Decline in gait propulsion in older adults over age decades

Reference:
Sloot Lizeth H., Malheiros Susanne, Truijen Steven, Saeys Wim, Mombaur Katja, Hallemans Ann, Van Criekinge Tamaya.- Decline in gait propulsion in older adults over age decades
Gait and posture - ISSN 1879-2219 - 90(2021), p. 475-482
Full text (Publisher's DOI): https://doi.org/10.1016/J.GAITPOST.2021.09.166
To cite this reference: https://hdl.handle.net/10067/1825360151162165141

Decline in gait propulsion in older adults over age decades

Abstract

Background: Despite strong evidence that walking speed and forward propulsion decline with increasing age, their relationship is still poorly understood. While changes in the ankle and hip mechanics have been described, few studies have reported the effect of ageing on the whole leg's contribution to propulsion.

Research question: The aim of this study was to investigate age-related changes in the work performed by the leg on the center of mass (COM) push-off power during walking in adults aged 20 to 86 years-Specifically, we evaluated how deterioration in COM push-off power relates to changes in ankle and hip kinetics as well as age and walking speed.

Methods: Motion, ground reaction forces and gastrocnemius muscle activity were recorded in 138 adults during overground walking at self-selected speed. Age-related differences in variables between decades were analyzed with an ANOVA, while the relation between COM push-off power and joint kinetic variables, as well as walking speed and biological age, was evaluated using correlations and multiple regression analysis.

Results: From the age of 70 years and onwards, COM push-off power was significantly decreased. The decline in COM push-off power was mostly explained by a decline in average ankle push-off power (72%), and to a lesser extent by peak hip extension moment (3%). There was no re-distribution of ankle-to-hip push-off power. The decline in COM push-off power seemed more related to walking speed (explaining 54% of the variance) than biological age (only 4%).

Significance:
Findings indicate that age-related decline in COM push-off power in able-bodied adults starts from the age of 70 years, which is before changes have been found in kinematics, but still later than generally presumed. This decrease in push-off power was more related to walking speed than biological age, which emphasizes the need to better understand the reason for speed decline in older adults.

Keywords: Ageing; Propulsion; Walking; Center of Mass; Joint Kinetics

Highlights

- Decline in propulsion was examined in persons from 20 to 89 years of age
- COM push-off power declined from 70 years onward, before kinematics changed
- Changes in ankle push-off power primarily explained the decline in COM push-off power
- Reduced ankle push-off power was not compensated by increased hip power
- Decreased COM push-off power was more related to walking speed than biological age

Introduction

To be able to walk is a prerequisite to perform daily activities and is therefore indirectly related to the quality of life.[1] Ageing is associated with a loss in ambulatory abilities resulting from a range of factors, including decreased muscle strength, declined energy efficiency and difficulties with motor control due to alterations in the central and peripheral nervous system.[2,3] This loss has been shown to lead to an increased incidence of falls in older adults[3,4], which in turn is the primary cause of traumatic injuries in adults over the age of 65 years. As the majority of fall incidents in community-dwelling older adults occur during walking[5], older adults often walk more slowly to reduce this fall risk. As such, walking speed is a relevant screening tool to detect fall risk and decline in general health.[6,7] As a lower walking speed has been almost linearly related to reductions in propulsion (i.e. forward movement of the body) in healthy young adults, it is no surprise that the forward propulsion has been linked to gait stability and falling.[8]

A decrease in forward propulsion has often been reported for older adults using different metrics, particularly a reduction in ankle push-off power and a compensatory increase in hip power.[9-13,] Our understanding of the relative contribution of these individual joints can be enlarged by looking at the work induced on the center-of-mass (COM) by each limb to support forward propulsion of the whole body. Particularly during the double support phase, when the body weight must be transferred between the legs, the COM power represents the contribution of the generated push-off power by the trailing limb and the absorbed collision power by the leading limb.[14,15] While this metric is straightforward to calculate using the COM velocity and ground reaction forces (instead of a summation of all internal joint powers),[15] and has been shown to provide insight into the metabolic cost of human walking,[14] COM push-off power has only been investigated in older adults by Hernandez et al.[12] Their results, however, might yield limited representativeness for slow-walking older adults, as their older group walked at a relatively high preferred speed. Thus, evaluation of COM push-off power in a large cohort of adults could summarize age-related changes in overall generated and absorbed energy during walking and underlying changes in the contribution of individual joints.

The effect of ageing on forward propulsion and walking speed is still ambiguous. On the one hand, a reduction in walking speed is said to result from age-related neuromuscular limitations, such as muscle weakness and soft tissue degeneration, that limit ankle push-off power generation. On the other hand, walking slowly is suggested to be a conscious preventive strategy, for instance out of fear of falling, that requires less ankle push-off power. The latter view seems supported by the observation that older adults can walk faster upon request, although they might employ compensatory hip strategies to accomplish this. The different age ranges of older participants included in various studies further complicate disentangling the interaction between propulsion and speed, as it is unknown from which age changes generally start to occur. Moreover, comparison between an older and younger group does not provide insight into any progressive change in forward propulsion with ageing. Thus, age-related changes in propulsion mechanisms should be examined in a large group of older adults spanning from middle-aged to very old (beyond 70 years[16]), while also taking walking speed into account.

This study aims to investigate the deterioration of forward propulsion, or COM push-off power, and underlying joint mechanics with ageing across the adult life span. Such insight enables us to identify the most important contributors to a decline in COM push-off power and thus aids in determining more targeted fall risk prevention exercises for the future. Specifically, we expected age-related changes in COM push-off power to 1) occur around 80 years of age as reported for sagittal kinematic changes; 2) have an underlying redistribution from reduced ankle push-off power and GAS muscle activity to increased hip push-off power; and 3) relate more to walking speed than biological age.

