Functional relevance of eccentric strength maintenance with age during walking

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Chapter 6

General discussion

The aim of this thesis was to determine the functional relevance of the age-related relative maintenance of maximal voluntary knee extensor eccentric strength to walking speed and underlying joint mechanics at prescribed walking speeds. We hypothesized that i) age-related differences in joint work during walking are attenuated during phases of eccentric force generation relative to phases of concentric force generation, and that ii) maximal voluntary eccentric knee extensor strength correlates positively with level and decline walking speed and with knee extensor negative work during decline walking in older adults.

6.1 Main findings

In chapter 2, we observed that the extent to which maximal knee extensor eccentric strength was relatively maintained with age did not differ between older males and females. Also, maximal knee extensor eccentric strength predicted walking speeds less accurately in younger and older adults compared to concentric strength, which we interpret as concentric strength being more of a limiting factor of walking speed than eccentric strength since eccentric strength is maintained with age. In chapter 3, we did not also find an age-related maintenance of eccentric strength for the ankle plantarflexors. Additionally, during walking positive joint work was redistributed with age whereas negative joint work was not, suggesting that eccentric strength maintenance is also apparent during common multi-joint movements. Moreover, the positive correlation between the knee extensors' eccentric strength and their negative work in elderly walking supports our idea that knee extensor negative work is preserved with age because this muscle group operates well below its maximum available capacity, partly due to the maintenance of eccentric strength. In chapter 4, we demonstrated that the preserved knee extensor mechanics during negative work in elderly walking is functionally relevant. Specifically, age did not affect the inter-joint moment strategy to control knee flexion movement during weight acceptance, with the knee extensor moment as the main decelerator of knee flexion. In chapter 5, we found no evidence suggesting an age-related increase in muscle activation per unit increase in net joint work, i.e., electromechanical cost, during walking nor that this cost reinforces the reconfiguration of joint work with age. Also, the ~15% reduction in plantarflexor muscle activation during push-off with age suggests that older adults underutilize their plantarflexor torque generation capacity when walking. Altogether, we conclude that the age-related maintenance of eccentric knee extensor strength is functionally relevant in healthy older adults. The findings are integrated and discussed in more detail below.

6.2 Age-related muscle mechanics

6.2.1 Age-related maintenance of eccentric muscle strength during single-joint movements

Like previous studies, we used conventional isokinetic dynamometry to quantify the maintenance of eccentric strength. Once the subject is fully accustomed to the task, isokinetic dynamometry is a valid and reliable method to determine maximal voluntary muscle torques under highly controlled conditions (i.e., fixed body positioning, joint excursion, angular velocity)[1].

In line with previous literature[2–5], the maintenance of eccentric knee extensor strength was evident at a range of isokinetic velocities (i.e., 60 to 120 °/s, chapters 2-3). In both younger and older adults, maximal eccentric torque plateaued whereas maximal concentric torque decreased with increased angular velocity. A minimal variation in eccentric force generation with contraction velocity is partly due to the viscoelastic properties of muscle during active stretch[6], which counteracts the reduction in muscle torque due to a decrease in the number of cross-bridge attachments with increased velocity[7]. In addition, older compared with younger adults showed a greater reduction in knee extensor torque with increased shortening velocity (i.e., from 0 °/s to 120 °/s) (chapter 3), which supports the age-related impairment in the rate of concentric torque development[8]. Based on these results, one may prescribe resistance training for older adults that emphasizes concentric muscle action over isometric or eccentric muscle action.

Expanding our current understanding of muscle weakness with age according to sex and muscle group would assist in designing interventions that could more specifically counteract such functional impairments. Previous literature seems to suggest an accentuated maintenance of eccentric strength in older females versus males[2,9,10], although we as well as others[4] observed no such sex effect for the knee extensors (chapter 2). We note that the present population sample was relatively small, which may have been especially problematic for the elderly group as the between-subject variability of muscle strength increases with age, possibly due to a larger variation in impaired motor function among older adults[11]. We suspect that any sex effect on the magnitude of eccentric knee extensor strength maintenance is likely modest at most.

In partial agreement with the single study that examined whether the age-related maintenance of eccentric strength is also evident for the ankle plantarflexors[12], we observed no such maintenance (chapter 3). Porter et al. (1997) did observe eccentric strength maintenance in an upright stance testing protocol but not in a supine position. Although the supine trials were conducted in fewer participants, which lowered the statistical power, the standing trials were influenced by the participants' weight shift onto the tested leg. Our participants sat with their knee slightly flexed (i.e., 30°) to minimize the additional force participants tend to produce by pushing from their hip while replicating the knee angle during push-off when walking. However, regardless of the positioning, participants typically find movement towards (e.g., plantarflexion) versus against gravity more difficult to perform on a dynamometer[1]. We recommend future studies to explore the suitability of demanding tasks that are more dynamic but controllable, such as landing from or jumping on an elevated platform, to determine maximal voluntary plantarflexor torques and the maintenance of eccentric strength with age.

