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Anticipatory postural adjustment patterns during gait initiation across the adult lifespan

Chiahao Lu, PhD[a], **Sommer L. Amundsen Huffmaster, PhD**[a], **Jack C. Harvey**[a], and **Colum D. MacKinnon, PhD**[a]

[a]Movement Disorders Laboratory, Department of Neurology, University of Minnesota, 516E, 717 Delaware St. SE, Minneapolis, MN 55414, USA

Abstract

Gait initiation involves a complex sequence of anticipatory postural adjustments (APAs) during the transition from steady state standing to forward locomotion. APAs have four core components that function to accelerate the center of mass forwards and towards the initial single-support stance limb. These components include loading of the initial step leg, unloading of the initial stance leg, and excursion of the center of pressure in the posterior and lateral (towards the stepping leg) directions. This study examined the incidence, magnitude, and timing of these components and how they change across the lifespan (ages 20–79). 157 individuals performed five trials of self-paced, non-cued gait initiation on a computerized walkway. At least one component of the APA was absent in 23% of all trials. The component most commonly absent was loading of the initial step leg (absent in 10% of all trials in isolation, absent in 10% of trials in conjunction with another missing component). Trials missing all four components were rare (1%) and were observed in both younger and older adults. There was no significant difference across decades in the incidence of trials without an APA, the number or type of APA components absent, or the magnitude or timing of the APA components. These data demonstrate that one or more components of the APA sequence are commonly absent in the general population and the spatiotemporal profile of the APA does not markedly change with ageing.

Keywords

gait initiation; anticipatory postural adjustments; balance; posture; ageing

Address correspondence to: Chiahao Lu, PhD, University of Minnesota, Department of Neurology, 516E. 717 Delaware, 717 Delaware St. SE. Minneapolis, MN 55414, USA, luxxx214@umn.edu, Tel: 612 626 8027.

Conflict of interest statement

The Zeno Walkway and PKMAS software for this study was provided, at no cost, by ProtoKinetics. A Protokinetics representative was present for the data collection. None of the authors have any financial or personal relationships with ProtoKinetics that could inappropriately influence this work.

Introduction

The transition from standing to locomotion is usually accompanied by a sequence of anticipatory postural adjustments (APA) that stabilize posture in anticipation of the stepping leg coming off the ground [1]. APAs that accompany forward stepping typically involve four primary components: loading of the initial stepping leg, unloading of the initial stance leg, and movement of the net center of pressure (CoP) posteriorly (generating an anterior ground reaction force to accelerate the center of mass (CoM) forwards) and laterally towards the stepping limb (generating a horizontal reaction force directed toward the initial stance limb). Gait initiation have been studied extensively in healthy young [2–4], older adults [5–12] and people with neurological or orthopedic disorders (e.g. [6, 13–17]). These studies have described the timing and amplitude of the APAs and their relationship to spatiotemporal characteristics of the initial step. The implicit assumption in these studies is that all APA components are present in the healthy control group and that reduced or absent components are indicative of pathology or compensation. A marked reduction in APA amplitude, increase in duration or the absence of APA components is also considered a risk factor for falls [18, 19]. However, APAs can be absent in older healthy individuals. For example, Rogers et al. [14] reported that 2 of the 7 healthy subjects (mean age 66 years) had two trials without an APA during self-initiated forward stepping. Similarly, Delval et al. [16] reported that APAs were absent in 5% of self-initiated trials in controls. The sample sizes in these studies were relatively small (less than 30) and the population sampled was restricted to individuals in the 50–80 year range. Currently, little is known about the incidence of the primary APA components in the general population and how this changes across the lifespan.

The purpose of this study was to characterize APAs during gait initiation in a large cohort and to quantify how the incidence, magnitude and timing of the four primary APA components change as a function of decade in life. Based on the observation of trials with absent APAs in older adults [14, 16], we hypothesized that the incidence of APAs with one or more component missing would increase over the age of 59 years (7th and 8th decade) in conjunction with decreased magnitude and increased duration.

