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Self-paced versus fixed speed treadmill walking

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ABSTRACT

Instrumented treadmills are increasingly used in gait research, although the imposed walking speed is suggested to affect gait performance. A feedback-controlled treadmill that allows subjects to walk at their preferred speed, i.e. functioning in a self-paced (SP) mode, might be an attractive alternative, but could disturb gait through accelerations of the belt. We compared SP with fixed speed (FS) treadmill walking, and also considered various feedback modes. Nineteen healthy subjects walked on a dual-belt instrumented treadmill. Spatio-temporal, kinematic and kinetic gait parameters were derived from both the average stride patterns and stride-to-stride variability. For 15 out of 70 parameters significant differences were found between SP and FS. These differences were smaller than 1 cm, 1°, 0.2 N m and 0.2 W/kg for respectively stride length and width, joint kinematics, moments and powers. Since this is well within the normal stride variability, these differences were not considered to be clinically relevant, indicating that SP walking is not notably affected by belt accelerations. The long-term components of walking speed variability increased during SP walking (43%, $p < 0.01$), suggesting that SP allows for more natural stride variability. Differences between SP feedback modes were predominantly found in the timescales of walking speed variability, while the gait pattern was similar between modes. Overall, the lack of clinically significant differences in gait pattern suggests that SP walking is a suitable alternative to fixed speed treadmill walking in gait analysis.

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1. Introduction

Instrumented treadmills are increasingly common in clinical gait analysis laboratory settings as an alternative to over ground gait analysis, because they allow for measurement of repetitive strides, require less laboratory space and facilitate the measurement of ground reaction forces through the embedded force plates. However, walking on a treadmill is known to affect gait performance, resulting in decreased preferred walking speed and stride length [1,2], slightly decreased joint range of motion and small changes in EMG activation [3,4]. It has been suggested that these differences are a result of the absent visual flow, limited length of the belt and imposing a fixed walking speed. Whereas the effects of a visual environment on gait have previously been investigated [5], the role of constraints imposed by the fixed walking speed remains unknown.

The drawbacks of an imposed walking speed could possibly be solved by a feedback-controlled treadmill that adapts treadmill speed to the user, i.e. allows for so called self-paced (SP) walking. This SP walking would allow the subjects to apply their natural way of controlling and varying walking speed, presumably leading to a more natural gait. Besides this, SP walking offers several practical advantages. First, it would no longer be necessary to establish the preferred walking speed prior to setting a fixed belt speed. In addition, SP walking offers new experimental possibilities such as measurement of long term gait variability or fatiguing. On the other hand, it comes at the cost of applying accelerations and decelerations in order to keep the subject around the center of the treadmill, variations that will probably be reflected as errors in gait kinematics and kinetics. Although the ability of SP systems to support smooth transitions from standing to walking has been demonstrated [6–8], the effect of SP walking on gait has yet to be established.

To date, a variety of SP modes have been developed based on standard PD-controllers, in which the belt speed is controlled by the feedback of the subject's position on the belt along with their walking speed. Several variations are reported including a central zone [6,9], a feed-forward term in the control mechanism [7], or differential gain as a function of position [10]. The extent to which SP walking will resemble the natural behavior of the subject is expected to depend on a specific feedback algorithm and its parameters. An optimum is likely to exist, with the unwanted effects of the accelerations and decelerations minimized, while physiological variability is facilitated.

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In this study we investigated possible differences between SP and fixed speed (FS) treadmill walking, in terms of spatio-temporal, kinematic and kinetic gait parameters, for both the average stride pattern as well as the within subject stride-to-stride variability. To assess the relevance of a specific control mechanism, three different SP modes with varying gains were also compared.

2. Methods

2.1. Protocol

Nineteen healthy subjects (age: 29.2 ± 5.0 yr; BMI: 24.2 ± 3.3; 12 male) walked on a split-belt instrumented treadmill, placed in a virtual environment with 180° projection (Fig. 1: GRAIL, Motek Medical BV, the Netherlands), of which the optical flow stayed at the same pace as the treadmill speed. Subjects gave informed consent in accordance with the procedures of the Institutional Review Board of the VU University. Ground reaction forces and moments were measured based on force sensors mounted underneath both treadmill belts (50 cm × 200 cm). Kinematic marker data of the lower extremities were collected via a passive marker motion capture system (Vicon, Oxford, UK) and synced at 120 Hz to the force data. Lower body joint kinematics and kinetics were calculated in real-time using the Human Body Model (HBM; Motek Medical BV).

