Age-related neuromuscular function during drop jumps

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Hoffrén M, Ishikawa M, Komi PV. Age-related neuromuscular function during drop jumps. J Appl Physiol 103: 1276–1283, 2007. First published August 9, 2007; doi:10.1152/japplphysiol.00430.2007.—Muscle- and movement-specific fascicle-tendon interaction affects the performance of the neuromuscular system. This interaction is unknown among elderly and consequently contributes to the lack of understanding the age-related problems on neuromuscular control. The present experiment studied the age specificity of fascicle-tendon interaction of the gastrocnemius medialis (GM) muscle in drop jump (DJ) exercises. Twelve young and thirteen elderly subjects performed maximal squat jumps and Djs with maximal rebound effort on a single apparatus. Ankle and knee joint angles, reaction force, and electromyography (EMG) from the soleus (Sol), GM, and tibialis anterior (TA) muscles were measured together with the GM fascicle length by ultrasonography. The results showed that the measured ankle joint stiffness (AJS) during the braking phase correlated positively with the rebound speed in both age groups and that both parameters were significantly lower in the elderly than in young subjects. In both groups, the AJS correlated positively with averaged EMG (aEMG) in Sol during the braking phase and was further associated with GM activation ($r = 0.68, P < 0.01$) and TA activation ($r = 0.75, P < 0.01$) in the elderly subjects. In addition, compared with the young subjects, the elderly subjects showed significantly lower GM aEMG in the braking phase and higher aEMG in the push-off phase, indicating less utilization of tendinous tissue (TT) elasticity. These different activation patterns are in line with the mechanical behavior of GM showing significantly less fascicle shortening and relative TT stretching in the braking phase in the elderly than in the young subjects. These results suggest that age-specific muscle activation patterns as well as mechanical behaviors exist during Djs.

stretch-shortening cycle; ultrasound; tendon

NORMAL LOCOMOTION INVOLVES use of stretch-shortening cycle (SSC) muscle action in which the active muscle is first stretched and subsequently shortened (see Ref. 23 for review). This definition applies to the entire muscle-tendon unit (MTU). However, the fascicle and tendon compartments inside MTU can behave differently in each functional phase of SSC (11, 14). This information of how muscle fascicles and tendons interact during human locomotion is very important for further understanding the muscle mechanics in real movement situations. For example, regulation of the fascicle length can play an important role in utilization of tendon elasticity during locomotion and can therefore influence the movement efficiency (11, 18).

Ultrasonographic scanning of muscle fascicles is currently a popular method to study the movement- and muscle-specific fascicle-tendon interaction, for example, in human walking, running, and jumping (34, 41). In addition to the action type-specific findings of these studies, it has been observed that there are also age-related differences in fascicle-tendon behavior during human walking (36). Higher compliance of tendon in elderly individuals may be the reason for the possible age-specific differences. In addition, the higher tendon compliance may explain the lower leg stiffness in elderly as estimated in countermovement jumps (35). However, both in walking and in countermovement jumps, the impact forces are relatively low, and the muscles demonstrate low activity during the braking phase of contact. Therefore, it remains unclear, how the fascicle-tendon interaction and consequently the tendon loading take place among elderly individuals at higher impact force conditions.

With aging humans, the fascicle length and pennation angle reportedly decrease (27, 39), and the tendon compliance increases (20, 29, 37). These changes may influence the force and power production not only in static but also in dynamic movements. Although it is not known in detail whether the muscle activation pattern in agonist muscles shows age-specific modifications, the measurements of antagonist coactivation have shown increased level of coactivation in elderly individuals (7, 15, 40). This increased coactivation may influence the joint stiffness, for example, in downward-stepping condition (17). On the other hand, high joint and/or leg stiffness in the braking phase has been suggested to be prerequisite for efficient SSC performance (3, 9, 12). Thus there is considerable need to explore whether there is age specificity in regulation of the fascicle-tendon interaction during SSC exercises. Such a knowledge can be helpful for planning and improving possible countermeasures for aging effects, for example, by building up more specific training programs for elderly individuals.

Consequently, the purpose of the present study was to explore the age specificity of fascicle-tendon interaction in drop jump (DJ) exercises. These exercises were designed so that both young and elderly subjects were exposed to similar impact loads followed by maximal rebound (push-off). Considering that muscle activation profiles for both agonist and antagonist muscles may show age-specific differences, the fascicle-tendon interaction was expected to demonstrate reduced rebound performance among elderly compared with young individuals in these controlled situations. Special focus was placed on the calf muscles function because the ankle joint has been shown to play an important role in leg stiffness adjustment (1, 10).

