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Relation between Step-To-Step Transition Strategies and Walking Pattern in Older Adults

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Abstract: In older adults, two different modes of step-to-step transition have been observed: an anticipated mode when the redirection of the centre of mass of the body (COM) begins before double stance and another when the transition begins during double stance. However, the impact of transition mode on gait kinetics and kinematics has not been investigated. Age and step-to-step-transition-related differences in intersegmental coordination and in the COM trajectory during walking were identified. Fifteen young (24.1 ± 0.7 y.o.) and thirty-six older adults (74.5 ± 5.0 y.o.) walked on a treadmill at 1.11 m s^{-1} and 1.67 m s^{-1}. Lower-limb motion and ground reaction force were recorded. The COM dynamics were evaluated by measuring the pendulum-like exchange of the COM energies. While all young adults and 21 of the older adults used an anticipated transition, 15 older adults presented a non-anticipated transition. Previously documented changes of intersegmental coordination with age were accentuated in older adults with non-anticipated transition ($p < 0.001$). Moreover, older adults with non-anticipated transition had a smaller pendulum-like energy exchange than older adults with anticipated transition ($p = 0.03$). The timing of COM redirection is linked to kinematic and mechanic modification of gait and could potentially be used as a quantitative assessment of age-related decline in gait.

Keywords: aging; gait analysis; biomechanics; coordination

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1. Introduction

Decline in gait and in the locomotion function with aging has been extensively documented [1]. The age-related differences in walking pattern between young and older adults are governed by interdependent combinations of factors occurring in parallel, such as neuromuscular and central nervous system degenerative changes [2–4]. Several studies have provided new insights into the plasticity of the walking patterns to adapt to those age-related physiological changes [5–7].

In particular, biomechanical changes have garnered considerable attention, with a distal-to-proximal redistribution of joint efforts established as the hallmark feature of older adults' walking [5,8]. Recently, Meurisse et al. [9,10] have identified a different step-to-step transition mode in the aged population, mainly related to trailing/leading limb ground reaction force redistribution. Indeed, during the step-to-step transition, a subset of their older subjects reduced the vertical push of the trailing leg, increasing that of the leading leg (Figure 1A). This subset of subjects used a so-called non-anticipated transition mode, since the down-to-up redirection of the centre of mass of the body (COM) begins during the double stance and lacked the activation of distal extensor muscles at the end of the stance [11]. In contrast, the anticipated transition mode occurs when the redirection begins before the contact of the leading leg, initiated by the push of the trailing leg. In addition to the inherently different ratio between the vertical push of the leading and trailing legs, static balance performance was linked with the transition mode [10]. Indeed, older adults with a non-anticipated transition mode exhibited a greater centre of pressure excursion during standing compared to younger and older adults with anticipated transition. However, how the different transition strategies affect the resultant walking pattern has never been investigated to our knowledge.

