric strength was tested for flexion, but further from this position for extension.

Differences in body size did not appear to explain the differences between Young and Old, as evidenced by comparing data normalized for size (Figure 7). To account for anthropometric variations between participants, torques were normalized by the product of body weight and leg length, and angular velocities were normalized by the pendulum frequency of the leg (square root of gravitational constant divided by leg length), resulting in dimensionless units. Even after this normalization, the differences between Young and Old were retained. The R^2 values for the normalized data were 0.72 for Young flexion, 0.72 for Old flexion, 0.62 for Young extension, and 0.68 for Old extension. It would have been preferable to normalize by fat-free mass, but this data was unfortunately not collected.

DISCUSSION

These data assessed the ability of participants to produce hip torque and to move their leg quickly. Our results show age-related decreases in maximum isometric hip torque (see Figure 2A), maximum hip velocity (Figures 2B and 3), as well as maximum hip power (Figure 4) in both hip flexion and extension directions. We found that strength declined to a slightly greater extent than velocity, as evidenced by the

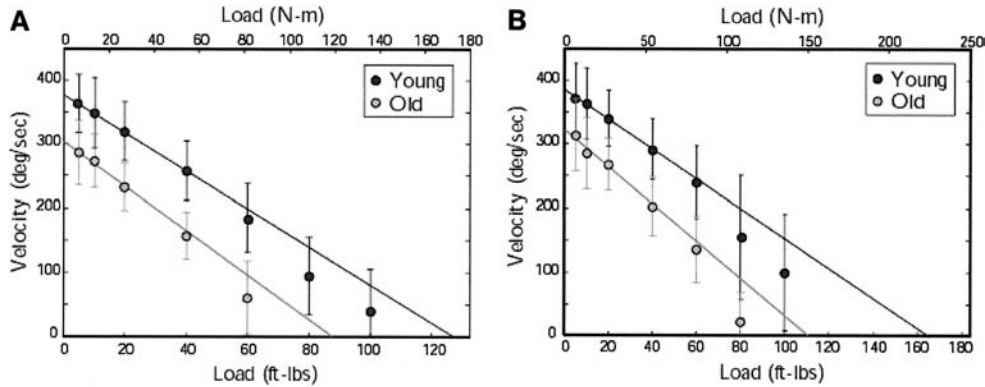


Figure 5. Maximum leg angular velocity generated at each load for (A) flexion and (B) extension, with a linear fit for each participant group. Linear fits indicate that maximum torques decreased to a greater extent than maximum velocities in Old participants. R^2 values ranged 0.68–0.78.

more negative slope of torque-velocity curves for Old participants (Figure 5). The Young–Old difference in maximum mean isometric strength was 22% in hip flexion and 31% in hip extension, while the average maximum velocity was lower in the Old by approximately 16% in both flexion and extension. Predictably, larger loads resulted in decreased maximum velocity. The fact that both isometric hip strength and maximum hip velocity were lower in the Old participants indicates that the maximum velocity generated against all loads will decrease with age.

Comparable declines in isometric strength have been reported in other studies. For example, we observed maximum isometric hip flexion torques of 108 N-m and 83 N-m for the Young and Old, both within the ranges of 105–150 N-m and 48–125 N-m, respectively, reported previously by others (3–5,17). We found age group differences in maximum isometric torques—22% and 31% for flexion and extension, respectively—that are slightly larger than differences of 14%–18% found in previous studies (3,4). This is likely due to differences in test measurement conditions, particularly in participant testing position (such as in hip and knee angle), and due to the fact that the mean age of the Old in the present study was greater than those in previous studies.

The decline in isometric muscle strength has been shown to accelerate as age increases (3).