METHODS

 Subjects. Twelve young (5 men and 7 women; age 25.2 ± 2.5 yr, height 171.4 ± 7.4 cm, weight 66.8 ± 10.7 kg) and thirteen elderly
adults (5 men and 8 women; age 69.0 ± 3.8 yr, height 168.0 ± 6.7 cm, weight 67.8 ± 9.8 kg) participated the study as subjects. Both groups were physically active. The young subjects were sport science students, and they exercised 6.3 ± 3.2 h/week. The elderly subjects were recruited from a local senior gym, and they exercised 5.1 ± 1.8 h/week. These volumes of physical activity did not differ between the age groups. Before measurements, the subjects were given an informed consent of the procedures and risks associated with the study, and they gave their written consent to participate. Medical screening was performed for the elderly subjects. Exclusion criteria included coronary artery disease, neurological diseases, and current lower extremity and low back pain as well as previous injuries in leg joints. The recommendations contained in the Declaration of Helsinki were followed, and the study was approved by the local ethics committee.

Experimental procedure. The subjects performed the maximal squat jump (SJ) and DJs bilaterally on a sledge apparatus (19). In the DJs, the following dropping heights were chosen: 10 cm, 15 cm, and 20 cm above standing height (DJ10cm, DJ15cm and DJ20cm, respectively). These heights are low for the normal subjects (24), but for safety reasons the elderly subjects could not be dropped from higher heights. The jumps were performed in randomized order. Five accepted trials were required for averaging. Before the measurements, the subjects were asked to perform a 10-min warm-up on a bicycle ergometer and then to perform several DJs to determine the lowest position of the sled seat for each subject (knee angle 34.4 ± 8.2°; 0° full extension). In DJs, the subjects were instructed to jump with as little knee bending as possible, and this predetermined position was monitored and checked in each trial. The inclination of the sled was 18° from the horizontal position.

Data recordings. Reaction forces (Fz; perpendicular to the movement plane of the sled seat), sled displacement, velocity of the sled displacement and electromyogram (EMG) activity from the gastrocnemius medialis (GM), soleus (Sol), and tibialis anterior (TA) muscles in the right leg were stored simultaneously to a personal computer through an analog-to-digital converter (sampling rate 2 kHz; Power 1401, Cambridge Electronics Design). Bipolar miniature-size surface electrodes (diameter 6 mm, interelectrode distance 21 mm; Blue Sensor N-00-S/25, Medicotest, Olstykke, Denmark) were used for EMG recording (bandwidth 10 Hz to 1 kHz per 3 dB; model 16-2, EISA, Freiburg, Germany). Before electrode placement, the skin was shaved, abraded, and cleaned with alcohol to secure an interelectrode resistance value below 5 kΩ. The electrode placement followed the procedures used in our laboratory’s earlier experiments (see Ref. 41).

All jumps were video recorded with a high-speed video camera at 200 frames/s (Peak Performance) from the right side perpendicular to the line of motion. Reflective markers were placed on trochanter major, the center of rotation of the knee, lateral malleolus, heel, and fifth metatarsal head. These points were then digitized automatically and filtered with Butterworth fourth-order filter (cutoff frequency 8 Hz) using Motus software (Peak Performance) to calculate knee and ankle joint angles.

Longitudinal images of GM muscle of the right leg were recorded (young n = 12, elderly n = 12) during all movements using a B-mode ultrasonography (model SSD-5500, Aloka) for (details see Ref. 41) with 6-cm linear-array probe (scanning frequency of 7.5 MHz). The images were obtained at 50 images/s. The probe was fixed securely with a special support device made of polystyrene. The superficial and deep aponeuroses and GM fascicle were digitized and tracked from each image. GM fascicle length was defined as the length of the fascicle line between the superficial and deep aponeuroses, and pennation angle was defined as the angle of fascicle line and the deep aponeurosis.

An electronic pulse was used to synchronize the kinetic, kinematic, EMG and ultrasonographic data.

Analyses. The model of Grieve et al. (13) was used to calculate GM MTU length changes. MTU data were resampled at 50 Hz to match the time scale of the ultrasound data. The length of the GM tendinous tissue (TT; free tendon and aponeuroses) was calculated by subtracting the horizontal length part of the fascicle from the MTU length as follows (33):

\[ L_{TT} = L_{MTU} - L_{fa} \cdot \cos \alpha, \]

where \( L_{TT} \) is the TT length, \( L_{MTU} \) is the MTU length, \( L_{fa} \) is the fascicle length, and \( \alpha \) is the fascicle angle between fascicle line and the aponeurosis.