Methods

Participants

A total of 138 adults (21-86 years) were assigned to an age category based on decades as those are intuitive to understand, ranging from decade 3 (20-29 years) to decade 9 (80-89 years), with 20-25 participants per decade (Table 1). Participants were excluded if they were not between 20 and 90 years old, had self-reported visual impairments, any known neurological or orthopaedic disorder (i.e. undiagnosed hip/knee osteoarthritis or spinal disorders), an antalgic gait pattern or abnormal mobility in the lower limbs that could influence motor performance and balance, based on visual inspection and interview by a trained physical therapist. Written informed consent was provided by all participants. The study was approved by the ethical committee of Antwerp University (B300201316328).

Insert Table 1: Participant characteristics per decade

Protocol

Participants were instructed to walk barefooted at a comfortable speed over a 12m overground walkway (Table 1).[17] Ground reaction forces (1000Hz, AMTI OR6-7 and AccuGait, AMTI, Watertown, USA) and motion capture data (100Hz, Vicon T10, Vicon Motion Systems Ltd., Oxford, UK), following the Plug-In-Gait marker model,[17,18] were collected. Gastrocnemius Lateralis (GAS) muscle activity was recorded with a wireless surface electromyography (EMG) system (1080Hz, Aurion Zerowire, Cometa, Rome, Italy) in a selection of the participants (Table 1) as published previously.[17]

Data processing

Events of foot strike and foot off were automatically determined using Vicon Nexus software based on foot marker and force plate (threshold 20N) data and visually checked. Trials with full and single-leg placement – whether left or right – on a force plate were analysed further, resulting in 2 to 9 strides per participant and a similar average between decades (Table 1).

Force and marker data were filtered with a 4^{th}-order bi-directional 10Hz low-pass Butterworth filter. Joint angles, moments and powers as well as center of mass (COM) position were modelled using the Plug-In-Gait model [17,18] (Vicon Nexus Software 1.8.5 and 2.10.3). To discriminate between the positive work performed by the trailing leg (push-off) and the negative work by the leading leg (breaking) during double support phase, we calculated the work induced on the COM by each limb (referred to as “COM power” from here on), as the dot product of the COM velocity vector and the individual limb’s ground reaction force vector (the individual limbs method).[14,19] EMG signals were band-pass filtered (10-300Hz, 2^{nd}-order bi-directional Butterworth filter), rectified, smoothed using a 50 msec moving average window, and normalized to the mean amplitude over the average gait cycle per leg.[17] EMG signals were visually checked but no strides with movement artefacts were found. All data were time-normalized to the gait cycle.

Statistics

The definition and normalization of the different variables can be found in Supplementary Table 1. Variables were calculated using custom code in Matlab (v2019a, Mathworks). All single-stride values were visually screened for outliers and averaged per participant. Statistical analyses were performed in SPSS (ANOVA, IBM Statistics) and Matlab (regressions and correlations). The level of significance was set at 0.05.

To evaluate how forward propulsion changed with ageing, we defined three sub-questions. First, we examined whether forward propulsion increased or decreased with increasing decade, using an ANOVA analysis with a first-order polynomial contrast. The primary variable was COM push-off power, defined as the average generated COM power over the push-off phase from zero-crossing of the anterior-posterior ground reaction force (GRF) until toe-off. As secondary variables, we examined peak push-off force (GRFp), as well as changes in COM power during the other phases of gait, including the average, absorbed power during the collision (initial contact) phase, generated power during the rebound (first half of first single-limb stance) and absorbed power during the pre-tension (second half of single-limb stance) phase (Suppl Table 1).[11,15] The assumption of normal distribution was checked using the Kolmogorov-Smirnov test and Q-Q plots; homogeneity of variance using Levene's test. When significant, further planned contrast testing compared each 'older' decade (Dec5 to Dec9) against the young (average of Dec3 and Dec4: 20-39 years) to establish from which decade changes became significant. In addition, we examined the relation between COM push-off power and the secondary variables using Pearson correlations, with $r>0.60$ considered strong, $0.41>r<0.60$ moderate and $0.21>r<0.40$ weak, and r^2 describing the explained proportion in variance of the independent variable.[20]

Second, we examined how mechanics at the legs' joint level underlying forward propulsion changed with age, using the same ANOVA approach, and how these changes related to changes in COM push-off power using Pearson correlations. The primary variables were peak ankle and hip moment and power during the push-off phase (Suppl Table 1). Secondary variables included ankle and hip average power during the push-off phase and their ratio, as well as the average GAS activity related to push-off. In addition, we examined kinematic parameters considered relevant for propulsion, including the peak trailing limb angle (TLA) during push-off as well as peak ankle, knee and hip extension angles.[21] In addition, a forward stepwise multiple regression analysis ($P_{IN}(0.05)$, $P_{OUT}(0.10)$) was performed to identify which of the joint kinetic variables explained the variance in COM push-off power ($r^2_{adjusted}$). Only variables with an effect of age and correlation to COM push-off power (r>0.40; i.e., ankle and hip peak moment and power as well as average ankle push-off power) were included in the regression analysis.

Third, we examined if forward propulsion was more related to speed or age. COM push-off power, GRFp, and age-affected joint kinetic variables from the second aim were correlated with both normalized walking speed and biological age using Pearson correlations. In addition, a regression analysis was performed, as described previously, to identify to what extend speed and age explained the variance in COM push-off power.

Lastly, to provide context to the changes in forward propulsion, the effect of age on the general walking pattern as described by spatio-temporal parameters was examined using the same ANOVA analysis. The normalized variables (Suppl Table 1) included walking speed, step length, stride time, stance phase (as a proxy for push-off duration) and step width (as a proxy for gait stability).[22]

Results

The overall gait pattern changed with age. Preferred walking speed reduced with age (p<0.001), with a 9% and 13% reduction for Dec8 (70-79 years) and Dec9 (80–89 years) compared to young (20-39 years old; Table 2; Suppl Table 2). As there was no ageing effect on stride time (p=0.40), the change in walking speed seemed due to an age-related reduction in stride length (p<0.001; -6% Dec8 and -10% Dec9). In addition, stance phase increased with age (p=0.001; 2% for both Dec8 and Dec9), while step width reduced (p<0.001; -6% Dec8 and -10% Dec9).