Our measurements were designed to be functionally relevant in that participants exerted hip torque from a standing posture similar to functional situations that might require fast leg movements. We used a Biodex dynamometer because it and similar devices are commonly available in rehabilitation settings, where functional measurements might be of interest. The external supporting frame was designed to allow participants to stand upright and move the hip against the dynamometer while keeping the leg straight. This differs from typical Biodex configurations where participants lie supine and produce hip torque with the knee flexed. When humans counter a fall, they might be expected to start from a standing position with the leg initially in a straight configuration. The load-velocity relationship is of potential interest for such leg movements, because they often involve accelerating the leg through a range of velocities. One difference with an actual fall arrest is that participants cannot realistically be expected to keep the leg straight through the entire movement. Bending the leg while stepping forward reduces the effective inertial load and potentially allows for faster movements. Our straight-leg measurements of

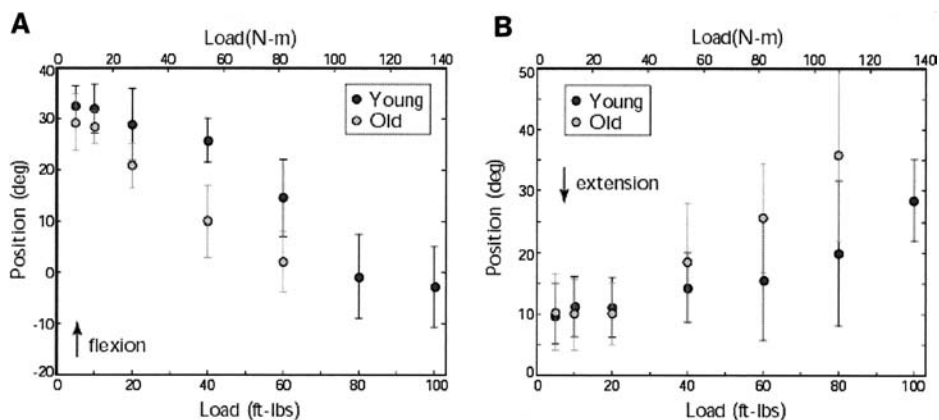


Figure 6. Leg position at which maximum hip-load velocity was reached, as a function of isotonic load, for (A) flexion and (B) extension. Leg position was

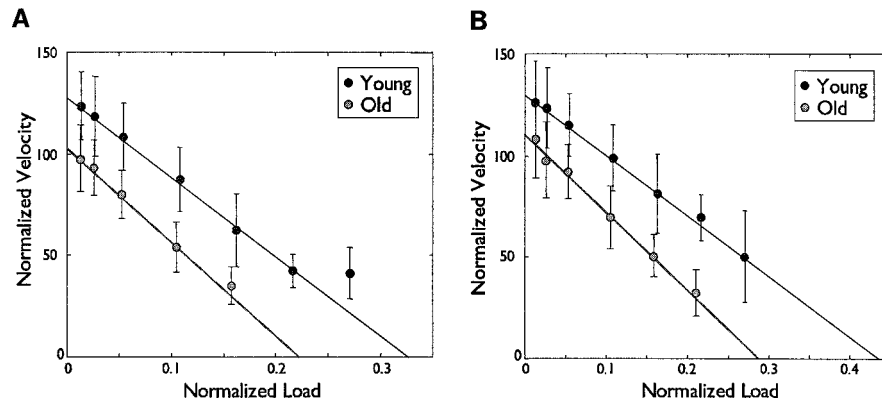


Figure 7. Maximum leg angular velocity generated at each load for (A) flexion and (B) extension, normalized for participant size and weight. Differences in maximum hip velocity between Old and Young are not explained by differences in size and weight. Load is shown normalized by body weight multiplied by leg length, and angular velocity is shown normalized by pendulum frequency $\sqrt{g/L}$, where g is the gravitational constant and L is leg length. R^2 values ranged 0.62–0.72.

maximum velocity are therefore somewhat conservative because they maximize the effective inertial load. Previous data present the opposite extreme, with dynamic hip strength measured with the knee flexed at 90° (4). Together, these data sets help to quantify hip strength in a controlled manner.

The functional advantages of our study make it difficult, however, to compare our data with more physiological measurements. The classic force–velocity relationship (18) is typically derived *in vitro*, with a single muscle acting directly on the load. In our study, there are several muscles acting through tendon to move the combined resistance of leg mass and the dynamometer arm, with the load measured in the dynamometer arm itself. The muscles also have individual moment arms, pennation angles, fiber compositions, and length–tension relationships, all of which can affect the load–velocity relationships observed here (19). In physiological experiments, it is also customary to control for muscle length or joint angle while measuring the force–velocity curve (4,20–24), in contrast to the present measurements, where participants moved as quickly as possible, and maximum velocity was recorded regardless of leg position. The combined effect of these differences makes it unsurprising that our load–velocity data (Figure 5) do not resemble the traditional hyperbolic force–velocity curve found *in vitro* (18). Given the many factors that can affect the load–velocity relationship, it appears to be reasonable to employ a linear fit as a simplification.