After being given at least 6 min to habituate to SP and FS treadmill walking, subjects first walked at SP and then at speed-matched FS, followed by three different SP modes in a random order. All conditions lasted 3 min and data were recorded during the last minute. Following each trial, subjects subjectively rated resemblances to normal over ground walking, fatiguing and comfortable walking speed on a scale from 1 to 10 each.

2.2. Self-paced algorithm

The following SP modes of the GRAIL software (version 1.0, Motek Medical BV, the Netherlands) were used:

(1) The initially applied SP mode:
  a. SP: a PD-controller, i.e. speed correction proportional to the difference in position between subject and middle of the belt, and to the speed of the subject, with its *D*-gain also a function of the position, i.e.: $\ddot{x} = P\Delta x - \Delta x D\dot{x}$
(2) After FS, the following modes were randomly applied:
  a. SP_p: same as SP;
  b. SP_{2p}: same as SP, but with a doubled gain for both *P* and *D*, i.e.: $\ddot{x} = 2(P\Delta x - \Delta x D\dot{x})$
  c. SP_v: a PD-controller, together with a speed dependent multiplication factor, i.e.: $\ddot{x} = \dot{x}(P\Delta x - \Delta x D\dot{x})$

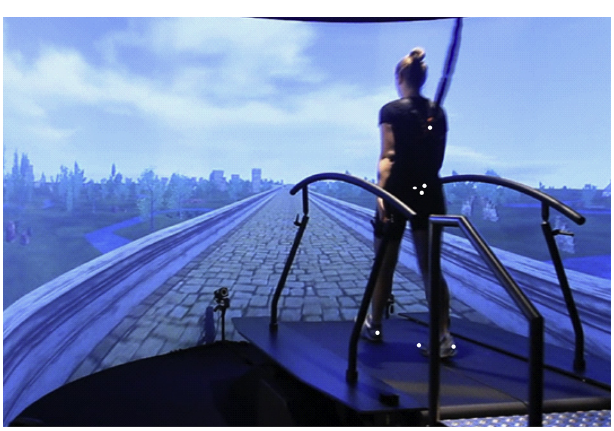

Fig. 1. Gait Real-time Analysis Interactive Lab (GRAIL), consisting of a dual-belt instrumented treadmill placed in a speed-matched virtual environment with 180° projection. An optoelectronic system with reflective markers was used to measure joint movement.

The position of the subject was calculated as the average position of four 2 Hz-filtered pelvic markers, to reduce the influence of marker occlusion and within-stride pelvic fluctuations. Treadmill speed was updated with 30 Hz, using a 6 kW motor per belt.

2.3. Data processing

Marker and forceplate data were low-pass filtered at 6 Hz. Using HBM, 3 DOF of trunk, pelvis, and hip, as well as 1 DOF of knee and ankle joint kinematics and kinetics were calculated. Subsequently, strides with correct foot placement on a single belt were selected based on force data and time-normalized to strides.

Stride length and time, walking speed, step width, and stance percentage per stride were calculated from the foot marker data. To compare kinematics between different conditions, the curves were quantified by their mean value ('offset') and offset-corrected RMS ('magnitude'). Similarly, the kinetic curves were quantified by dividing the surface area under the SP curve by the area under the FS curve ('gain') and by calculating the gain-corrected RMS. In addition, to compare clinically relevant features of the gait pattern, kinematic parameters of the Gillette Gait Index [11] and similar relevant kinetic parameters were derived from the curves (Table 1). Average values and stride variability, taken as the standard deviation, were calculated for each subject.

To quantify the variations in actual walking speed over time, 0.5 Hz low-pass filtered belt speed as registered by the controller was summed with equally filtered pelvis marker speed. The resulting walking speed as function of time was Fourier transformed to the frequency domain. In addition, the position of a subject on the belt was deducted from the pelvis marker data and defined by its range (i.e. ±3 standard deviations).

2.4. Statistics

To compare SP and FS, data were tested for normality and, depending on the outcome, statistically analyzed using paired *t*-tests (in 66% of the cases) or non-parametric sign-rank tests (α = 5%). To test if subjects were given enough habituation time, SP was compared with the second SP-trial, i.e., SP_p, in a similar manner. The three SP modes were compared using a repeated measure ANOVA (in 74% of the cases) or a Kruskal–Wallis test.