Change in forward propulsion with ageing

COM push-off power reduced with increasing age from 70 years and older (p<0.001), with a 26% reduction in Dec8 and 30% in Dec9 compared to young (Fig 1, Table 2 and Suppl Table 2 for outcomes per decade). The decrease in GRFp (p<0.001; -22% Dec8 and -25% Dec9; Fig 2) correlated strongly with the decrease in COM push-off power (r=0.87, r^2=0.76; Table 2). Ageing also changed COM power during other gait phases: older adults absorbed less power during early stance collision (p<0.001; -36% Dec8 and -48% Dec9) and pre-tension (p=0.005; -20% Dec8 and -21% Dec9), both of which correlated strongly to the reduction in COM push-off power ($r=0.61$, $r^2=0.38$; $r=-0.73$, $r^2=0.53$ respectively). No ageing effects were found for the generated COM power during the rebound phase ($p=0.96$).

Insert Figure 1.

Insert Figure 2.

Change in underlying leg joint mechanics

Both ankle and hip kinetics reduced with increasing age from 70 years and older (Fig 3, Table 2, Suppl Table 2). Reductions were found for ankle peak moment ($p=0.009$; -10% both Dec8 and Dec9), peak power ($p=0.001$; -21% Dec8, -19% Dec9) and average push-off power ($p=0.001$; -22% Dec8, -18% Dec9) as well as hip peak moment ($p=0.009$; -23% Dec9) and peak power ($p=0.009$; -18% Dec8, -16% Dec9). Average hip push-off power ($p=0.10$), average knee absorbed power ($p=0.17$) as well as ankle and hip push-off power ratio ($p=0.44$) were not affected by age.

In line with the reduction in ankle push-off power, GAS muscle activity reduced with increasing age ($p=0.02$; -12% Dec9; Fig 2). Posture also changed during push-off: peak ankle plantarflexion ($p<0.001$; -59% Dec9) and hip extension ($p<0.05$; -56%; Dec9) reduced with age, with a trend of reduced knee extension ($p=0.07$) but no change in maximal TLA ($p=0.36$).

Insert Figure 3

All age-affected joint kinetic variables showed a moderate to strong correlation with the decline in COM push-off power ($r_{abs}=0.51$-0.86, $r^2=0.26$-0.75; Table 2), with the strongest correlation for average ankle push-off power. The reduction in GAS muscle activity did not correlate with COM push-off power ($r=0.12$, $p=0.22$, $r^2=0.01$). The age-affected kinematic variables only showed fair correlations ($r_{abs}=0.24$-0.31, $r^2=0.06$-0.10). Regression analysis indicated that the variability in COM push-off power was mostly explained by average ankle push-off power (75%), followed by peak hip extension moment (2.5%; Suppl Table 3).

Change in forward propulsion: age versus speed

The decline in COM push-off power correlated strongly with normalized walking speed (r=0.74, r^2=0.55) and moderately with age (r=-0.41, r^2=0.179; Table 2). Similarly, the other age-affected ~~push-off~~ kinetic variables showed strong correlations to normalized walking speed (r_{abs}=0.61-0.81, r^2=0.37-0.66), except for peak ankle moment (r=0.36, r^2=0.13) and GAS activity (r=0.05, r^2=0.00). The kinetic variables showed only weak correlations to age (r_{abs}=0.20-0.28, r^2=0.04-0.08), except for GRFp (r=-0.48, r^2=0.23). Regression analysis indicated that normalized walking speed explained 54.2% of the variation in COM push-off power, while age only an additional 3.5% (Suppl Table 4).

Insert Figure 4

Insert Table 2: Effects of age and correlations

Discussion

The relation between the lower walking speed of older compared to younger adults and reduction in forward propulsion has yet to be untangled, especially given their independent relation to falls. The investigation of age-related changes in forward propulsion and the underlying leg joint mechanics as well as their relationship with walking speed in a large dataset, determined from which age changes - and thus a greater fall risk - become eminent and identified which major contributors to a decline in propulsion should be targeted during fall risk prevention strategies.

The reported decline in forward propulsion, in terms of both COM push-off power and peak push-off force (GRPp), corresponds to the previously reported decrease in COM push-off power.[11,12] Interestingly, this study reports a compensatory increase in positive work performed by the leading limb during mid-stance.[12] We did not find an increase in positive work during the rebound phase, but unlike their participants, our older adults walked slower. We did find age-related reductions in absorbed COM power during the collision (early stance) and pre-tension phase (late single-stance). During the double-support phase, the COM motion must be redirected from one leg to the other, which is typically accomplished with equal amounts of positive push-off work performed by the trailing limb and negative collision work by the leading limb.[23] Thus, it is not unexpected that we found both reduced push-off power and less collision power absorption, indicating that the coordination between both legs during double stance is not altered with age. As this transition work has been related to about two-thirds of the metabolic cost of moderate walking, the reduction in work performed by both limbs might represent a strategy to reduce the effort of walking.[23] The relation between generated push-off and absorbed pre-tension COM power seems more ambiguous, i.e. whether less push-off power results in less energy stored in the Achilles tendon and other passive tissues, or vice versa due to for instance soft tissue degeneration.[24] We did not find a change in trailing limb angle, indicating similar stretching of the Achilles tendon between decades. However, it should be noted that the tendon elastic properties might be altered with ageing, which has been associated with altered muscle function in both younger and older adults.[25] Thus, the cause of reduced pre-tension COM power deserves further investigation.

Looking at joint mechanics, the decline in COM push-off power was mostly explained by reduced average ankle push-off power (75%), with reductions in peak hip extension moment explaining only a little more (2.5%). Similar to our results, a decrease in hip extension and plantar flexion angle, ankle push-off power and GAS muscle activity throughout adulthood and a lack of age-related changes in knee kinetics have been reported in previous literature.[9,17] Although contributions of the ankle to COM push-off power changes were large in our study, changes in GAS activity contributed to a lesser extent. This could indicate that not the amount of muscle force but the speed at which the muscle can contract is limited by age, which would correspond to the reduction in peak plantar-flexion angle in our older groups. It should be noted that ageing effects in muscle activity might have been underestimated, as only a smaller dataset was available, especially for the younger participants. In addition, GAS activity is not the only muscle responsible for (ankle) push-off or motor control of walking in general, thus future research should include EMG assessment of additional lower limb muscles.