As stated in the results, the load–velocity curves could be used to calculate the theoretical maximum isometric torque and maximum unloaded velocity. In the flexion direction, the average theoretical maximum torque was 172.7 N·m for the Young and 118.9 N·m for the Old, while the theoretical maximum velocity was 376.1 %/s for the Young and 303.5 %/s for the Old. In the extension direction, average theoretical maximum torque was 224.6 N·m for the Young and 150.5 N·m for the Old, while the theoretical maximum velocity was 385.6 %/s for the Young and 322.7 %/s for the Old. The predicted maximum and experimentally determined velocity values were within 5% of each other, indicating a reasonable prediction. In contrast, the predicted values for maximum torque exceeded the experimentally determined maximum

isometric torques by 60.5% for Young flexion, 42.6% for Old flexion, 105.5% for Young extension, and 100.4% for Old extension.

In contrast to the expectation that higher torque should be produced isometrically than when muscles are shortening, we found that maximum torques produced isometrically were sometimes lower than those produced at low velocities. Similar findings have also been reported in other studies (22,24). There are several possible explanations for this discrepancy. First, the dependence of maximum torque on leg position (25), deriving from the muscle length–tension relationship, could affect the isotonic data. Also, the position of the leg affects the load produced by the weight of the leg and Biodex arm, altering the actual load felt at the hip. Second, the low isometric torque may be due to decreased motivation or experience. There are relatively few natural situations where hip torque is produced against an immovable load as opposed to a dynamic contraction. Participants may therefore have given a less than true maximal effort in the isometric case. Third, it is possible that participants cocontracted antagonistic hip muscles in the isometric conditions. Cocontraction may have reduced the net torque, even though the effort level seemed maximal. Further data, perhaps incorporating electromyographic measurements, are necessary to test these possibilities.

A number of studies have previously found age-related leg strength decrements at other joints, particularly at the knee and ankle. A study of knee extension in young and older adult participants found a decrease of 26% in isometric strength and a 7% decline in maximum velocity (2). Age-related declines in calculated maximum force and maximum velocity of 30% and 15%, respectively, were found in a study examining the force–velocity relationship in a functional biking test (26). Among the causes of strength loss with aging include loss of muscle fibers, reduction of muscle cross-sectional area, and the reorganization of motoneurons controlling the muscle. On the other hand, decreased maximum muscle velocity is more directly caused by a change in muscle composition, as the percentage of fast muscle fibers falls with age (1). In the current study, the relative velocity decreased more quickly in the Old with

higher loads. A similar result was found in another study examining knee extensor torque developed at various isokinetic speeds, with a relatively larger decrease in torque in Old than in Young participants (27). In both cases, differences between young and old participants were more noticeable during high intensity tasks, whether either load or velocity is controlled. The decreased speed we observed at relatively modest loads may contribute to poorer step recovery responses exhibited by the Old versus the Young (12,28). Although maximum isometric hip flexion strength appears only weakly correlated with fall prevention under some conditions (29), the ability to produce power or high velocity about the hip may be important for step recovery. By understanding how each of these factors decline with age, and their relationships to each other, we may find a link between leg muscle power and performance of daily activities (30).

In activities of daily living, it is rarely relevant to separate the effects of muscular changes on purely maximum strength or maximum velocity. Every muscular contraction must overcome some load, such as body weight, to generate a movement. Force is undoubtedly necessary, but most contractions are not isometric. As the load or movement speed reaches a person's limit, age-related decreases in performance can constrain the ability to avoid falling. Assessments of leg strength and speed may prove useful as partial indicators of fall risk, or as target variables in a power training program. From a purely mechanical standpoint, the data reported here may eventually be used in conjunction with a model to investigate the relative importance of leg strength and speed for fall avoidance.

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An Appendix with tables detailing the actual values shown in Figures 2–7 is available upon request. Please contact the corresponding author to request these tables.

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