3. Results

3.1. FS versus SP walking

Subjects rated FS and SP walking as comparable in their resemblance to normal over ground walking, fatiguing and comfortable walking speed (average values: SP: 7.1, FS: 7.0). For 15 out of 70 tested parameters, significant but small differences were found in the stride pattern between SP and FS walking (Fig. 2 and Table 1). Since FS walking speed was imposed, SP and FS walking speed were equal. During SP walking, stride length and stance percentage were decreased by less than 1% compared to FS walking ($p < 0.02$), and step width was increased by 5.2% ($p < 0.05$). For joint kinematics, SP resulted in a reduced range of motion, but with differences smaller than 1.0°, in hip abduction (2.3% RMS, $p = 0.02$), hip flexion (−1.5% range, $p < 0.01$), knee flexion (4.8% peak at initial contact, $p = 0.02$; −1.5% range, $p < 0.01$), and ankle plantar flexion (−2.6% peak during stance, $p = 0.02$). Differences in joint kinetics were below 0.2 N m or 0.2 W/kg, with reduced abduction moment of the knee (10.9% RMS,

Table 1
Mean values and standard deviations are given for fixed speed (FS) and self-paced (SP) walking, for both the mean stride and stride variance values.

	FS	SP
Mean stride		
Spatio-temporal parameters		
Walking speed (m/s)	1.32 ± 0.11	1.32 ± 0.11
Stride length (m)	1.44 ± 0.10	1.43 ± 0.09*
Step width (m)	0.11 ± 0.03	0.12 ± 0.03*
Stride time (s)	1.10 ± 0.06	1.09 ± 0.06
Stance percentage (%)	63.81 ± 1.24	63.45 ± 1.38**
Kinematic/kinetic parameters[a]		
Hip abduction RMS (°)	5.57 ± 0.71	5.44 ± 0.65*
Range of hip flexion (°)	43.1 ± 5.14	42.4 ± 4.90**
Range of knee flexion (°)	63.9 ± 4.01	62.9 ± 4.02**
Knee flexion at initial contact (°)	9.26 ± 3.46	9.71 ± 3.38*
Time to peak knee flexion during swing (%)	73.5 ± 1.06	73.3 ± 1.06**
Peak ankle plantar flexion during stance	20.7 ± 3.00	20.1 ± 3.08*
Knee abduction moment RMS (N m/kg)	0.19 ± 0.06	0.17 ± 0.07*
Knee abduction moment gain (N m/kg)	1.00	0.90 ± 0.16*
Peak knee abduction moment (N m/kg)	0.41 ± 0.12	0.38 ± 0.13*
Hip flexion power gain (W/kg)	1.00	0.96 ± 0.07*
Ankle flexion power RMS (W/kg)	0.92 ± 0.17	0.86 ± 0.21*
Ankle flexion power gain (W/kg)	0.95 ± 0.09*	0.95 ± 0.09*
Stride variance		
Spatio-temporal parameters		
Walking speed (m/s)	0.034 ± 0.014	0.052 ± 0.033**
Stride length (m)	0.033 ± 0.018	0.046 ± 0.034*
Step width (m)	0.021 ± 0.005	0.020 ± 0.005
Stride time (s)	0.016 ± 0.007	0.019 ± 0.012
Stance percentage (%)	1.73 ± 1.12	1.26 ± 0.75
Kinematic/kinetic parameters[a]		
Peak hip abduction during swing (°)	0.763 ± 0.170	0.674 ± 0.122**
Hip rotation moment gain (N m/kg)	0.179 ± 0.065	0.145 ± 0.066**
Knee abduction moment RMS (N m/kg)	0.020 ± 0.005	0.019 ± 0.006*
Knee abduction moment gain (N m/kg)	0.119 ± 0.037	0.110 ± 0.035*
Peak knee abduction moment (N m/kg)	0.053 ± 0.011	0.049 ± 0.012*
Knee rotation moment gain (N m/kg)	0.333 ± 0.132	0.262 ± 0.110**
Hip flexion power RMS (W/kg)	0.065 ± 0.019	0.070 ± 0.020**

[a] Note that only the significant kinematic and kinetic parameters (either mean stride or stride variance) are given, for a complete overview of all parameters we refer to Appendix A. Also note that kinetic gains are expressed as the ratio of SP versus FS. Significant differences between FS and SP walking are indicated (*$p < 0.05$; **$p < 0.01$), with IC, initial contact; plantflex, plantar flexion; RMS, root-mean-square value.

$p = 0.03$; −9.7% gain, $p = 0.01$; −6.0% peak, $p = 0.03$) as well as reduced hip power (−4.2% gain, $p = 0.02$) and ankle flexion power (−6.6% RMS, $p = 0.03$; −4.7% gain, $p = 0.04$) during SP walking.