6.2.2 Age-related maintenance of eccentric muscle strength during multi-joint movements

Although the measures of maximal voluntary muscle strength during single-joint movements performed on an isokinetic dynamometer are valid and relevant, these examinations are performed in an unfavorable ecological setting. To illustrate, natural events such as dynamic inter-joint coordination[13], segmental energy flows[14], and stretch-shortening muscle behavior[15] affect muscle function and are evident during walking but absent during dynamometry. Not to mention that during dynamometry the participant is in a contrived body position and the examination of maximal eccentric strength can be experienced as uncomfortable and unnatural. Therefore, for the first time, we also examined (chapters 3 and 5) and observed (chapter 3) the maintenance of eccentric strength during common multi-joint movements. That is, relative to younger adults, older adults redistributed positive joint work (i.e., concentric muscle function) during level and incline walking, but maintained the distribution of negative joint work (i.e., eccentric muscle function) during level and decline walking. This age-related reconfiguration of joint work supports our first hypothesis and is governed in part by differences in muscle (i.e., the muscle-tendon units) action and their related maximum force capacity, which is lower during muscle shortening vs. lengthening - an effect magnified with age (chapter 3). Specifically, whereas the ankle plantarflexors shorten when performing positive work associated with a ~30% reduction in concentric strength with age, the knee extensors lengthen when performing negative work associated with a ~15% reduction in eccentric strength with age. In addition, older vs. young adults showed a lower plantarflexor muscle activation during the push-off phase (chapter 5), in line with other studies[16,17]. Collectively, we argue that older vs. younger adults performed less plantarflexor positive work because they underutilized (i.e., reduced muscle activation) the maximum capacity of this muscle group. Had this reduction not occurred, the plantarflexors would have operated at their maximum capacity due to their weakness. On the other hand, knee extensor negative work was maintained with age likely because this muscle group operated well below their maximum capacity, even in older adults during decline walking. One implication of the present findings is that age-related changes to lower limb joint mechanics during walking are likely to occur during phases of positive work before phases of negative work.

In our final experiment (chapter 5), older vs. younger adults performed almost 20% less negative knee extensor work during walking, which seems to contradict the age-related maintenance of eccentric strength during walking (chapter 3). However, we suggest that factors other than muscle strength explain this contrasting finding. First, the older adults' knee extensors in chapters 3 and 5 likely operated at comparable relative efforts, because their lower limb muscle function (based on the SPPB score) were comparable as was the physical task demand. Second, other physiological, psychological, and environmental factors also affect the joint mechanics of walking but were not measured in this thesis[18–20]. For example, the simple presence of handrails or wearing a safety harness, as in chapter 3 but not in 5, might have a psychological effect on safety precautions taken, like a maintained (chapter 3) or reduced (chapter 5) step length with age. Such precaution may be especially evident for decline walking in which instability is high and the consequences of falling severe[13,21]. Indeed, the lower knee extensor negative work with age decreased to 12% after accounting for differences in step length (chapter 5).

The age-related redistribution of positive joint work during walking (chapters 3 and 5) is a robust phenomenon[22–24] and its underlying mechanism is likely multifactorial[25–27]. However, this mechanism may not include the amount of energy absorbed preceding energy generation, as the age-related shift in positive work but not in negative work suggests the absence of a correlation between lengthening and shortening muscle function (chapter 3). Yet, the ankle plantarflexors partly re-use energy absorbed by the Achilles tendon during push-off[15]. Thus, perhaps age adversely affects eccentric-concentric coupling, possibly through the reduction in Achilles tendon stiffness with age[28]. To illustrate, muscle fascicle force would stretch a less stiff vs. stiff tendon more and as a result the muscle fascicles operate at shorter lengths that may be less optimal for generating force[29]. Future studies could examine whether Achilles tendon stiffness correlates with the fascicle-tendon interaction during muscle lengthening and shortening when walking using in vivo ultrasound. Also, we found no evidence to suggest that the electromechanical cost (work/agonist activation) reinforces the age-related reconfiguration of joint work (chapter 5). Specifically, we observed age-related differences in knee extensor negative work and plantarflexor positive work, while at the same time the relationship between these phases of work and their underlying agonist muscle activation was unaffected by age. As various other factors could mediate the age-related redistribution of joint work[27], a more systematic approach is required to determine the relative importance of each factor on this robust age-related phenomenon.

6.3 Functional relevance of eccentric strength maintenance with age

We suggest that the maintenance of knee extensor eccentric strength partly underlies the preservation of knee extensor negative work during the weight acceptance phase of decline walking, based on the positive correlation found between the two variables in older adults (chapter 3). In chapter 4, we demonstrated that this preserved knee extensor eccentric function during walking is functionally relevant by quantifying the knee moment effect on knee flexion deceleration, along with the effects of the hip and ankle moment. Knee flexion deceleration likely helps to decelerate the center of mass in order to prevent limb collapse[14]. What we observed is that the inter-joint moment strategy to decelerate knee flexion was preserved with age during level and decline walking, with the knee extensor moment as the main decelerator of knee flexion in decline walking. These quantitative results support the previous qualitative inferences made from inverse dynamics and surface EMG results[30,31]. More importantly, the present findings suggest that eccentric strength maintenance with age is important to preserve the joint moment strategy that controls knee flexion under different biomechanical demands, including a hazardous task such as decline walking[21,32].