Methods

Subjects

The study consented 187 adults from a sample of convenience at the 2014 Minnesota State Fair. Subjects were excluded if they were unable to walk independently for 50m without an assistive device (e.g. cane) or required help from a caregiver. Subjects who had consumed more than one alcoholic beverage during the day were also excluded. Four additional subjects were excluded due to technical problems or inability to follow task instructions. 157 subjects (54 men and 103 women) were included in the final analysis. The Institutional Review Board at the University of Minnesota approved the protocol and informed consent was obtained from all subjects before study participation.

Instrumentation

Whole life health histories and gait initiation data were collected. Gait initiation was collected at 120 Hz using the Zeno Electronic Walkway© and associated software (ProtoKinetics Movement Analysis Software (PKMAS), ZenoMetrics LLC, Peekskill, NY). The 14 ft. long × 4 ft. wide mat contained 46,080 sensors (0.4″ square) with 16 levels of dynamic pressure per sensor. This system has been shown to provide reliable and valid measures of gait kinetics in healthy adults [20].

Protocol

Trials started with the subject in quiet standing with their feet placed in their preferred natural stance. Following a verbal cue of "anytime", subjects waited a self-selected time interval (no less than 3 s) then initiated forward stepping at their self-chosen pace, with their self-chosen stepping leg, and walked to the end of the mat. Trials initiated less than 3 s after the "anytime" were recollected to eliminate cue-triggered gait. Five valid trials were collected and reviewed online to ensure a steady-state baseline before the "anytime" instruction. Trials without a period of steady-state standing were discarded and repeated.

Data analysis

Gait initiation data were exported from PKMAS and analyzed using customized scripts written in MATLAB 2014b (MathWorks, Natick, MA). The primary APA components measured from each trial were: (1) peak step leg loading, (2) peak stance leg unloading, (3) peak posterior excursion of the CoP and (4) peak lateral excursion of the CoP toward the step leg, along with step and stance leg toe-off times, and first step time and length (normalized to leg length, measured from the greater trochanter to the floor). Loading/unloading measures beneath each leg were normalized to percent total body weight (BW, determined from steady-state standing) [21]. Onset times of the APA variables were calculated with a threshold of >3 standard deviations from the mean quiet stance baseline, verified by visual inspection, and adjusted if necessary [22].

Statistical analysis was performed using SPSS (version 22, SPSS Inc., Chicago, IL). Between group (6 age groups: 20–29, 30–39, 40–49, 50–59, 60–69, 70–79 years old) differences in demographic variables were tested with a chi-square test for categorical variables and a one-way analysis of variance (ANOVA) for continuous variables. A multivariate one-way analysis of covariance (MANCOVA) was used to compare group differences in the APA and first step amplitude with the initial stance width entered as a covariate [23]. Group differences in APA timing were tested with a MANOVA. Generalized estimating equations (GEE) with repeated measures was performed to determine group differences in the incidence of APA patterns. The incidence of each APA pattern (1=present, 0=absent) was entered into GEE with the number of each APA pattern out of the total trials in each subject. Effects were considered to be significant at $p < 0.05$.

Results

Subject Demographics

Table 1 provides the demographic summary across subjects and decade of life. Ageing was associated with a progressive increase in the individuals reporting neurological and/or orthopedic-related problems (chi-square = 29.85, df = 15, p = 0.012).

Incidence of APA components

Complete data sets were captured in 149 of 157 subjects. Nine trials across 8 subjects were excluded during post-hoc processing due to unstable baselines. Table 2 summarizes the incidence of APA components and patterns across all subjects and decades of life. At least one APA component was absent in 23.8% of all trials across all subjects. Trials with 3 components present were relatively common (12.7%), whereas trials with 2 components or less were considerably less frequent. Trials with all four APA components absent were relatively rare (1.3%). The component most commonly missing was step leg loading (absent in 20.5% of trials; 10.3% in isolation, 10.2% in conjunction with other components). There was no significant difference in the incidence of trials with 4, 3, 2, 1, or 0 components across groups (Wald chi-square < 8.1, df = 5, p > 0.15). To examine if the APA patterns might be associated with a systematic asymmetry in weight bearing between the legs prior to gait initiation, the baseline step-to-stance leg loading ratio was calculated (Table 2). The average ratio was near 1.00 for all APA patterns and the distribution of ratios for each pattern was Gaussian (with the exception of some rare patterns with only a few trials).