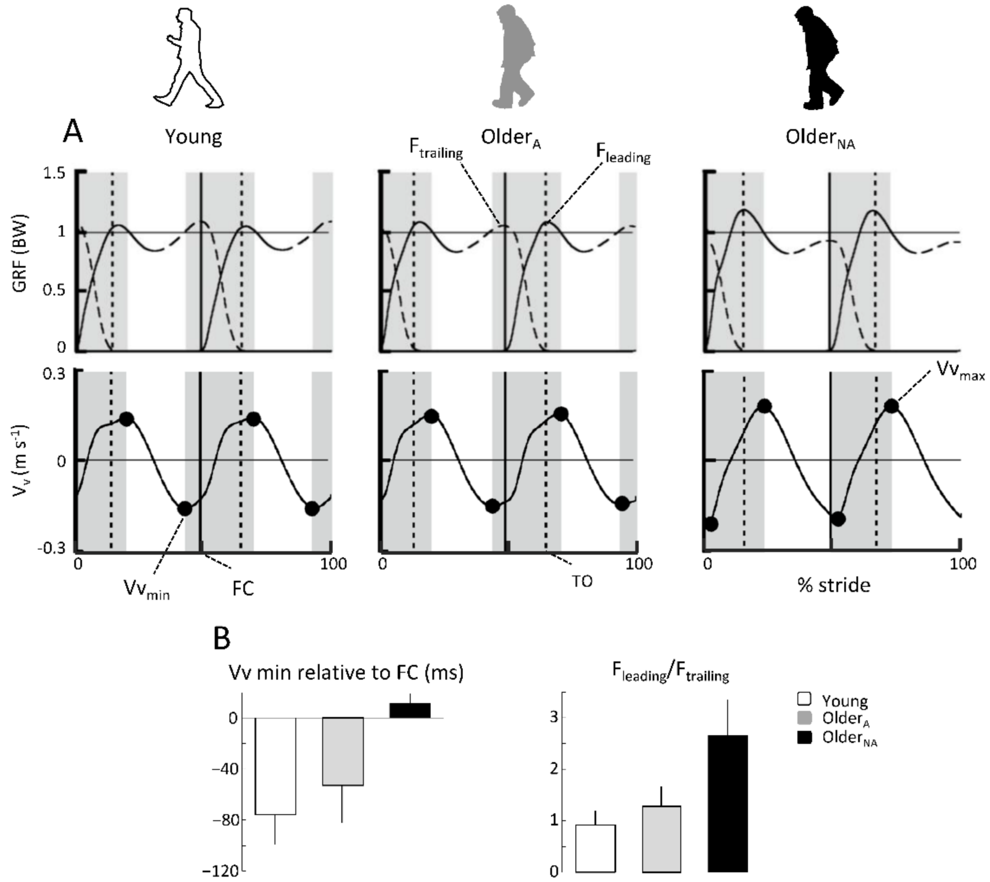

Figure 1. Definition of the step-to-step transition modes. (**A**) Mean curves of the vertical component of the ground reaction force (GRF, expressed in body weight) acting upon each leg separately (continuous line: leading leg; dotted line: trailing leg) for young and older groups with an anticipated (Older$_A$) and non-anticipated step-to-step transition (Older$_{NA}$). (**B**) Left: time of occurrence distribution of Vv_{min} relative to foot contact (FC). Negative values indicate anticipated transition. Right: ratio between the mean value of impact force on the leading leg ($F_{leading}$) and on the trailing leg ($F_{trailing}$) during the step-to-step transition. Bars correspond to mean value and the line to 1 standard deviation. White: young adults; grey: older adults with anticipated step-to-step transition; black: older adults with non-anticipated step-to-step transition (all plots are redrawn with permission from Meurisse et al. [10]).

The aim of this study was to identify age and step-to-step-transition-related differences in the kinematics and kinetics of walking at different speeds. To do that, the kinematics and kinetics data collected at the same time and on the same subjects as in Meurisse et al. [10] were analysed. In particular, we intended to analyse the intersegmental coordination of the lower limb segment, using a principal component analysis [7,12–14], and the dynamics of the COM, focusing on the pendulum-like exchange of mechanical energies during walking [15,16]. A modified coordination pattern, mainly linked to a more in-phase shank and foot motion, has previously been documented in older adults, especially at slow walking speeds [7,14,17]. We expected that due to the reduced contribution of the trailing limb to COM redirection in older adults with non-anticipated transition (Figure 1A), the modification of the coordination pattern will be greatly evidenced in that group. In addition, while no modification of COM dynamics is observed with aging [18], we hypothesized that based on the distinct ground reaction force profiles, the pendulum-like exchange of energy will be different depending on the step-to-step transition mode. The detection of age-related deterioration in gait associated with the step-to-step transition strategies may potentially lead to simple quantitative assessment of gait in clinical practice and may also help to design and test early therapies.

2. Materials and Methods

2.1. Subjects and Experimental Procedures

Data were collected at the same time and on the same subjects as in the study of Meurisse et al. [10]. The inclusion criteria were the following: ability to walk a kilometre, no locomotor system injury complaints and no previous history of neurological disorders. All subjects gave their written informed consent to participate in the study, and the experiments were performed according to the Declaration of Helsinki and were approved by the local ethics committee ("Commission d'éthique Biomédicale Hospitalo-Facultaire de l'Université catholique de Louvain", 2015/18MAI/245, Belgian Registration Number: B403201524765).

The participants were asked to walk on an instrumented treadmill at 1.11 and 1.67 m s^{-1}. These speeds were arbitrarily fixed and allowed us to evaluate the effect of various step-to-step transitions at an intermediate speed close to the spontaneous walking speed (the spontaneous speed was measured by two photocells placed at the level of the neck and separated by 5 m in the middle of a 12 m corridor and was equal to 1.23 ± 0.16 m s^{-1}; already reported in [10]) and relatively faster walking speed (1.67 m/s) below the spontaneous walk-to-run transition. All participants performed a warmup trial on the treadmill before data acquisition. At each speed, data were recorded for 15 s after 3 min of walking at constant speed. The treadmill (h/p/cosmos-Stellar) was instrumented with four custom-made force transducers, measuring the ground reaction forces (GRFs). The stride was defined as the period between a right foot-contact (FC; 0%) and the next one (100%). FC and toe-off (TO) were estimated from the displacement of the centre of pressure on the belt [19]. Reflective markers were glued on the subject's skin at the chin–neck intersect, greater trochanter, lateral femoral condyle, lateral malleolus and fifth metatarsophalangeal joint. The position of the markers in the sagittal plane was recorded every 5 ms by means of a high-speed video camera (BASLER piA 640-210), 3 m to the right side of the treadmill. Horizontal and vertical coordinates of the markers in the sagittal plane were measured in each frame using dedicated tracking software (LABVIEW2010, National Instruments, Austin, TX, USA).