The ankle joint moment was estimated from the Fz, and kinematics similarly to Kawakami et al. (21). The quotient of change in ankle joint moment generated by a right leg (from contact to peak) divided by change in ankle joint angle (from contact to minimum) (31) was used as a value of ankle joint stiffness (AJS) during the braking phase. It must be noted that the peak ankle joint moment and the minimum ankle joint angle do not necessarily occur at the same time. Originally, we calculated the AJS in two ways: with minimum ankle joint angle and peak ankle joint moment and also with minimum ankle joint angle and corresponding moment. Because the results were similar, it was decided to use the peak ankle joint moment for AJS calculations.

EMG signals were first full-wave rectified and then low-pass filtered at 50 Hz. The filtered EMG signals were integrated and then averaged (aEMG) in the following three phases: preactivation, braking, and subsequent push-off phases. The preactivation phase was defined as the 100-ms period preceding the ground contact (25). The transition from the braking to the push-off phase was determined while the sled was at its lowest position. EMG activities during DJs were normalized to maximal SJ push-off phase aEMG. Force and EMG-data were resampled at 50 Hz to match the time scale of kinematics and ultrasound data.

TA muscle serves as an antagonist to plantar flexors during the contact phase of DJs. To obtain the TA activation during the braking phase more accurately, the braking phase was divided into two halves, and TA aEMGs were calculated separately for those two halves. After that, the activation relative to TA preactivation was defined (change in activation in relation to preactivation value). These calculations were done only for the two highest dropping conditions because the 10-cm dropping height was so low that it was initiated with greater dorsiflexion by some subjects and therefore higher TA preactivation.

Statistics. The results are presented as means ± SD. ANOVA for repeated measurements on two factors was used to test the main effects of dropping condition and age as well as the interactions on different parameters. When applicable, the ANOVA for repeated
Fig. 1. Averaged force-time and electromyograph (EMG)-time curves for the young and elderly subjects in different drop jump (DJ) conditions [dropping heights 10 cm, 15 cm, and 20 cm above standing height (DJ10cm, DJ15cm and DJ20cm, respectively)]. Fz, vertical ground reaction force; GM, gastrocnemius medialis; Sol, soleus; TA, tibialis anterior. Vertical lines denote the contact moment, the transition point from the braking to push-off phase, and the take-off moment. EMG is normalized to maximal squat jump (SJ) push-off phase average EMG.
measures on one factor and post hoc Bonferroni were used to determine the significant differences between dropping height conditions separately in young and elderly. Relationships between variables were investigated using Pearson’s product-moment correlation coefficient. The level of statistical significance was set at $P < 0.05$.

**RESULTS**

**Mechanical parameters.** Sledge take-off speed was used to determine the jumping performance. Take-off speed increased significantly with increasing dropping height in both age groups ($P < 0.01$; Table 1). As expected, the young subjects showed significantly higher values than the elderly subjects in all conditions: in SJ ($P < 0.001$) and in all three DJs ($P < 0.01$).

The elderly subjects had longer total contact time than the young subjects in all jumping conditions (SJ $P < 0.001$, DJs $P < 0.01$). Total contact time decreased with increasing dropping height in the young ($P < 0.05$) but not in the elderly subjects. Also, the duration of the braking phase decreased with increasing dropping height in the young ($P < 0.05$) but not in the elderly subjects. The push-off phase time decreased with increasing dropping height both in the young ($P < 0.01$) and in elderly ($P < 0.01$). The elderly had a significantly longer push-off phase than the young subjects ($P < 0.001$).

Although the absolute dropping heights were the same in both groups, the relative peak $F_z$ (per body weight) was lower in the elderly than in the young subjects ($P < 0.001$). Peak force increased from SJ to DJs ($P < 0.001$ in both groups) and with increasing dropping height (young $P < 0.01$, elderly $P < 0.05$).

**EMG activation.** The averaged EMG patterns for the young and elderly subjects in different DJ conditions is shown in Fig. 1. Clear preactivation of GM and Sol muscles was followed by the increasing activity in the braking phase and by decreasing activity toward the late push-off.

The young and elderly subjects showed different activation patterns. The young subjects activated their GM muscles more in the braking phase than the elderly subjects ($P < 0.05$). Thereafter, the elderly subjects had higher activation in the push-off phase in both GM and Sol muscles compared with the young subjects ($P < 0.05$). When EMG ratio of braking phase $aEMG$ divided by push-off phase $aEMG$ was calculated, the young subjects showed higher values in both muscles ($P < 0.05$; Fig. 2).