Examples of the three most common patterns observed across subjects are shown in Figure 1. Nearly three quarters of trials had a four component APA. The second most common pattern was the step leg loading component absent in isolation (10.3%). Trials that lacked kinetic components in the medial-lateral plane but still contained a posterior shift in the CoP were the third most common pattern (5.0%). This pattern was usually associated with an early and gradual unloading of the step leg (see Figure 1). Trials with just an absent posterior CoP shift (1.4%), stance leg unloading (0.6%) or lateral CoP shift (0.4%) in isolation were rare. There was no significant difference in the incidence of APA patterns across groups (Wald chi-square < 9.2, df = 5, p > 0.10).

Peak amplitude and timing of the APA components

Average peak amplitudes and timings of the APA components and the first step across subjects and decades are presented in Table 3. There was a distinct asymmetry in the relative levels of step leg loading and stance leg unloading. The average peak step leg loading was approximately one third of the peak unloading (4.0 vs. −12.2% BW respectively). The average excursions of the CoP were 1.9 ± 1.0 cm posterior and 2.0 ± 1.2 cm lateral towards the stepping leg. The APA was immediately followed by unloading of the step leg, loading of the stance leg (21.7 ± 6.0% BW), excursion of the CoP towards the stance leg and a second posterior shift in the CoP (2.0 ± 1.5 cm) prior to toe-off. The only significant group effect was found in the normalized first step length (F = 2.74, df = 5, p = 0.021). Post-hoc showed the first step length was 8% greater in the 50–59 age group than in the 70–79 age group (p = 0.026). Initial stance width was a significant covariate for all APA amplitude variables except for the second posterior shift in the CoP ($p = 0.063$), but stance width did not significantly vary across groups.

The time to peak loading of the step leg was an average of 68 ms earlier than the time to peak unloading. The timings of all components of the APA were similar across groups. While the timing of toe-off of the step and stance leg were generally later in the 70–79-year-old group, there was no significant effect of group ($F < 2.06$, df = 5, $p > 0.08$).

Discussion

Our novel findings were: (1) one or more components of the APA were absent in approximately one quarter of all gait initiation trials and (2) the incidence of absent APA components was similar across decades of life. These results demonstrate that gait initiation in the general adult population, regardless of age, does not require the presence of all four APA components and alternative strategies are commonly employed.

Early research of gait initiation emphasized the close temporal coupling of ground reaction forces and muscle activation patterns [1, 24, 25], suggesting that the APAs prior to gait initiation represent a preset motor program, or anticipatory synergy, that can be modulated by the task-dependent postural requirements. Consistent with this idea, altering initial step length, speed or direction of gait initiation can impact the magnitude and timing of the APAs [1, 23, 26–28]. While a central motor program may contribute to APA generation during gait initiation, the incidence data derived from our study demonstrates that there is considerable variability within- and across-individuals in the strategies employed.

In our sample population, approximately one quarter of all trials were missing one or more APA components. The second most common pattern (10.3%) was the absence of initial loading of the stepping leg with all other components present. This strategy still generates a posterior and lateral excursion of the CoP towards the step leg and a net force couple to accelerate the CoM forward and towards the stance limb, in the same manner as a four component APA. In contrast, trials without unloading of the stance limb in isolation were very rare (0.6%) even though this strategy would also move the CoM towards the stance side. There were also marked differences in the timing and amplitudes of the reciprocal peak loading and unloading components; the average loading force was +4% BW and the unloading force was −12% BW (Table 3). The time to peak loading preceded peak unloading by an average of 68 ms. Previous studies have typically reported ground reaction forces beneath the step and stance limbs that are comparable in magnitude but opposite in polarity (e.g. loading = 12%, unloading = −12% BW) [4]. The low average peak loading force on the step leg side can be explained partly by the relatively high incidence of trials missing initial loading of the stepping leg. It is important to note that these asymmetric gait initiation patterns could not be explained by a consistent weight-bearing asymmetry during the baseline period immediately prior to stepping since the ratio of step-to-stance leg loading remained near 1.00. These data suggest that unloading of the stance limb was frequently uncoupled from the reciprocal loading of the stepping limb, and thus there is considerable flexibility in the net flexion-extension patterns generated by the stance and step legs during gait initiation.