Participants were grouped based on their step-to-step transition mode during walking on a treadmill based on the group assignment conducted by Meurisse et al. [10]. In brief, they defined the transition mode by the time of occurrence of the minimal vertical velocity of the CoM (Vv_{min}) relative to the beginning of the double contact phase (FC; Figure 1) [10,20]. Note that Meurisse et al. [10] based the group division on the step-to-step transition observed at 1.11 m s^{-1}. In the present paper, any effects of walking speed on the timing of Vv_{min} (p = 0.211) were observed, making the group classification consistent across speeds. There were no significant differences between the three groups in terms of body mass and height, and no significant difference in age among older adults with an anticipated or non-anticipated transition (t-test, $p > 0.05$).

2.2. Data Analysis

Kinematic parameters. From the marker's location, the orientation of the thigh, shank, foot and trunk relative to the vertical axis (elevation angle) was computed as described in Borghese et al. [13]. The joint angles (hip, knee and ankle) were then computed from the elevation angles of adjacent segments. For each subject, all strides of each trial were time-interpolated to fit a normalized 400-point time base and then averaged. To analyse the time-course of the elevation angles during the stride, a Fourier series component was performed [12,21]. The phase shift between the first harmonic of two adjacent limb segments was computed as the difference between the phase shift of the proximal and distal adjacent segments. A principal component analysis was applied to determine the covariance matrix of the segment elevation angles. Eigenvalues and eigenvectors were computed by factoring the covariance matrix from the set of original signals by using a singular value decomposition algorithm. The first two eigenvectors lay on the best-fitting plane of angular covariation, and the data projected onto these axes corresponded to the first and second principal components. The planarity was evaluated for each condition by calculating the percentage of variance that was explained by the first and second principal components (PV_1 and PV_2, respectively). If the data lay perfectly on a plane, $PV_1 + PV_2$ would be 100%. By definition, the third eigenvector u_{3t} is orthogonal to the plane. The parameter u_3 corresponded to the direction cosine with the positive semi-axis of the thigh's angular coordinates and provides a measure of the orientation of the plane.

COM mechanics. The acceleration, velocity and displacement of the COM and the energy of the COM (E_{COM}) were determined from the GRF, using the procedure described in detail in Willems and Gosseye [22]. E_{COM} was computed as the algebraic sum at each instant of the gravitational potential energy (E_p) and of the kinetic energy (E_k) of the COM. W_{COM} was then computed as the sum of the positive work needed to increase the energy in the COM [23,24]. The periods during which an E_p–E_k transduction occurs was determined by measuring the recovery at each instant *t* of the step (in %) from E_k and E_p changes [15,16]. The % recovery was defined as the average recovery across a stride. Two periods of energy transduction (T1 and T3) were defined: T1 occurs when E_p increases while E_k decreases, whereas T3 occurs when E_p decreases while E_k increases [16]. In order to quantify the effectiveness of the transduction between E_p and E_k in the different phases of the step, the absolute amount of energy saved by this transduction E_{int} was measured over the period T1 and T3, as described in Dewolf et al. [16].

2.3. Statistics

The statistical analysis was designed to assess the effect of group (Young, $Older_A$ and $Older_{NA}$), speed of progression and of the interaction between these two factors. A two-level linear mixed model was applied: speed and group were set as fixed effects, and the participant was set as a random effect. The normality of the residuals was checked by the Kolmogorov–Smirnov. Linear regression analysis, using Pearson's correlation coefficient (r), was used to quantify the relationship between variables. Independent sample Student's *t*-tests with Bonferroni corrections were used in the figures. In all analyses, the significance level was fixed at $p < 0.05$.

3. Results

While all young adults (n = 15, age: 24.1 ± 0.7 y.o., weight: 68.6 ± 14.6 kg; height: 1.73 ± 0.09 m) have an anticipated transition (Vv_{min} occurs before FC), older adults were divided in two groups: 21 older adults (age: 73.3 ± 0.7 y.o., weight: 67.7 ± 12.5 kg; height: 1.69 ± 0.08 m) presented an anticipated transition (called $Older_A$) and fifteen older adults (age: 74.7 ± 0.8 y.o., weight: 71.7 ± 14.3 kg; height: 1.71 ± 0.07 m) presented a non-anticipated transition, i.e., Vv_{min} occurs after FC (called $Older_{NA}$).

3.1. Joint and Elevation Angles

At the level of the hip, there is a modification of the maximum hip extension ($F_{2,86} = 5.6$; $p = 0.005$): the hip extension is similar among Young and $Older_A$ groups ($p = 0.149$) but smaller in $Older_{NA}$ ($p = 0.002$; Figure 2A). In all groups, no effect of speed is observed ($F_{1,86} = 0.1$; $p = 0.765$). At the level of the knee, at FC, no significant effect of group is noticed. At the level of the ankle, a modification of the maximum ankle plantar-flexion is observed

($F_{2,86}$ = 24.1; p < 0.001): the maximal plantar-flexion is smaller in Older$_A$ compared to Young (p < 0.001), and in Older$_{NA}$ compared to Older$_A$ (p < 0.001). In each group (interaction: $F_{2,86}$ = 0.6; p = 0.527), the ankle plantar-flexion increases with speed ($F_{1,86}$ = 6.6; p = 0.012).