The absence in our study of age-related increases in hip push-off power contribution, and thus a distal-to-proximal redistribution, seems to contradict previous literature.[10,11] However, Boyer et al. (2017) concluded in a meta-analysis that age-effects in hip kinetic measures were only observed when older adults were asked to walk at speeds matched to younger adults.[9,13] In addition, a larger contribution of the hip has generally been found in more demanding environments such as up- or downhill walking, perturbed walking or treadmill walking.[9,26] We focused on overground walking at comfortable speed, which might have limited the need for older adults to employ additional hip push-off power, but this allows us to generalize our findings to real-life settings.

Based on our large database with a wide age range, we could show that age-related decline in COM push-off power and underlying joint mechanics started from the age of 70 years in healthy adults, which is later than generally expected[17,27]. This suggests that ageing studies should recruit participants above the age of 70 years to prevent underestimating any age-related effects while being mindful of the increasing presence of co-morbidities with older age. However, it seems that the cut-off age depends on the outcome- and anatomical planes of motion. Van Criekinge et al. observed decreased motion in the frontal plane from the age of 60, while sagittal motion started to decrease from the age of 80.[27] As forward propulsion is linked to sagittal plane kinematics, it is no surprise that propulsion outcomes follow the same ageing trend, although changes were observed even before changes in kinematics were noticeable. This suggests that looking at motion patterns (i.e., kinematics) solely is inadequate to capture an entire picture of the effect of ageing.

Nonetheless, the variations in COM push-off power are more strongly explained by normalized walking speed (54%) than age itself (3.5%). This reflects the direct mechanical relation between walking speed and forward propulsion – and vice versa -, while age is more an indirect and general indicator of the decline that negatively affects propulsive capacity and thus walking speed. Interestingly, while a more gradual decline can be visually seen for walking speed (see Figure 4), the kinetic and kinematic variables (Figure 3 and Supplementary Figure 1), visually seem to decline more suddenly from the age of 70. However, it should be noted that while we found a weak correlation between biological age and walking speed, stronger correlations have been reported[16], and such collinearity could have changed the outcome of our regression analysis. Either way, physical fitness age, which is the age estimated from the level of physical ability, including components of cardiorespiratory fitness, muscle strength, flexibility and balance, might be a better age-related predictor of forward propulsion, particularly for physically active older adults who have a considerable younger biological age.[28,29] Neuromechanical properties involved with ageing, such as reduced coordination, soft tissue degeneration, muscle weakness and/or cognitive decline are considered markers of physical fitness age and therefore useful to assess when discussing effects of ageing in the future.[29]

To this date, we are still unable to answer the question of whether walking speed is decreased in older adults due to a decline in propulsive ability or vice versa. The capability of older adults to walk at similar speeds as the young,[13] suggests that there might be other reasons than muscle weakness or reduced motor control why they choose to walk slower. For instance, as a conscious strategy due to fear of falling or because compensatory mechanisms to walk faster are fatiguing. As such, it would be interesting to evaluate their ability to maintain higher walking speeds for longer periods in more demanding conditions (e.g., outside or on an unstable surface) as well as include an assessment of fear of falling. In addition, age-related changes in forward propulsion in frail older adults, with comorbidities, motor or cognitive decline, warrants further investigation. While the current results are only representative for the healthy part of the older population, these older adults do portray the natural ageing process of the gait pattern without interference of other pathology or disease on the degeneration of soft tissue.

The inability to disentangle the relation between push-off power, walking speed and biological age is not only related to the limited experimental conditions we could measure, but also their interaction with other important variables.[30] For instance, reduced stability, altered posture, fear of falling and other compensatory mechanisms observed with ageing can significantly affect walking speed. Since ageing has been shown to reduce the mediolateral margins of stability as well as trunk rotations,[31,32] future work will address propulsion in the context of stability and trunk kinematics specifically. However, it should be noted that complex analysis that aim to relate many variables increase the number of performed comparisons. In this study, we aimed to control the number of post-ANOVA comparisons using a limited number of pre-planned contrasts. While we cannot exclude that the type I error was inflated in our analysis, the consistency of the results between the different kinetic variables supports the main outcome of the paper. To reduce this error and increase the power to be able to find more subtle changes, we aim to further increase our database.

In conclusion, COM push-off power decreased from the age of 70 years, which is before age-related changes in kinematics occur. The reduction in COM push-off power was mostly related to a decrease in ankle push-off power, without observing a redistribution of ankle-to-hip power. The reductions in COM push-off power seemed more related to walking speed than biological age, although weak correlations between speed and age make it difficult to entirely disentangle their contributions.

Financial information

The results presented here have been obtained as part of the project HeiAge, which was funded by the Carl Zeiss-Foundation (Germany).

Acknowledgements

Declarations of interest: none.