Gait initiation strategies that did not generate both a net anterior and lateral acceleration of the CoM towards the initial stance side were relatively rare. APAs without kinetic components in the medial-lateral plane (no stance leg unloading, step leg loading or lateral shift in the CoP towards the stepping side) were seen in 5% of all trials. Trials without an posterior shift of the CoP were also rare (1.4%). This latter pattern might be generated by a progressive forward lean and anterior tilt of the torso whereby anterior shear forces are generated without an initial posterior excursion of the CoP; a strategy often employed by lower limb amputees [29, 30]. All four APA components were absent in 1.3% of trials. This is consistent with studies reporting only a small percentage of trials with no APA components in healthy older adults [14, 16]. Moreover, it demonstrates that trials without an APA are not indicative of pathology when seen with low incidence. In contrast, some neurological disorders, such as Parkinson's disease, are associated with a relatively high incidence of trials with no APA (e.g. Rogers et al., 2001: 20% of all self-initiated trials; Delval et al., 2014, 14–43% of all trials) [14, 16], suggesting that the persistent absence of APAs may be associated with pathological processes or abnormal compensatory mechanisms.

Our findings did not support the hypothesis that the older age groups (60–79 years in particular) would show a higher incidence of APAs with missing or attenuated APAs. Previous studies comparing APAs between young and older groups have been equivocal. The most consistent observation has been a significant decrease in the peak posterior excursion in the CoP in older adults [8, 11], often accompanied by a reduced first step length and speed, particularly in older adults who are transitioning to frailty [5]. Yet, other studies found no significant effect of age during self-initiated stepping [6, 7, 9]. Comparisons between studies are confounded by different sample sizes, cohort ages, and step initiation modes (self-paced vs. fast-paced and self-initiated vs. externally cued significantly modify APAs). In our study, the magnitude and timing of the APA were not significantly different across decades. The incidence of trials without a medial-lateral shift (12.8%) or with only one component of an APA (14.1%) was higher in the 70–79 age group, but did not reach significance. Differences in group sample sizes may have influenced our incidence data, as a smaller sample has a lower probability of seeing a missing component, but this is an inherent limitation in a sample of convenience. Our sample of older adults may also have been biased towards individuals who are not frail and have little to no movement disability. Risk of falls has been associated with the duration of cued step initiation in several studies [18, 19]. However, without knowing the fall history in our subjects, our findings on APA patterns during gait initiation cannot be generalized to fall risk. Nonetheless, the lack of a distinct change in the timing, magnitude or pattern of APAs in the older groups, particularly the 50–79 range, is noteworthy since more than 30% of these subjects self-reported a history of significant orthopedic issues affecting the lower limbs (Table 1). With only a self-reported medical history, it is difficult to discern whether the maintenance of the APA patterns reflects a compensatory response or the musculoskeletal issues were insufficiently severe to impact performance.

Our results should be interpreted and extrapolated cautiously. First, these data are relevant only to self-initiated, self-paced gait initiation from a quiet standing position. The APAs associated with gait initiation in response to a sensory cue (e.g. acoustic tone) are usually significantly larger in magnitude and shorter in duration than self-initiated stepping [14, 31, 32]. Second, the relatively high incidence of APAs with missing components in the present study might be explained by the task instructions. Subjects were asked to “initiate forward stepping, at their comfortable pace at any self-selected time”, thus the strategies used to initiate stepping, both in terms of effort and timing, were likely to be different across subjects. Most gait initiation studies have used instructions, such as “initiate stepping as quickly as possible” to standardize effort across subjects. Trials with a faster initial step speed are preceded by a larger posterior excursion of the CoP [1, 23, 26–28]. In addition, we did not standardize the initial conditions during quiet standing in terms of the location of the CoP or relative loading of the stance and step legs. We recognize that the incidence of the various APA patterns may have been different if these constraints had been placed on the task. Additional limitations of the study are the low number of trials collected per subject (5 trials) and the disproportionately low number of subjects in some of the age groups (Table 2).