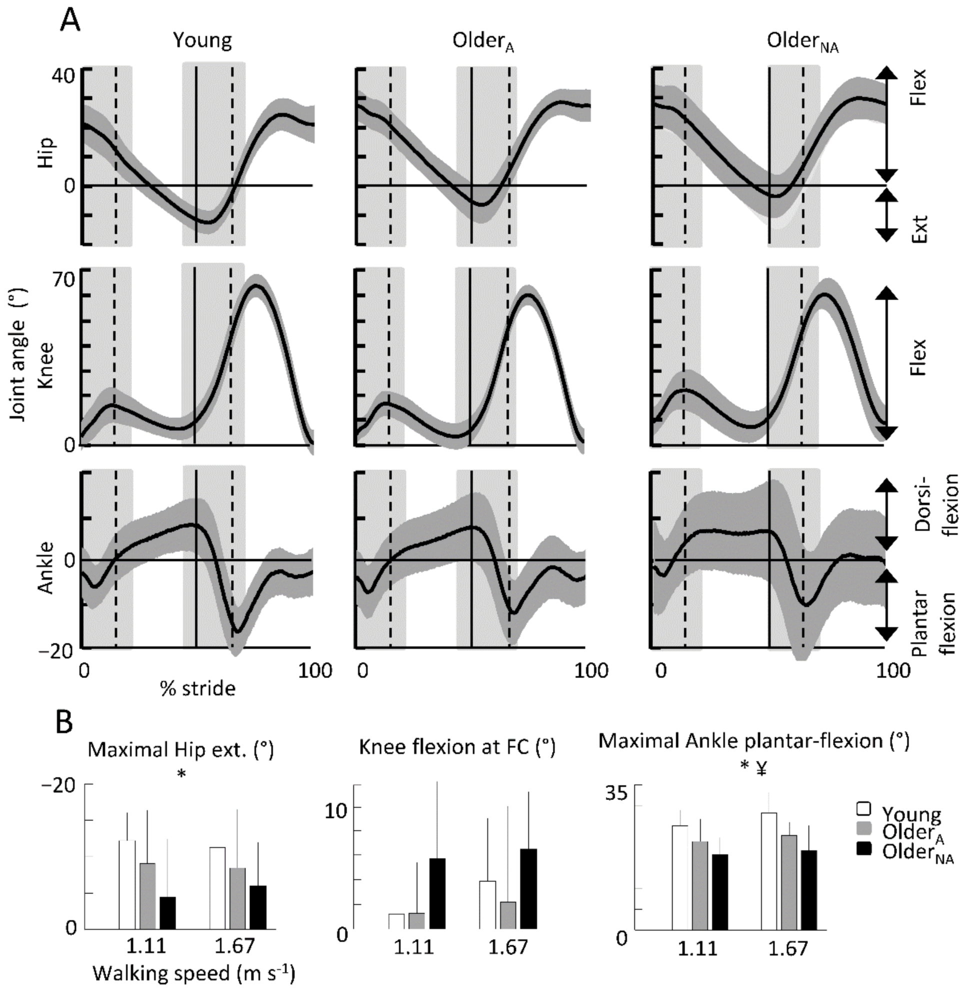

Figure 2. Joint kinematics. (**A**) Ensemble-average traces of the hip, knee and ankle angle joint taken from the right side of the subjects during a stride for the three groups walking at 1.11 m·s^{-1}. All the curves of each subject were first averaged (mean curve). The curves presented here are the average of the mean curves of all the subjects (ensemble-average) and the dark grey areas are the standard deviations. Positive values correspond to flexion (dorsiflexion for the ankle) and negative values correspond to extension (plantar-flexion for the ankle). (**B**) Maximal hip extension (left), knee flexion at foot contact (middle) and maximal ankle plantar-flexion (right). The symbols * and ¥ indicate a significant effect of age and speed, respectively. Other indications as in Figure 1.

When looking at the elevation angles, the mean trunk inclination differs between groups: at 1.11 m s^{-1}, the inclination is $-3.1 \pm 1.7°$, $-8.0 \pm 4.3°$ and $-9.5 \pm 4.9°$ in Young, Older$_A$ and Older$_{NA}$, respectively. The inclination is greater in Older$_{NA}$ compared to Older$_A$ (p = 0.045), and in Older$_A$ compared to Young (p < 0.001). Moreover, the shank and foot ROM are different between groups (shank: $F_{1,86}$ = 3.4; p = 0.037; foot: $F_{1,86}$ = 6.6; p = 0.032): the ratio between thigh and shank ROM is smaller in Young than in Older$_{NA}$ (p = 0.001) but similar compared to Older$_A$ (p = 0.065), whereas the ratio between shank and foot ROM is different among Young and older adults ($F_{1,86}$ = 10.8; p = 0.001) but not among Older$_A$ and Older$_{NA}$ (p = 0.830; Figure 3A). In addition, the phase shift between shank and foot segments is smaller (more in phase) in Older$_{NA}$ than in Older$_A$ (p = 0.002) and in Young (p = 0.012; Figure 3A), whereas the phase shift between the thigh and shank segments is not different between groups ($F_{2,86}$ = 1.1; p = 0.320).