References

1. Rantakokko M, Portegijs E, Viljanen A, Iwarsson S, Kauppinen M, Rantanen T. Changes in life-space mobility and quality of life among community-dwelling older people: a 2-year follow-up study. *Qual Life Res.* 2016;25(5):1189-1197.
2. Ferrucci L, Cooper R, Shardell M, Simonsick EM, Schrack JA, Kuh D. Age-Related Change in Mobility: Perspectives From Life Course Epidemiology and Geroscience. *J Gerontol A Biol Sci Med Sci.* 2016;71(9):1184-1194.
3. Granacher U, Muehlbauer T, Gollhofer A, Kressig RW, Zahner L. An intergenerational approach in the promotion of balance and strength for fall prevention - a mini-review. *Gerontology.* 2011;57(4):304-315.
4. Barker AL, Nitz JC, Low Choy NL, Haines TP. Mobility has a non-linear association with falls risk among people in residential aged care: an observational study. *J Physiother.* 2012;58(2):117-125.
5. Berg WP, Alessio HM, Mills EM, Tong C. Circumstances and consequences of falls in independent community-dwelling older adults. *Age Ageing.* 1997;26(4):261-268.
6. Kyrdalen IL, Thingstad P, Sandvik L, Ormstad H. Associations between gait speed and well-known fall risk factors among community-dwelling older adults. *Physiother Res Int.* 2019;24(1):e1743.
7. Quach L, Galica AM, Jones RN, et al. The nonlinear relationship between gait speed and falls: the Maintenance of Balance, Independent Living, Intellect, and Zest in the Elderly of Boston Study. *J Am Geriatr Soc.* 2011;59(6):1069-1073.
8. Epro G, McCrum C, Mierau A, Leyendecker M, Bruggemann GP, Karamanidis K. Effects of triceps surae muscle strength and tendon stiffness on the reactive dynamic stability and adaptability of older female adults during perturbed walking. *J Appl Physiol (1985).* 2018;124(6):1541-1549.
9. Boyer KA, Johnson RT, Banks JJ, Jewell C, Hafer JF. Systematic review and meta-analysis of gait mechanics in young and older adults. *Exp Gerontol.* 2017;95:63-70.
10. Browne MG, Franz JR. More push from your push-off: Joint-level modifications to modulate propulsive forces in old age. *PLoS One.* 2018;13(8):e0201407.
11. Tesio L, Rota V. The Motion of Body Center of Mass During Walking: A Review Oriented to Clinical Applications. *Front Neurol.* 2019;10:999.
12. Hernandez A, Silder A, Heiderscheit BC, Thelen DG. Effect of age on center of mass motion during human walking. *Gait Posture.* 2009;30(2):217-222.
13. DeVita P, Hortobagyi T. Age causes a redistribution of joint torques and powers during gait. *J Appl Physiol (1985).* 2000;88(5):1804-1811.
14. Donelan JM, Kram R, Kuo AD. Mechanical work for step-to-step transitions is a major determinant of the metabolic cost of human walking. *J Exp Biol.* 2002;205(Pt 23):3717-3727.
15. Kuo AD, Donelan JM, Ruina A. Energetic consequences of walking like an inverted pendulum: step-to-step transitions. *Exerc Sport Sci Rev.* 2005;33(2):88-97.
16. Hirono T, Ikezoe T, Yamagata M, et al. Age-related changes in gait speeds and asymmetry during circular gait and straight-line gait in older individuals aged 60-79 years. *Geriatr Gerontol Int.* 2021;21(5):404-410.
17. Van Criekinge T, Saeys W, Hallemans A, et al. Age-related differences in muscle activity patterns during walking in healthy individuals. *J Electromyogr Kinesiol.* 2018;41:124-131.
18. Davis RB, Õunpuu S, Tyburski D, Gage JR. A gait analysis data collection and reduction technique. *Human Movement Science.* 1991;10(5):575-587.
19. Donelan JM, Kram R, Kuo AD. Simultaneous positive and negative external mechanical work in human walking. *J Biomech.* 2002;35(1):117-124.
20. Altman DG. *Practical statistics for medical research.* Boca Raton, Fla.: Chapman & Hall/CRC; 1999.
21. Matsuda F, Mukaino M, Ohtsuka K, et al. Analysis of strategies used by hemiplegic stroke patients to achieve toe clearance. *Japanese Journal of Comprehensive Rehabilitation Science.* 2016;7:111-118.
22. Pierrynowski MR, Galea V. Enhancing the ability of gait analyses to differentiate between groups: scaling gait data to body size. *Gait Posture.* 2001;13(3):193-201.
23. Soo CH, Donelan JM. Coordination of push-off and collision determine the mechanical work of step-to-step transitions when isolated from human walking. *Gait Posture.* 2012;35(2):292-297.

24. Clark WH, Franz JR. Triceps surae muscle-subtendon interaction differs between young and older adults. *Connect Tissue Res.* 2020;61(1):104-113.
25. Stenroth L, Peltonen J, Cronin NJ, Sipila S, Finni T. Age-related differences in Achilles tendon properties and triceps surae muscle architecture in vivo. *J Appl Physiol (1985).* 2012;113(10):1537-1544.
26. Franz JR. The Age-Associated Reduction in Propulsive Power Generation in Walking. *Exerc Sport Sci Rev.* 2016;44(4):129-136.
27. Van Criekinge T, Saeys W, Hallemans A, Vereeck L, De Hertogh W, Truijen S. Age-related differences in gait kinematics across the gait cycle in healthy individuals. *Gait & Posture.* 2016;49:247.
28. Mitnitski AB, Graham JE, Mogilner AJ, Rockwood K. Frailty, fitness and late-life mortality in relation to chronological and biological age. *BMC Geriatr.* 2002;2:1.
29. Kimura M, Mizuta C, Yamada Y, Okayama Y, Nakamura E. Constructing an index of physical fitness age for Japanese elderly based on 7-year longitudinal data: sex differences in estimated physical fitness age. *Age (Dordr).* 2012;34(1):203-214.
30. Mekhael M, Labaki C, Bizdikian AJ, et al. How do skeletal and postural parameters contribute to maintain balance during walking? *Hum Mov Sci.* 2020;72:102658.
31. Herssens N, van Criekinge T, Saeys W, et al. An investigation of the spatio-temporal parameters of gait and margins of stability throughout adulthood. *J R Soc Interface.* 2020;17(166):20200194-20200194.
32. Cury AC, Pinto RZ, Madaleno FO, Resende RA. Do older adults present altered pelvic and trunk movement pattern during gait? A systematic review with meta-analysis and GRADE recommendations. *Braz J Phys Ther.* 2021.

Figures

Figure 1: Changes in center of mass (COM) power with age. Stride-normalized COM push-off power curves are shown averaged per decade. The grey area illustrates the approximate collision, rebound, pre-tension and push-off phases averaged over the different decades. The individual values and average decade statistics of the COM push-off power, calculated as the integral per phase, is shown in the lower graphs. On each boxplot, the central mark indicates the median value, and the bottom and top edges of the box indicate the 25th and 75th percentiles, while the whiskers extend to the most extreme data points. Decades that were found to be significantly different ($p<0.05$) from the young were marked with an asterisk.