This study shows for the first time that APA components can commonly be absent during self-timed, self-paced gait initiation in ambulatory adults. The incidence of patterns, magnitudes, and timing of APAs were similar across age groups. Under comparatively unconstrained task instructions, adults use a variety of strategies to generate the first forward step of gait initiation.

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Highlights

- APAs during gait initiation usually include four core kinetic components.
- APA components are commonly absent during self-paced gait initiation in 157 adults.
- The incidence of alternative APA strategies was similar across decades of life.
- Adults commonly use alternative APA strategies during self-paced gait initiation.

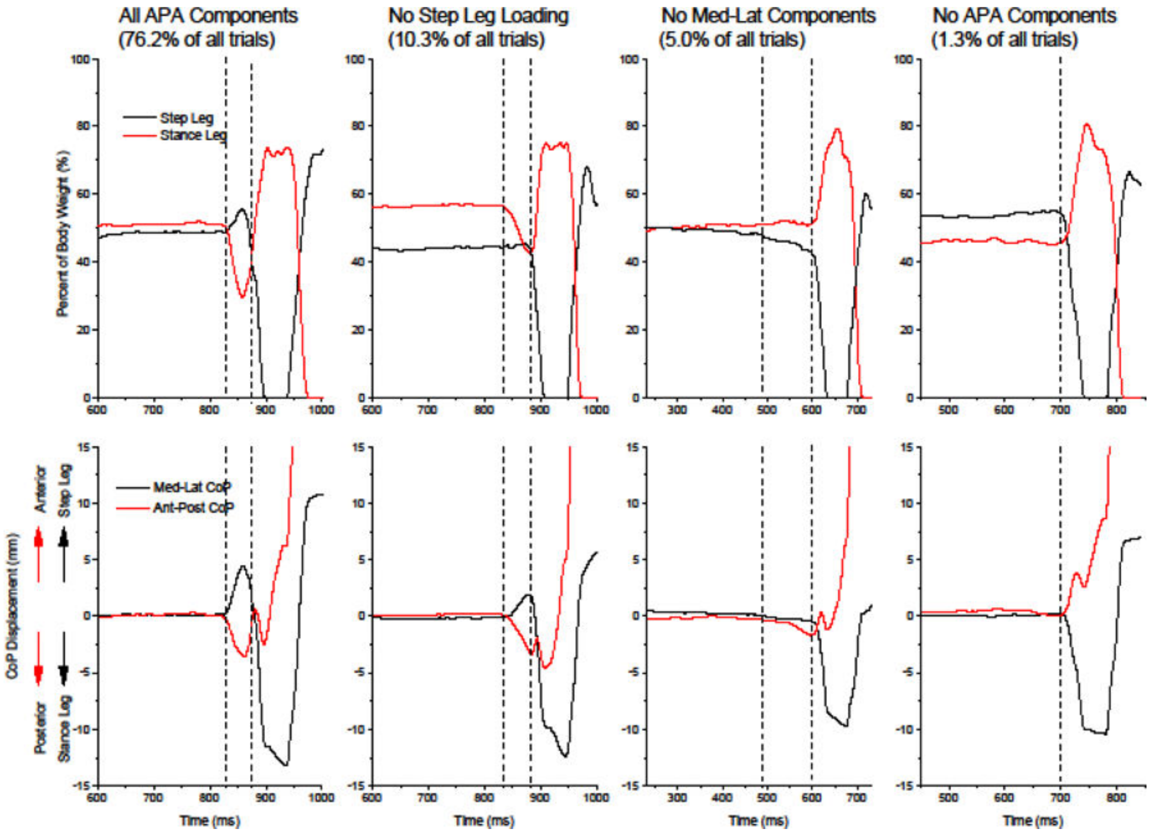

Figure 1.