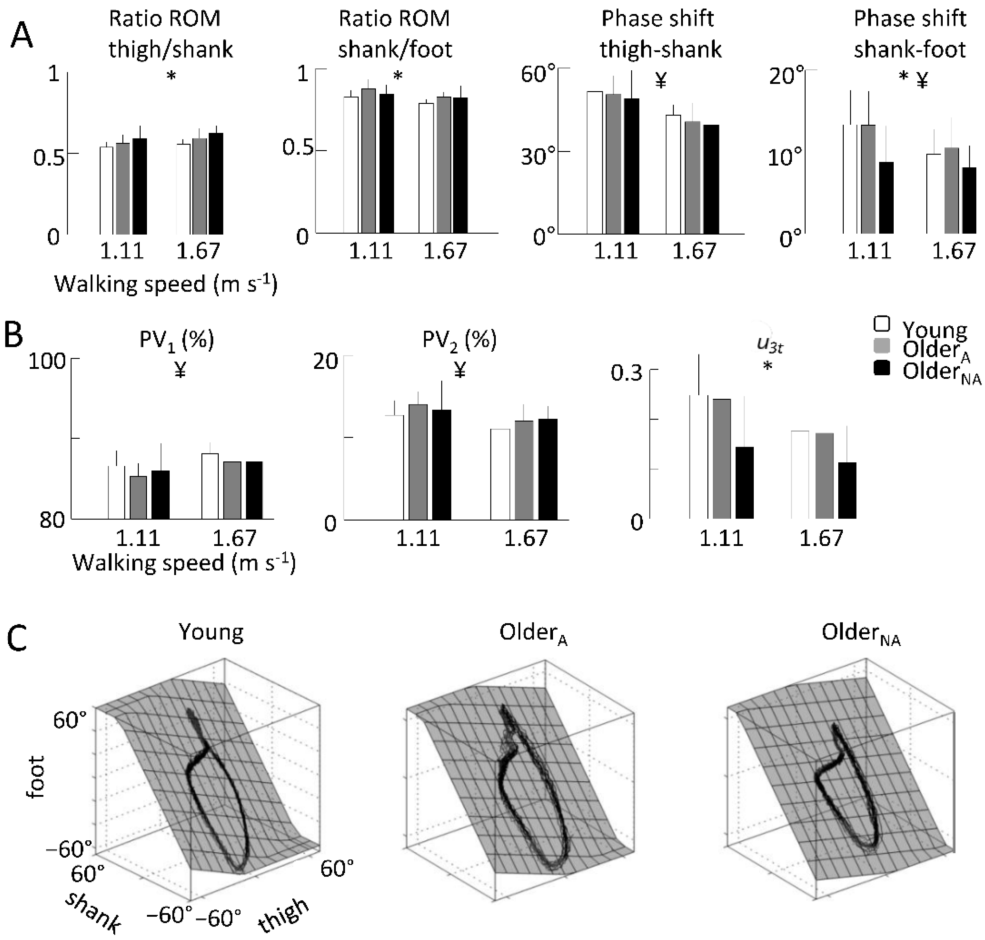

Figure 3. Intersegmental coordination. (**A**) Ratio between the range of motion of thigh and shank segments, shank and foot segments, phase shift between the first harmonic of thigh and shank and shank and foot elevation angles. (**B**) Percentage of variance accounted for by the first (PV_1, left) eigenvector; the second (PV_2, middle) eigenvector of the principal component analysis and the orientation of the principal plane (right), defined by the direction cosines of the normal to the covariation plane with the positive semi-axis of the thigh angular coordinates (u_{3t}). (**C**) Covariation of the limb-segment elevation angles during walking at 1.11 m s^{-1} in the three groups. For each group, all the strides of one typical subject per group were plotted. Note that when the elevation angles of thigh, shank and foot are plotted one versus the other in a x-y-z space, and they co-vary along a loop constrained on a plane (x–y). Grids show the best-fitting plane. The symbols * and ¥ indicate a significant effect of age and speed, respectively. Other indications as in Figure 2.

When speed increases, the range of motion (ROM) of the trunk, thigh and foot elevation angles increased (trunk: $F_{1,86} = 4.1$; $p = 0.045$; thigh: $F_{1,86} = 5.2$; $p = 0.025$; foot: $F_{1,86} = 4.8$; $p < 0.032$) in each group, whereas the ROM of the shank elevation angle and the trunk mean inclination were not affected (shank ROM: $F_{1,86} = 1.2$; $p = 0.276$; trunk mean: $F_{1,86} = 3.9$; $p = 0.051$).