Figure 2: Changes in ground reaction force and gastrocnemius muscle activity with age. Time-normalized ground reaction forces are averaged per decade for each dimension in the upper row. The peak anterior ground force values are indicated with orange dots and their individual values, as well as the statistics per decade, are shown in the lower row. In the lower right, the individual values and group statistics of the root-mean-square of the normalized gastrocnemius (GAS) muscle activity are given. On each boxplot, the central mark indicates the median value, and the bottom and top edges of the box indicate the 25th and 75th percentiles, while the whiskers extend to the most extreme data points. Decades that were found to be significantly different ($p<0.05$) from the young (defined as the average of the 3rd and 4th decade) by the contrast analyses are indicated with an orange asterisk.

Figure 3: Changes in lower body joint kinetics with age. Time-normalized moment and power curves for the ankle, knee and hip are averaged per decade. The peak moment and power values of the ankle and hip around push-off are indicated with the orange dots. The boxplot graphs show the individual peak values as well as the decade statistics. In addition, the average joint powers over the area related to push-off for the respective joint are shown on the bottom row. On each boxplot, the central mark indicates the median value, and the bottom and top edges of the box indicate the 25th and 75th percentiles, while the whiskers extend to the most extreme data points. Decades that were found to be significantly different ($p<0.05$) from the young (defined as the average of the 3rd and 4th decade) by the contrast analyses are indicated with an orange asterisk.

Figure 4: Change in self-chosen normalized walking speed with age. The individual's preferred walking speed as the average walking speed over the included strides normalized to leg length is shown, as well as the decade group statistics. The Pearson correlation results between walking speed and age are given (fitted grey line on the correlation coefficients). On each boxplot, the central mark indicates the median value, and the bottom and top edges of the box indicate the 25th and 75th percentiles, while the whiskers extend to the most extreme data points. Decades that were found to be significantly different ($p<0.05$) from the young (defined as the average of the 3rd and 4th decade) by the contrast analyses are indicated with an orange asterisk.

Supplementary Figure 1: Changes in lower body joint kinematics with age. Time-normalized ankle, knee and hip angles are averaged per decade group in the upper row. The peak ankle plantar flexion, knee extension and hip extension angle around the push-off phase are indicated with the orange dots. The individual values of these peak joint angles as well as the decade group statistics are shown in the lower row. On each boxplot, the central mark indicates the median value, and the bottom and top edges of the box indicate the 25th and 75th percentiles, while the whiskers extend to the most extreme data points. Decades that were found to be significantly different ($p<0.05$) from the young (defined as the average of the 3rd and 4th decade) by the contrast analyses are indicated with an orange asterisk.

Tables

Table 1: Participant characteristics per decade

Decade	Subs	Age	Gender	BMI	Number of steps	Walking speed	Subs EMG
	#	yrs	% M	kg/m^2	#	m/s	#
3 (20-29)	25	24.4 ± 2.3	44	25.3 ± 4.2	4.5 ± 1.2	1.21 ± 0.04	16
4 (30-39)	20	33.4 ± 2.6	55	25.1 ± 5.8	3.9 ± 1.5	1.24 ± 0.07	16
5 (40-49)	20	45.0 ± 2.8	45	26.4 ± 4.2	4.1 ± 1.3	1.22 ± 0.06	16
6 (50-59)	24	54.1 ± 2.8	42	23.9 ± 3.0	4.3 ± 1.3	1.22 ± 0.02	17
7 (60-69)	16	63.6 ± 3.0	44	27.4 ± 4.5	3.2 ± 1.0	1.20 ± 0.04	15
8 (70-79)	18	74.3 ± 2.8	50	28.4 ± 3.9	4.8 ± 1.9	1.11 ± 0.03	15
9 (80-89)	15	82.5 ± 2.0	53	28.3 ± 2.7	4.5 ± 2.0	1.06 ± 0.04	14

With yrs: years, M: male; BMI: body mass index.

Table 2: Effects of age and correlations

Variable	Effect of Age				Correlation COM prop power			Correlation Speed			Correlation Age		
	ANOVA Fval	ANOVA pval	Dec8 pval	Dec9 pval	r	pval	r2	r	pval	r2	r	pval	r^2
Kinetics													
COM PUSH-OFF POWER (W/kg %gc)	26.98	**<0.001**	**<0.001**	**<0.001**				0.74	**<0.001**	0.55	-0.41	**<0.001**	0.17
COM collision power (W/kg %gc)	13.49	**<0.001**	**0.022**	**0.001**	-0.61	**<0.001**	0.38						
COM rebound power (W/kg %gc)	0.00	0.964											
COM pre-tension power (W/kg %gc)	8.12	**0.005**	**0.017**	**0.016**	-0.72	**<0.001**	0.53						
Peak push-off force GRFa (N/kg)	40.44	**<0.001**	**<0.001**	**<0.001**	0.87	**<0.001**	0.76	0.78	**<0.001**	0.60	-0.48	**<0.001**	0.23
PEAK ANKLE MOMENT (Nm/kg)	7.04	**0.009**	**0.017**	**0.013**	0.63	**<0.001**	0.40	0.36	**<0.001**	0.13	-0.22	**0.010**	0.05
PEAK ANKLE POWER (W/kg)	12.23	**0.001**	**0.003**	**0.007**	0.86	**<0.001**	0.73	0.67	**<0.001**	0.45	-0.28	**0.001**	0.08
Ankle mean push-off power (W/kg %gc)	10.70	**0.001**	**0.004**	**0.013**	0.86	**<0.001**	0.75	0.68	**<0.001**	0.47	-0.27	**0.002**	0.07
PEAK HIP MOMENT (Nm/kg)	6.99	**0.009**	0.302	**0.003**	-0.51	**<0.001**	0.26	-0.61	**<0.001**	0.37	0.20	**0.018**	0.04
PEAK HIP POWER (W/kg)	7.06	**0.009**	**0.040**	**0.031**	0.60	**<0.001**	0.36	0.81	**<0.001**	0.66	-0.22	**0.009**	0.05
Hip average push-off power (W/kg %gc)	2.80	0.097											
Ratio ankle/hip push-off power (1)	0.60	0.439											
Knee average power (W/kg %gc)	1.95	0.165											
GAS push-off activity (norm)	5.78	**0.018**	0.403	**0.007**	0.12	0.219	0.01	0.05	0.615	0.00	-0.23	**0.017**	0.05
Kinematics													
Peak ankle angle (°)	18.33	**<0.001**	0.141	**<0.001**	-0.31	**<0.001**	0.10						
Peak knee angle (°)	3.40	0.067											
Peak hip angle (°)	3.93	**0.049**	0.720	**0.004**	-0.29	**0.001**	0.09						
Peak trailing limb angle (°)	0.86	0.357											
Spatio-temporal													
SPEED (norm)	15.08	**<0.001**	**0.016**	**0.001**							-0.30	**<0.001**	0.09
Stride time (norm)	0.74	0.390											
Stride length (norm)	24.49	**<0.001**	**0.007**	**<0.001**									
Stance phase (%)	12.53	**0.001**	**0.008**	**0.001**									
Step width (norm)	23.74	**<0.001**	**0.009**	**<0.001**									