Representative single trials showing examples of the three most common strategies used to initiate gait and a trial with no APA components. The top row shows the loading force beneath the initial step and stance legs (as a percentage of body weight) and the bottom row shows the excursion of the center of pressure (CoP) in the medial-lateral (Med-Lat) and anterior-posterior (Ant-Post) directions.

Table 1

Summary of the subject demographics and histories.

		Age (Years)					
	Total	**20–29**	**30–39**	**40–49**	**50–59**	**60–69**	**70–79**
No. Subjects	157	27	13	15	44	42	16
Sex (M/F)	54/103	11/16	3/10	3/12	14/30	18/24	5/11
Stepping Leg	L = 11 R = 141 NP = 5	L = 1 R = 25 NP = 1	L =2 R = 10 NP = 1	L = 0 R = 15 NP = 0	L = 5 R = 37 NP = 2	L = 2 R = 39 NP = 1	L = 1 R = 15 NP = 0
History total (% total)							
None	102 (65)	24 (89)	11 (86)	12 (80)	26 (61)	22 (52)	7 (44)
Neurologic	10 (6)	3 (11)	1 (7)	1 (7)	3 (7)	0 (0)	2 (13)
Orthopedic	42 (27)	0 (0)	1 (7)	2 (13)	14 (30)	19 (46)	6 (38)
Neuro+Ortho	3 (2)	0 (0)	0 (0)	0 (0)	1 (2)	1 (2)	1 (6)

NP: no preferred initial stepping leg

Table 2

Summary of the incidence of APA components and patterns and weight distribution prior to APA onset.

		Age (Years)					
	Total	**20–29**	**30–39**	**40–49**	**50–59**	**60–69**	**70–79**
Number of Subjects	157	28	11	15	46	41	16
Number of Trials	776	133	64	74	219	208	78
Number of APA Components	Percentage of trials (across subjects) with component count						
4 components	76.2	82.7	73.4	67.6	79.9	75.5	66.7
3 components	12.7	9.0	14.1	17.6	12.3	14.4	10.3
2 components	4.1	3.0	6.3	5.4	4.1	2.9	6.4
1 component	5.7	3.0	4.7	6.8	3.7	6.3	14.1
0 component	1.3	2.3	1.6	2.7	0	1.0	2.6
Most Common APA Patterns	Percentage of trials (across subjects) with APA pattern						
1. All APA components Present	76.2	82.7	73.4	67.6	79.9	75.5	66.7
2. Loading Component Absent	10.3	5.3	10.9	14.9	11.4	12.5	5.1
3. Lateral CoP shift, Loading & Unloading Absent	5.0	3.0	3.1	5.4	3.2	5.8	12.8
4. Just Posterior CoP Shift Absent	1.4	3.0	1.6	1.4	0.5	1.0	2.6
5. All APA Components Absent	1.3	2.3	1.6	2.7	0	1.0	2.6
Baseline step:stance leg loading ratio	Mean ratio (± 1 std. dev.)						
All APA components Present	1.00 (0.21)	0.99 (0.19)	0.99 (0.17)	1.07 (0.28)	1.02 (0.21)	0.97 (0.19)	0.94 (0.25)
Loading Component Absent	0.99 (0.25)	1.08 (0.15)	0.95 (0.12)	1.27 (0.48)	0.89 (0.13)	0.98 (0.18)	0.83 (0.21)
Lateral CoP shift, Loading & Unloading Absent	0.97 (0.12)	1.04 (0.10)	0.84 (NA)	1.06 (NA)	1.08 (NA)	0.90 (0.02)	0.88 (0.19)
Just Posterior CoP Shift Absent	1.02 (0.24)	1.07 (0.12)	1.04 (0.14)	1.12 (0.31)	0.93 (0.12)	1.02 (0.16)	1.04 (0.38)
All APA Components Absent	1.00 (0.23)	1.04 (0.28)	1.20 (NA)	1.15 (0.01)	NA	1.03 (0.07)	0.68 (0.08)

NA: not applicable

Table 3

Summary of the mean amplitude (± 1 std. dev.) and timing (± 1 std. dev.) of the primary APA and step variables.