GM preactivity increased with increasing dropping height both in the young ($P < 0.05$) and in elderly subjects ($P < 0.05$). In addition, a significant age × dropping height interaction was observed in the push-off phase activities of GM and Sol muscles ($P < 0.05$ in both muscles): with increasing dropping height the GM and Sol push-off phase aEMGs increased in the elderly but decreased in the young subjects.

Activation of TA muscle, which serves as an antagonist to plantar flexors during the contact phase of DJs, decreased in the braking phase rapidly after the contact in the young subjects (Fig. 1). However, in the elderly subjects, the TA activation remained higher during the braking phase. Therefore, the elderly subjects had higher TA activation than the young subjects during the first half of the braking phase ($P < 0.05$). Also, when coactivation was calculated for both age groups, the elderly subjects showed higher values in TA/Sol activation during the whole braking phase ($P < 0.05$) (Fig. 2).

**AJS.** The elderly subjects had lower AJS during the braking phase of DJs than the young subjects ($P < 0.05$; Table 1). There was a positive correlation between AJS and jumping performance both in the young and elderly subjects (Table 2). In both age groups, the AJS correlated positively with Sol
braking phase aEMG and the relative TT stretch (TT/MTU stretch) and negatively with TA/Sol EMG during the braking phase. In the elderly subjects, there was also a positive correlation between GM braking phase EMG and AJS and negative correlation between TA/GM EMG and AJS, but those were not observed in the young subjects.

Mechanical behavior of GM. The braking phase was characterized by stretch of MTU and TT, whereas the fascicles shortened. Then, in the push-off phase, MTU as well as TT and fascicles shortened. The age comparison showed slight differences in this behavior (Fig. 3).

First, the elderly subjects had shorter GM fascicle length than the young subjects at the contact moment (5.4 ± 0.9 cm in young vs. 4.5 ± 0.7 cm in elderly; *P < 0.05). Total fascicle shortening during the contact phase was also less in the elderly than in young subjects (2.0 ± 0.4 cm in young vs. 1.4 ± 0.5 cm in elderly; †P < 0.01). This was due to less shortening of fascicle in braking phase in the elderly subjects (†P < 0.05; Fig. 4) because the shortening amplitude in push-off phase was similar between the groups (1.2 ± 0.4 cm in young vs. 0.9 ± 0.5 cm in elderly).

Second, the lengthening of MTU and TT in the braking phase increased with increasing dropping height both in the young (MTU ‡P < 0.001, TT ‡P < 0.01; Fig. 4) and in the elderly subjects (MTU ‡P < 0.001, TT ‡P < 0.01; Fig. 4). Although there was a trend for greater MTU stretch in the elderly compared with the young subjects (‡P = 0.07), the absolute stretching amplitudes of MTU and TT did not show significant differences between the age groups. However, when TT stretch was calculated in relation to MTU stretch (TT/MTU stretch), the elderly subjects showed lower values (‡P < 0.05; Fig. 4). TT/MTU stretch ratio also decreased with increasing dropping height in the elderly (‡P < 0.01) but not in the young subjects.

Finally, in the push-off phase, there were no significant differences in shortening amplitudes of either MTU, TT or fascicle between the age groups. However, with increasing dropping height, the recoil amplitude of TT increased (2.7 ± 1.0 cm in DJ10cm vs. 3.1 ± 1.1 cm in DJ20cm; †P < 0.05) and shortening of fascicle decreased (1.4 ± 0.4 cm in DJ10cm vs. 1.1 ± 0.4 cm in DJ20cm; †P < 0.01) in the young but not in the elderly subjects. Therefore, TT/MTU shortening ratio increased with increasing dropping height in the young (0.64 ± 0.10 in DJ10cm vs. 0.72 ± 0.12 in DJ20cm, †P < 0.05) but not in the elderly subjects.

**DISCUSSION**

As expected, the results demonstrated that the elderly had clearly lower performance than the young subjects, as measured by the take-off velocity. Interestingly the elderly had also lower AJS compared with the young subjects. These two parameters were also interrelated, and the age groups showed different activation patterns on the sledge DJs. However, both groups showed similar peak EMG activation levels during the braking phase of DJ relative to SJ. The results therefore suggest that the elderly subjects utilize tendon elasticity less...
efficiently than their younger counterparts because of the age specificity in activation patterns.

In order for the SSC exercise to be efficient, the high joint stiffness in the braking phase is needed (16, 43). That can be achieved by high activation of agonist muscles in the preactivation and early braking phases (3, 9, 43). In the present study, the DJ performance in the young subjects resembled the more efficient SSC exercise than in the elderly subjects: they had higher AJF (Table 1) and higher GM activation in the braking phase (Fig. 1) than the elderly subjects and thus better jumping performance (Table 1). This higher activation in the braking phase affects also the mechanical behavior of the muscle because the fascicle shortened more in the young subjects in the braking phase, and therefore they had higher TT/MTU stretch ratio than the elderly subjects (Fig. 4).