With COM center-of-mass, gc gait cycle, Fval the F-statistics, pval the p-value indicating significance, r the Pearson correlation coefficient, and r^2 the variability explained of the independent variable. Dec8 and Dec9 give the contrast p-values of these decades versus the young and values are only given if the ANOVA gave a significant age effect. Only the relevant outcomes are shown (i.e., only post-ANOVA planned contrast testing if there was a main ANOVA effect, and only the correlations that were included in the analysis. Primary outcome measures are indicated in capitals and significant p-values ($p<0.05$) in bold.

Supplementary Table 1: Definition of outcome variables

Variable (P = primary)	Unit	Definition
Gait phases		
Push-off phase		From zero crossing of anterior-posterior ground reaction force (i.e., from braking to push-off force) to ipsilateral leg toe-off
Extended push-off phase		From zero crossing of anterior-posterior ground reaction force (i.e., from braking to push-off force) to half of the swing time of the ipsilateral leg
Kinetics		
COM push-off power **(P)**	W/kg %gc	Generated (positive) COM push-off power integrated over the main positive peak during the second double-limb-support phase (to percentage gait cycle, to not take differences in stride time between participants into account), typically from slightly before contralateral initial contact to ipsilateral toe-off, normalized to body mass. COM (push-off) power was calculated as the dot product of the COM velocity vector and the individual limb's ground reaction force vector
COM collision power	W/kg %gc	Absorbed (negative) COM push-off power integrated over the main negative peak typically during the first double-limb support phase (to percentage gait cycle), from ipsilateral initial contact to slightly after contralateral toe-off, normalized to body mass
COM rebound power	W/kg %gc	Generated (positive) COM push-off power integrated over the main positive peak typically during the first half of first single-limb support phase (to percentage gait cycle), from contralateral toe-off to contralateral initial contact, normalized to body mass
COM pre-tension power	W/kg %gc	Absorbed (negative) COM push-off power integrated over the mean negative peak typically during the second half of the single-limb support phase (to percentage gait cycle), normalized to body mass
Peak push-off force	N/kg	Peak ground reaction force during the push-off phase
Ankle peak moment **(P)**	Nm/kg	Peak ankle extension moment during the push-off phase, normalized to body mass
Ankle peak power **(P)**	W/kg	Peak ankle generated (positive) power during the push-off phase, normalized to body mass
Ankle average power	W/kg %gc	Generated (positive) ankle power integrated over the push-off phase (to percentage gait cycle), normalized to body mass
Knee average power	W/kg %gc	Absorbed (negative) knee power integrated over the extended push-off phase (to percentage gait cycle), normalized to body mass
Hip peak moment **(P)**	Nm/kg	Peak hip extension moment during the gait cycle
Hip peak power **(P)**	W/kg	Peak hip generated (positive) power during the extended push-off phase, normalized to body mass
Hip average power	W/kg %gc	Generated (positive) hip power integrated over the extended push-off phase (to percentage gait cycle), normalized to body mass
Ratio ankle/hip average power	1	Average ankle push-off power divided by the sum of the average ankle and hip push-off power times 100%
EMG		
GAS activity	1	The root-mean-square value of the EMG signal from toe-off of the contralateral leg to toe-off of the ipsilateral leg, to account for the onset of muscle activity before actual force production (thus taken into account the electrophysiological time delay). The EMG signal was normalized to the mean amplitude of the average stride-normalized signal of the respective leg
Kinematics		
Trailing limb angle	°	The maximum sagittal plane angle between the vertical axis of the lab and the vector joining the limb's ankle joint center and the middle of the pelvis (average of the anterior superior iliac spine and posterior superior iliac spine markers to represent the not available location of the greater trochanter) during the push-off phase
Peak ankle angle	°	Peak plantarflexion angle during the push-off phase
Peak knee angle	°	Peak knee extension angle during stance
Peak hip angle	°	Peak hip extension angle during the gait cycle
Spatiotemporal		
Speed **(P)**	1	Normalized stride length divided by normalized stride time divided by the square root taken of the standing leg length divided by 9.81 ms^{2}
Stride length	1	The corresponding linear distance (in the forward direction) of the heel marker at the timing of foot contact and following foot contact of the respective leg, normalized by standing leg length
Stride time	1	The duration between the timing of foot contact and following foot contact of the respective leg divided by the square root of 9.81 divided by standing leg length
Stance phase	%	The duration between foot contact and foot off of the respective leg expressed as percentage gait cycle
Step width	1	The mediolateral distance between the contralateral and ipsilateral heel marker position at their respective foot contact, normalized by standing leg length

Primary outcome parameters are indicated with (P), with gc gait cycle.