3.2. Intersegmental Coordination

On average, $PV_1 + PV_2 = 99.3 \pm 0.26\%$ (Figure 3B). However, PV_1 and PV_2 are similar between groups (PV_1: $F_{2,86} = 2.7$; $p < 0.074$; PV_2: $F_{2,86} = 2.5$; $p < 0.084$). Furthermore, PV_1 increases and PV_2 decreases with speed (PV_1: $F_{1,86} = 11.2$; $p = 0.001$; PV_2: $F_{1,86} = 12.1$; $p = 0.001$).

The orientation of the plane, evidenced by the direction cosine u_{3t} (Figure 3B,C), is smaller in $Older_{NA}$ than in $Older_A$ ($p < 0.001$) and in Young ($p < 0.001$), but there is no difference among $Older_A$ and Young ($p = 0.99$). In addition, in each group u_{3t} is reduced with speed of progression ($F_{1,86} = 11.3$; $p = 0.001$).

3.3. E_k–E_p Pendulum-Like Energy Exchange

The W_{COM} is different between groups ($F_{2,86}$ = 8.0; p = 0.001): W_{COM} is greater in $Older_{NA}$ than in $Older_A$ (p = 0.03), whereas no difference is observed among Young and $Older_A$ (p = 0.9). The % recovery also differs between groups (Figure 4A,B; $F_{2,86}$ = 7.0; p = 0.001): % recovery is smaller in $Older_{NA}$ than in $Older_A$ (p = 0.013) and Young (p = 0.012), whereas no difference is observed among $Older_A$ and Young (p = 0.999; Figure 4B).

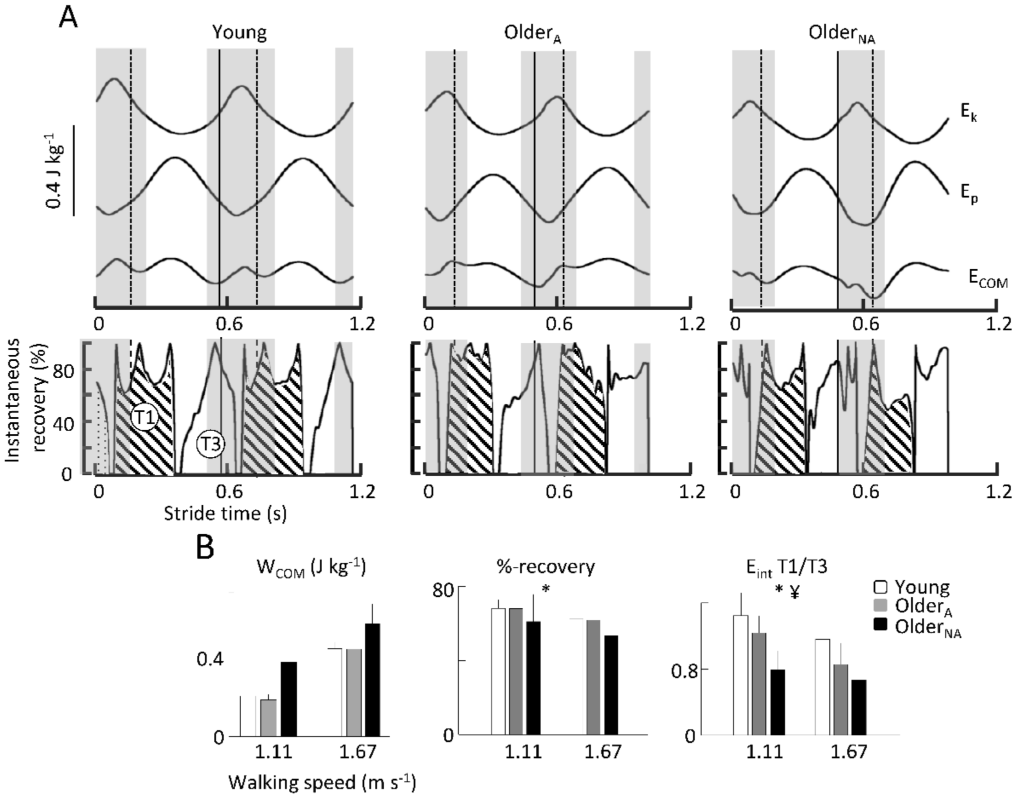

Figure 4. Pendulum mechanism of walking. (**A**) Typical traces of one representative stride of one subject in each group. Top panels: trace of the kinetic, potential and total energies of the COM during one stride during walking at 1.11 m·s^{-1}. Middle panels: instantaneous recovery at each instant t of the same stride, varying from 0% when the E_k and E_p curves are in phase to 100% when the decrease in one curve equals the increase in the other. (**B**) Positive external work carried out over one stride (W_{COM}), average recovery during the stride (% recovery) and ratio between the absolute amount of energy saved during T1 and T3 (E_{int} T1/T3). The symbols * and ¥ indicate a significant effect of age and speed, respectively. Other indications as in Figure 2.