		Age (Years)					
	Total	**20–29**	**30–39**	**40–49**	**50–59**	**60–69**	**70–79**
Number of Subjects	157	27	13	15	44	42	16
Amplitude Components							
Peak Loading Step Leg (% BW)	4.0 (2.2)	4.6 (2.1)	3.8 (2.1)	3.5 (2.4)	4.1 (2.0)	3.9 (2.4)	3.8 (1.8)
Peak Unloading Stance Leg (% BW)	−12.2 (5.7)	−12.6 (5.8)	−12.1 (5.5)	−10.8 (5.3)	−12.7 (5.0)	−12.6 (6.6)	−10.5 (5.2)
Peak Loading Stance Leg (% BW)	21.7 (6.0)	22.4 (7.0)	21.6 (5.9)	24.4 (7.1)	21.1 (5.4)	20.5 (5.7)	22.8 (5.4)
Posterior CoP Peak 1 (cm)	−1.9 (1.0)	−1.9 (1.0)	−2.0 (0.9)	− 1.6 (0.8)	−2.0 (0.8)	−2.0 (1.2)	−1.8 (1.1)
Posterior CoP Peak 2 (cm)	−2.0 (1.5)	−2.1 (1.7)	−1.6 (1.5)	−1.5 (1.7)	−2.2 (1.3)	−2.2 (1.4)	−2.0 (1.5)
Peak lateral CoP (cm)	2.0 (1.2)	2.3 (1.4)	2.1 (1.3)	1.8 (1.0)	2.1 (1.2)	2.1 (1.3)	1.6 (0.9)
Timing of Components (ms)							
Peak Loading Step Leg	290 (88)	287 (84)	299 (69)	273 (78)	311 (94)	278 (85)	287 (116)
Peak Unloading Stance Leg	358 (79)	338 (73)	376 (96)	350 (64)	376 (82)	352 (74)	351 (90)
Peak Loading Stance Leg	722 (123)	685 (131)	732 (127)	710 (139)	760 (122)	707 (100)	723 (142)
Time to Posterior CoP Peak 1	385 (94)	357 (105)	405 (60)	430 (146)	384 (94)	384 (77)	383 (94)
Time to Posterior CoP Peak 2	689 (122)	639 (114)	746 (72)	686 (143)	715 (133)	675 (110)	694 (121)
Peak Lateral CoP	338 (78)	324 (61)	370 (98)	337 (70)	353 (79)	327 (69)	329 (112)
Step Leg Toe-off	680 (134)	639 (119)	668 (104)	709 (116)	725 (156)	656 (111)	676 (162)
Stance Leg Toe-off	1372 (162)	1314 (146)	1370 (184)	1368 (197)	1398 (153)	1375 (142)	1404 (205)
Stance and Step Measures							
Initial Stance Width (cm)	20.7 (4.7)	21.8 (4.9)	22.2 (5.0)	20.0 (5.2)	20.5 (4.8)	20.8 (4.5)	19.1 (3.6)
Initial Stance Width (ratio leg length)	0.24 (0.05)	0.25 (0.06)	0.25 (0.05)	0.23 (0.07)	0.23 (0.05)	0.24 (0.05)	0.22 (0.05)
First Step Length (cm)	55.3 (7.8)	56.6 (6.9)	56.7 (4.8)	55.3 (6.4)	57.9 (6.8)	53.5 (7.8)	50.0 (11.1)
First Step Length (ratio leg length)	0.64 (0.09)	0.64 (0.08)	0.65 (0.06)	0.64 (0.07)	0.66 (0.08)	0.62 (0.09)	0.58 (0.12)
First Step Width (cm)	15.7 (4.0)	15.4 (4.2)	17.5 (3.8)	14.8 (5.1)	15.5 (4.1)	16.1 (3.6)	15.3 (3.4)
First Step Width (ratio leg length)	0.24 (0.05)	0.25 (0.06)	0.25 (0.05)	0.24 (0.07)	0.23 (0.05)	0.24 (0.05)	0.22 (0.05)