Supplementary Table 2: Outcomes per decade

	Parameter	Dec3 20-29 yr		Dec4 30-39 yr		Dec5 40-49 yr		Dec6 50-59 yr		Dec7 60-69 yr		Dec8 70-79 yr		Dec9 80-89 yr	
		Mean	std	Mean	std	Mean	std	Mean	std	Mean	std	Mean	std	Mean	std
Body propulsion	**COM push-off power (W/kg %gc)**	1.602	0.435	1.606	0.305	1.571	0.302	1.630	0.375	1.421	0.296	1.194	0.288	1.127	0.193
	COM collision power (W/kg %gc)	-0.667	0.451	-0.641	0.341	-0.614	0.303	-0.712	0.436	-0.533	0.253	-0.421	0.188	-0.341	0.149
	COM rebound power (W/kg %gc)	0.234	0.147	0.278	0.182	0.255	0.153	0.324	0.183	0.220	0.143	0.193	0.083	0.270	0.104
	COM pre-tension power (W/kg %gc)	-0.698	0.176	-0.765	0.138	-0.725	0.112	-0.765	0.164	-0.654	0.106	-0.585	0.169	-0.580	0.112
	Peak push-off force (GRFp) (N/kg)	2.058	0.376	2.046	0.283	1.991	0.294	1.987	0.373	1.837	0.323	1.599	0.250	1.530	0.246
Joint kinetics	**Ankle peak moment (Nm/kg)**	1.453	0.189	1.499	0.163	1.469	0.189	1.509	0.131	1.411	0.144	1.332	0.189	1.332	0.130
	Ankle peak power (W/kg)	3.417	0.856	3.557	0.674	3.698	0.694	3.695	0.939	3.165	0.573	2.760	0.590	2.835	0.517
	Ankle work / average push-off power (W/kg %gc)	1.832	0.503	1.934	0.422	1.984	0.371	1.990	0.515	1.697	0.373	1.476	0.301	1.541	0.316
	Hip peak moment (Nm/kg)	-1.018	0.286	-0.895	0.210	-1.058	0.153	-1.129	0.338	-0.932	0.314	-0.909	0.339	-0.734	0.279
	Hip peak power (W/kg)	1.645	0.490	1.625	0.364	1.698	0.387	1.738	0.625	1.664	0.458	1.334	0.335	1.367	0.310
	Hip work / average push-off power (W/kg %gc)	0.812	0.263	0.821	0.215	0.900	0.178	0.983	0.401	0.860	0.234	0.720	0.166	0.708	0.224
	Ratio ankle/hip work (1)	68.953	5.190	70.035	6.537	68.715	4.221	67.403	7.006	66.073	8.734	67.307	3.703	68.780	6.647
	Knee work / average push-off power (W/kg %gc)	-0.533	0.195	-0.528	0.139	-0.580	0.125	-0.635	0.273	-0.543	0.138	-0.474	0.148	-0.479	0.173
	GAS push-off activity (norm)	2.097	0.260	2.111	0.263	2.001	0.241	2.003	0.359	2.089	0.216	2.013	0.286	1.845	0.292
Posture	Ankle angle (°)	-16.801	7.617	-17.595	4.652	-16.965	6.835	-14.582	4.965	-14.746	6.324	-14.006	7.169	-7.122	2.993
	Knee angle (°)	2.050	5.192	-0.005	4.652	0.739	3.732	0.130	6.412	-0.087	5.612	1.503	5.380	5.633	3.057
	Hip angle (°)	-12.565	5.526	-10.253	10.497	-15.096	3.715	-14.818	7.959	-12.554	11.084	-11.896	7.671	-5.050	8.938
	Trailing limb angle (°)	3.484	1.468	3.856	1.019	4.127	1.117	3.736	1.841	3.701	0.828	4.260	1.098	3.761	1.639
Spatio-temp	**Walking Speed (norm)**	0.414	0.060	0.413	0.040	0.423	0.044	0.429	0.068	0.409	0.039	0.376	0.046	0.361	0.040
	Walking Speed (m/s)	1.235	0.171	1.246	0.111	1.243	0.147	1.265	0.197	1.216	0.124	1.104	0.144	1.057	0.129
	Stride time (norm)	3.543	0.243	3.445	0.243	3.450	0.210	3.421	0.241	3.430	0.243	3.586	0.188	3.577	0.225
	Stride length (norm)	1.456	0.123	1.415	0.095	1.452	0.111	1.455	0.157	1.398	0.101	1.344	0.134	1.286	0.113
	Stance phase (%)	62.631	1.771	61.218	1.039	61.994	1.331	61.455	1.819	61.825	1.251	63.149	1.646	63.429	1.180
	Step width (norm)	0.726	0.059	0.706	0.048	0.721	0.057	0.729	0.076	0.695	0.050	0.672	0.066	0.644	0.060

With the mean and standard deviation (std) given for each decade.

Supplementary Table 3: Regression analysis joint mechanics

Model variables	coefficients (beta)	SE beta	T-stat	p-val	RMSE	R^2	R^2 adjusted	R^2 adj contribution
Step 1					0.191	0.748	0.746	74.6
Constant	0.163	0.069	2.374	0.019				
Average ankle power	0.727	0.037	19.853	<0.001				
Step 2					0.181	0.774	0.771	2.5
Constant	0.072	0.069	1.039	0.301				
Average ankle power	0.665	0.038	17.349	<0.001				
Hip peak moment	-0.215	0.055	-3.925	<0.001				

With RMSE = root-mean-square error, SE = standard error of coefficients. Starting parameters for regression analysis: ankle and hip peak moment and power as well as average ankle push-off power. After two steps, none of the other variables added a significant contribution to the model.

Supplementary Table 4: Regression analysis speed and age

Model variables	coefficients (beta)	SE beta	T-stat	p-val	RMSE	R^2	R^2 adjusted	R^2 adj contribution
Step 1					0.256	0.546	0.542	54.2
Constant	-0.566	0.164	-3.449	<0.001				
Normalized walking speed	5.065	0.401	12.639	<0.001				
Step 2					0.246	0.583	0.577	3.5
Constant	-0.194	0.191	-1.013	0.313				
Normalized walking speed	4.644	0.404	11.481	<0.001				
Biological age	-0.004	0.001	-3.434	<0.001				

With RMSE = root-mean-square error, SE = standard error of coefficients. Starting parameters for regression analysis: walking speed and biological age.