The AJF correlated positively with jumping performance also in elderly (Table 2). This indicates that those elderly subjects who had higher agonist activation in the braking phase and thus higher AJF jumped better. In general, however, the elderly subjects activated their muscles less in the braking phase than the young subjects and thereafter had more activation in the following push-off phase (Fig. 1). According to previous studies (2, 3, 5), this activation pattern in elderly individuals reflects decreased efficiency to utilize the stored negative work. Interestingly, the activation pattern of the elderly subjects in the present study resembles that of young individuals after excessive SSC exercises (marathon running and DJs) (26, 32). Although the mechanisms in these situations can be totally different, it may be suggested that in both situations (in fatigued marathon runners and in elderly individuals) the impact loads are not sufficiently tolerable. This comparison suggests, however, that there may be room for the proper training to possibly modify the activation pattern and/or joint stiffness among elderly individuals so that they would resemble closer to those of young individuals.

In addition to differences in agonist activation, the elderly showed also greater coactivation of TA muscle during the braking phase of DJs than the young subjects (Fig. 2). High coactivation is reportedly associated with increased joint stiffness in stabilizing actions (4, 42). However, in SSC exercise, like DJ in the present study, it is likely that increased antagonist coactivation makes the ankle joint more compliant in the braking phase (Table 2). Although it is not easy to understand why elderly had higher coactivation, it may be related to the strategy to reduce joint stiffness and lower the impact loads during the braking phase. Even if this were true, it still remains open whether this happens purposely or unconsciously.

Contrary to many animal experiments (see Ref. 22 for review), the human studies have suggested that tendon stiffness may decrease with aging (20, 29, 37). Although the stiffness was not calculated in the present study, its decrease would increase the tendon strain for a given load and therefore could be advantageous in utilization of elastic energy in SSC exercises (9, 28, 30). However, the present study suggests that elderly individuals utilize tendon elasticity less efficiently than young individuals. This is likely to be due to the observed
lower muscle activation in the braking phase among elderly individuals and consequently their less ability to stiffen the fascicles and ankle joints resulting in lower TT/MTU stretch ratio. In line with this suggestion, TT/MTU stretch ratio and jumping performance intercorrelated positively in both age groups (Fig. 5). This would mean that those elderly subjects who could shorten the fascicle more in the braking phase and thus had higher TT/MTU stretch ratio jumped better. A more compliant tendon could also increase the TT/MTU stretch ratio under high agonist activation, that would allow the adequate joint stiffness.

Because we were only examining calf muscles in the present study we do not know whether similar findings could be observed, for example, for thigh muscles. It can also be argued whether the present study design, that uses the same absolute dropping heights (stretch levels), is appropriate when measuring two age groups with obviously different neuromuscular characteristics. It is generally known that the optimal dropping height varies between the individuals and also between the age groups (6). The highest dropping height used was closer to the optimal dropping height for elderly subjects and was very much in the ascending phase in the dropping height vs. rebound height curve for young subjects. However, to use relatively similar stretch levels, the maximum stretch level have to be measured first, which is challenging and certainly risky, when measuring elderly subjects. On the other hand, we believe that it is not totally wrong to use the same stretch levels because the requirements and challenges that young and elderly individuals have to encounter in natural locomotion and in activities of daily living are also similar in absolute level. To confirm the results of the present study, it would be beneficial to study also the relatively similar stretch levels in young and elderly subjects while staying still in the submaximal level.

An important question that remains, however, is whether the present results can be explained 1) by the influence of reduced physical activity with increasing age and/or 2) by the aging process itself. With regard to physical activity level, the both age groups had similar habitual physical activity level in hours per week. Consequently the major cause for differences may be the aging process itself. On the other hand, elderly do not usually utilize high-intensity loads in daily activities (8, 38), and the present study made no effort to quantify the possible differences in exercise-intensity levels. Thus to separate the roles of changes in physical activity and the aging process itself may not be so simple.

Finally, the present study gives an impression that elderly individuals perform DJ in a way that it resembles damping in a landing type of movement followed by the increased activation in the less economical push-off phase. Consequently, the resulting lower AJS in the elderly subjects in the braking phase is characterized by lower agonist activation and higher antagonist coactivation. Differences in muscle activation also affect the mechanical behavior of the GM muscle, resulting in lower TT/MTU stretch ratio in the elderly subjects. Therefore, this study suggests that elderly individuals utilize tendon elasticity less efficiently than young individuals.

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