During T1—when E_p increases while E_k decreases—the amount of energy saved through the pendulum-like energy exchange (E_{int}) is significantly different between groups ($F_{2,86}$ = 20.1; p < 0.001), whereas no significant difference is observed during T3, when E_p decreases while E_k increases ($F_{2,86}$ = 2.5; p = 0.086). As a result, the ratio between E_{int} during T1 and T3 is smaller in $Older_{NA}$ than in $Older_A$ (p < 0.001) and Young (p < 0.001, Figure 4B).

3.4. Correlation with COM Redirection

During walking at 1.11 m s^{-1}, the maximum ankle plantar-flexion (r = 0.452; p = 0.001), the average inclination of the trunk (r = 0.497; p < 0.001), the maximum hip extension (r = 0.480; p < 0.001), u_{3t} (r = 0.372; p = 0.007), the ratio between the thigh and shank ROM (r = 0.351; p = 0.011), the phase shift between the shank and foot elevation angles (r = 0.382; p = 0.006) and the ratio between E_{int} during T1 and T3 (r = 0.845; p < 0.001) are correlated with the timing of Vv_{min} relative to foot contact (Figure 5). These correlations hold true for walking at 1.67 m s^{-1}, except for u_{3t} and the phase shift between the shank and foot elevation angles (Figure S1).

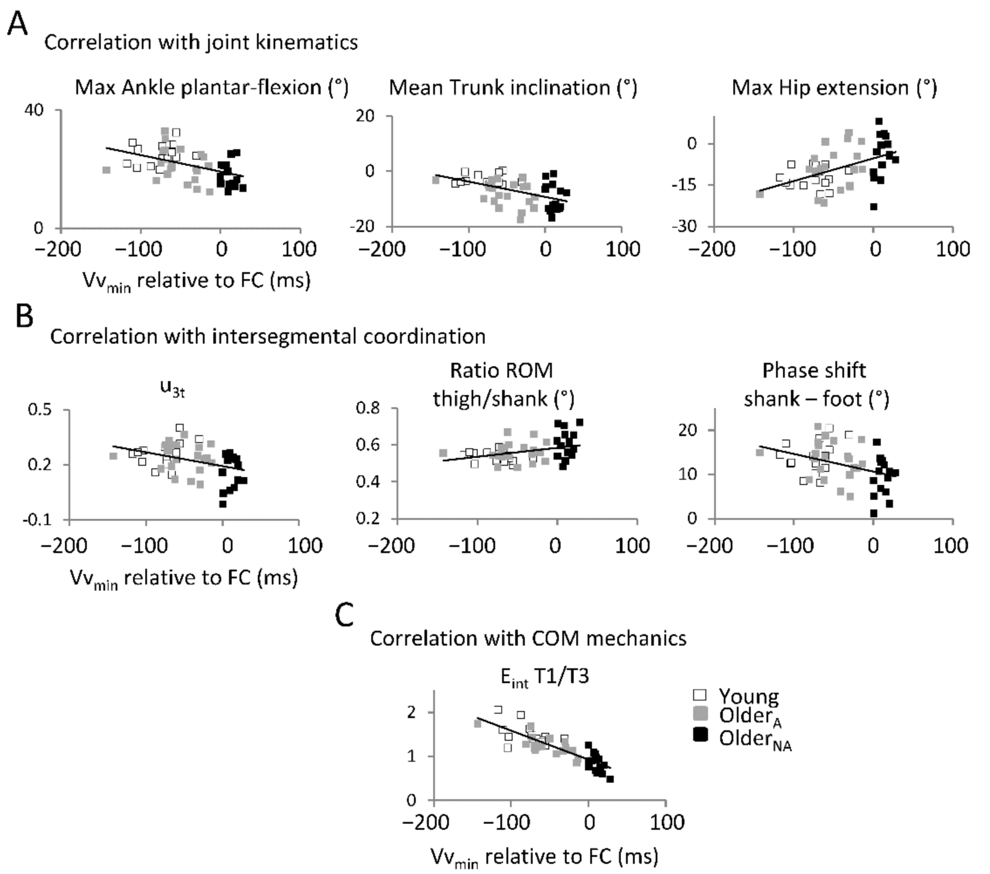

Figure 5. Correlations between step-to-step transition and other gait parameters. Each point represents the stride-averaged value for one subject walking at 1.11 m s^{-1}. Linear regression lines are also plotted. (**A**) Relationships between the delay between the minimal vertical velocity of the COM (Vv_{min}) and foot contact (FC) and joint kinematics: maximal ankle plantar-flexion, mean trunk orientation and maximal hip extension. (**B**) Relationships between the delay between Vv_{min} and FC and intersegmental coordination: orientation of the plane (u_{3t}), ratio between the range of motion of thigh and shank segments and the phase shift between shank and foot segments. (**C**) Relationships between the delay between Vv_{min} and FC and the ratio between E_{int} measured during T1 and T3. Other indications as in Figure 2.