Older adults with greater vs. lesser knee extensor eccentric strength perform more knee extensor negative work during decline walking (chapter 3) but do not necessarily walk faster (chapter 2), not even during tasks biased towards eccentric muscle contractions, i.e., stair and ramp descent. Specifically, maximal knee extensor eccentric and concentric strength were both unrelated to habitual walking speed at any surface inclination (descent, level, ascent). In addition, contrary to concentric strength, eccentric strength was a weak predictor of maximal walking speed on an incline (R^2: 39 vs. 9%) and decline (R^2: 36 vs. 20%). From these results, one may infer that knee extensor negative work, and ultimately knee extensor eccentric strength, does not affect walking speed. However, we favor the idea that the relative demand on the knee extensors was insufficient to discriminate the fit and healthy older participants on their strength, except for the maximal, non-level walking speed condition. This argument especially applies to eccentric strength, as its maintenance with age would lead to an even lower relative demand during eccentric vs. concentric force generation when walking. Indeed, the knee extensors operate at ~30% and ~60% of their maximum available capacity during habitual level walking[33,34] and stair descent[35,36], respectively. Thus, we argue that knee extensor concentric strength is a limiting factor of walking speed in healthy older adults whereas eccentric strength is not, because eccentric strength is relatively well-maintained with age. Therefore, eccentric strength maintenance is also functionally relevant. This idea should be further examined in older adults with less eccentric knee extensor strength than the older population sample in this thesis.

Although the specificity hypothesis between knee extensor strength and non-level walking speed is conceptually well founded based on muscle mechanics[37,38], muscle activation[39], and metabolic cost[40], we observed no such specificity (chapter 2). Concentric strength predicted incline (i.e., concentric-biased) and decline (i.e., eccentric-biased) walking at maximal speed equally well, and even predicted decline walking better than eccentric strength. These results imply that maximal knee extensor concentric strength would predict future mobility disability more accurately than eccentric strength. Altogether, the present findings on the functional relevance of eccentric strength maintenance with age partially agree with our second hypothesis.

6.4 Limitations and future recommendations

This thesis has several limitations. First, we measured maximal voluntary muscle torques of younger and older adults. There is, however, an increasing emphasis to use maximal voluntary muscle power because muscle power generally predicts functional performance more strongly than muscle torque[41–43]. Second, using dynamometry to determine maximal muscle strength in order to predict walking performance may have been suboptimal as compared to extracting muscle strength from demanding tasks that are functionally more related to walking (see the beginning of section 6.2.2). A third limitation is that some findings are explained through the concept of relative effort, although actual relative muscle efforts were not computed because our method used to determine joint torques differed for dynamometry and walking, which can lead to physiologically implausible (i.e., >100%) estimates[33,44]. Fourth, this thesis focused on the knee extensors to study the relationship between eccentric strength and walking performance. There is, however, evidence suggesting that ankle plantarflexor eccentric strength is the limiting factor in decline walking speed, at least during stair descent[36,45,46]. Lastly, the present findings are limited to fit and healthy elderly.

Based on these limitations, we encourage future studies to include measures of maximal muscle power extracted from demanding, multi-joint movements in order to predict walking performance. Future studies are also recommended to examine whether maximal ankle plantarflexor and knee extensor negative powers associate with walking speed in both strong and weaker older adults. These studies should include measures of other physiological and psychological factors that are known to affect walking performance (see section 6.2.2) to be able to better appreciate the relative importance of eccentric muscle function during walking.

6.5 Conclusions

This thesis offers insights into the functional relevance of eccentric knee extensor strength maintenance on walking speed and underlying joint mechanics in healthy older adults. During walking, positive joint work was redistributed with age whereas negative joint work was not, suggesting that eccentric strength maintenance is also apparent in multi-joint movements besides single-joint movements. Eccentric strength maintenance partly underlies the preservation of knee extensor negative work in elderly walking, which was found to be functionally relevant as the knee extensors were the main decelerators of knee flexion during weight acceptance irrespective of age. Nevertheless, compared to concentric strength, knee extensor eccentric strength poorly predicted walking speeds, even during eccentric-biased tasks. We suggest that knee extensor concentric strength is a limiting factor in healthy elderly gait whereas eccentric strength is not, because eccentric strength is relatively well-maintained. We recommend future studies to further examine this idea in older adults weaker than the older population sample in this thesis. All in all, we conclude that the age-related maintenance of eccentric knee extensor strength is functionally relevant in healthy older adults. As eccentric strength maintenance seems to arise naturally with aging, we recommend to emphasize concentric muscle action over eccentric muscle action in resistance training for healthy older adults.

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