4. Discussion

The aim of this study was to understand the relation between the modifications in walking pattern with aging and with step-to-step transition mode. Based on the transition mode, Meurisse et al. [9,10] identified two groups of older adults: one group with an anticipated transition ($Older_A$) and another with a non-anticipated transition ($Older_{NA}$). They suggested that the emergence of a non-anticipated transition with age could be an early sign of walking impairments and related it to static balance. In the present study, using the same subjects and the same classification of transition mode, we showed that the transition has direct consequence on the gait pattern. Indeed, as hypothesized, our results show that the differences in kinematics and mechanics among Young and $Older_{NA}$ are greater than those among Young and $Older_A$, suggesting that the step-to-step transition mode is reflected in gait pattern.

Based on joint kinetics, a handful of studies have documented a distal-to-proximal redistribution of joint effort (e.g., [7,9,14]). Here, we found a reduction in the maximal ankle plantar-flexion during stance (Figure 2B), together with a more inclined trunk, possibly adopted to increase the force generation by the hip extensors [5,8]. As hypothesized, these changes with age were more evident in $Older_{NA}$ than in $Older_A$. In addition, the modifications in intersegmental coordination also reflect the different walking strategy adopted by

Older$_{NA}$, potentially to reduce ankle plantar-flexion at the end of stance [5]. Indeed, compared to Young, the modified orientation of the plane (u_{3t}) observed in Older$_{NA}$ (Figure 3A) is mainly related to a change in the phase shift between the shank and foot elevation angles (Figure 3B) [12,14,25], as Older$_{NA}$ "lock their ankle" during mid-stance [26]. These changes in the pattern of intersegmental coordination may result in different trajectories of the COM [27] and thus in a modification of the pendulum-like COM energy exchange.

Regarding this COM energy exchange, to our knowledge, no study has identified an effect of age. Indeed, it has been documented that older and young adults perform similar mechanical work to lift and accelerate the COM during walking (and similar % recovery) [18,28]. While we observed similar results among Young and Older$_A$, our results underline a greater W_{COM}, partly due to a smaller % recovery in Older$_{NA}$ as compared to Young (Figure 4B). In addition, the pendular energy savings E_{int} is modified with the transition mode (Figure 4B) and diminished in non-anticipated walking pattern. Indeed, in Older$_{NA}$, a greater amount of the energy transformation is performed during T3 as compared to T1, when the COM falls and accelerates forward. This modification could be due to the inability of Older$_{NA}$ to accelerate the COM upward before double stance because of a lack of trailing leg push-off at the end of stance ([11]; Figure 1A). Consequently, the COM accelerates upward and forward (reducing % recovery) after the foot contact, mainly thanks to the ground reaction force exerted by the leading leg [10]. In addition, the inclined trunk may also contribute to the modification in COM position relative to the foot and change the COM trajectory.

In conclusion, our results show that the modifications in kinematics and mechanics with age are greater in older adults with non-anticipated transition. We also observe that the effect of age on kinematics seems to be more evident at the lowest tested speed (Figures 2B and 3B,C), whereas the age-related changes in mechanics seem to be greater at the highest walking speed (Figure 4B), suggesting that the investigation of different walking speeds is important to have a complete picture of the changes occurring with age. Indeed, as speed increases, the adaptive capacity of the system decreases [12,25,29] and the intersegmental coordination becomes more stereotyped. It could also explain why no correlation is observed between the orientation of the covariance plane and Vv_{min} at the higher speed (Figure S1). Interestingly, the non-anticipated transition mode has also been associated with pathologies [30]. For example, stimulation applied in the midbrain of Parkinson's disease patients has been shown to improve the transition (i.e., more anticipated) and to decrease their balance disorders [31]. In older adults, the postural sway during standing, reflecting instability, has been reported to be smaller in Old$_A$ as compared to Old$_{NA}$ [10]. In addition, while two modes of transition were defined here based on the vertical velocity of the COM (anticipated or not), we observed a progressive modification of our walking parameters with the timing of Vv_{min} (Figure 5). This suggests that in future studies, instead of classifying older adults into two restrictive classes, the timing step-to-step transition initiation could be directly compared to normative data of young adults. It would also allow for comparison between young and older adults in various walking conditions modifying the step-to-step transition, such as walking on slopes [11]. Therefore, assessing step-to-step transition in clinical practice may potentially be used as quantitative assessment of age-related decline in gait.

Limitations of the Study

In this study, the movements were only analysed in the sagittal plane because those represent the major and most systematic components of walking gait [32]. Using the data of Dewolf et al. [17], we compared the thigh, shank and elevation angles computed from both 3D and 2D data in young and older adults walking at 1.11 m s^{-1} on a treadmill. The difference in elevation angles was always <5%, and no effect of age was observed on that difference (t-test; p = 0.959).

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app12105055/s1, Figure S1: Correlations between step-to-step transition and other gait parameters.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board (or Ethics Committee) of Université catholique de Louvain, 2015/18MAI/245, Belgian Registration Number: B403201524765.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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