Nine out of 70 parameters describing stride-to-stride variability showed significant changes. During SP, variability of walking speed and stride length were increased by 54% and 39%, respectively (both $p < 0.02$), while the range of positions on the belt was smaller (40 ± 15 cm FS versus 33 ± 12 cm SP, $p = 0.02$). The increased variation in SP walking speed mostly occurred over longer time scales of multiple strides (Fig. 3A and B), this finding was supported by the predominance of SP in the low frequencies (Fig. 3C). Decreased variability during SP was found in the transversal plane, i.e. hip rotation moment (−18% gain, $p < 0.01$) and knee rotation moment (−21.2% gain, $p < 0.01$), as well as in the frontal plane for hip abduction (−12% peak during swing, $p < 0.01$) and knee abduction moment (−6.6% RMS, $p = 0.01$; −8.3% gain, $p = 0.01$; −6.9% peak, $p = 0.03$). Hip flexion power varied more during SP compared to FS walking (7.8% RMS, $p < 0.01$).

3.2. Different SP modes

Subjects rated SP_p as most similar to comfortable walking on each component (average values: SP_p: 7.2; SP_{2p}: 6.2; SP_v: 6.1, $p < 0.01$). Significant differences in both stride pattern and variability (14 out of 140 total tests) were found predominantly between SP_p/SP_{2p} and SP_v walking (Table 2). While walking speed was comparable between the trials, SP_v showed enlarged hip and knee rotation moments (15% RMS; 11% gain and 36% RMS, 26% gain, all $p < 0.01$), as well as reduced hip flexion (0.3% offset, $p = 0.02$). During SP_v, walking speed variability was decreased by 33% ($p = 0.03$), together with reduced variance in stride length (−41%, $p = 0.01$), hip extension (−16% peak, $p = 0.04$), hip abduction moment (−2.1% gain, $p = 0.04$), as well as in hip and knee rotation moment (−12% RMS; −25% gain and −3.7% RMS; all $p < 0.01$) and ankle flexion moment (−2% gain, $p < 0.01$). Both SP_p and SP_{2p} showed low frequency components, thus long-term variations, in walking speed (Fig. 3D and F). In contrast, SP_v resulted in variations with higher frequency components, using a smaller range of positions on the belt (30 ± 11 cm SP_p; 38 ± 13 SP_{2p}; 18 ± 6 SP_v, $p < 0.001$, Fig. 3E).

Regarding habituation between SP and SP_p, we found that the second trial resulted in increased walking speed and stride length (5.8% and 4.1%, $p < 0.01$) and decreased stride time (−1.9%, $p = 0.03$). In addition, 38 out of 130 kinematic and kinetic parameters were enlarged, with differences smaller than 1.9°, 0.25 N m and 0.20 W/kg. They also showed increased variability during the second trial.

4. Discussion

As a fixed, imposed treadmill speed has been suggested to affect gait, we examined the difference between SP and FS treadmill walking and compared different SP control modes. Although gait patterns were comparable between SP and FS walking, we noticed a trend toward slightly reduced values for almost all kinematic and kinetic parameters during SP walking. We suggest that this may be due to the decreased stride length seen during SP walking. Also, walking speed and stride length were more variable during SP walking, whereas some frontal and transversal plane kinematic and kinetic parameters were more constant.

We did not consider the few and minor differences in gait pattern between SP and FS walking to be clinically relevant for several reasons. First, the magnitude of the differences was very small, with the stride pattern changing by less than 1.0°, 0.2 N m and 0.2 W/kg for the various kinematic and kinetic parameters, whereas differences in stride length and stance percentage were below 1 cm and 1%, respectively. Second, the detected differences were well within normal inter-session variability, since they never exceeded 57% of the associated stride-to-stride variability and were below the stride-to-stride variability as seen during over ground walking [3,12]. The differences also never exceeded the measurement errors inherent to 3D gait analysis, which are reported to be between 2° and 5° joint rotation [13], and were also far below the threshold of 5° above which clinical decision making might be affected [13]. Furthermore, we tested conservatively, with a level of $p < 0.05$ chosen as statistically significant, without a correction for multiple measures. Thus, in light of the number of tests performed, differences that were found to be significant may be so by coincidence. Finally, the equality of SP and FS is supported by the fact that subjects did not prefer either one over the other in terms of their perceived resemblance to over ground walking.

The variability of walking speed and stride length was increased during SP walking. The increased fluctuations in both measures were anticipated, since the SP mechanism allows subjects to vary their walking speed. During over ground walking, long-range

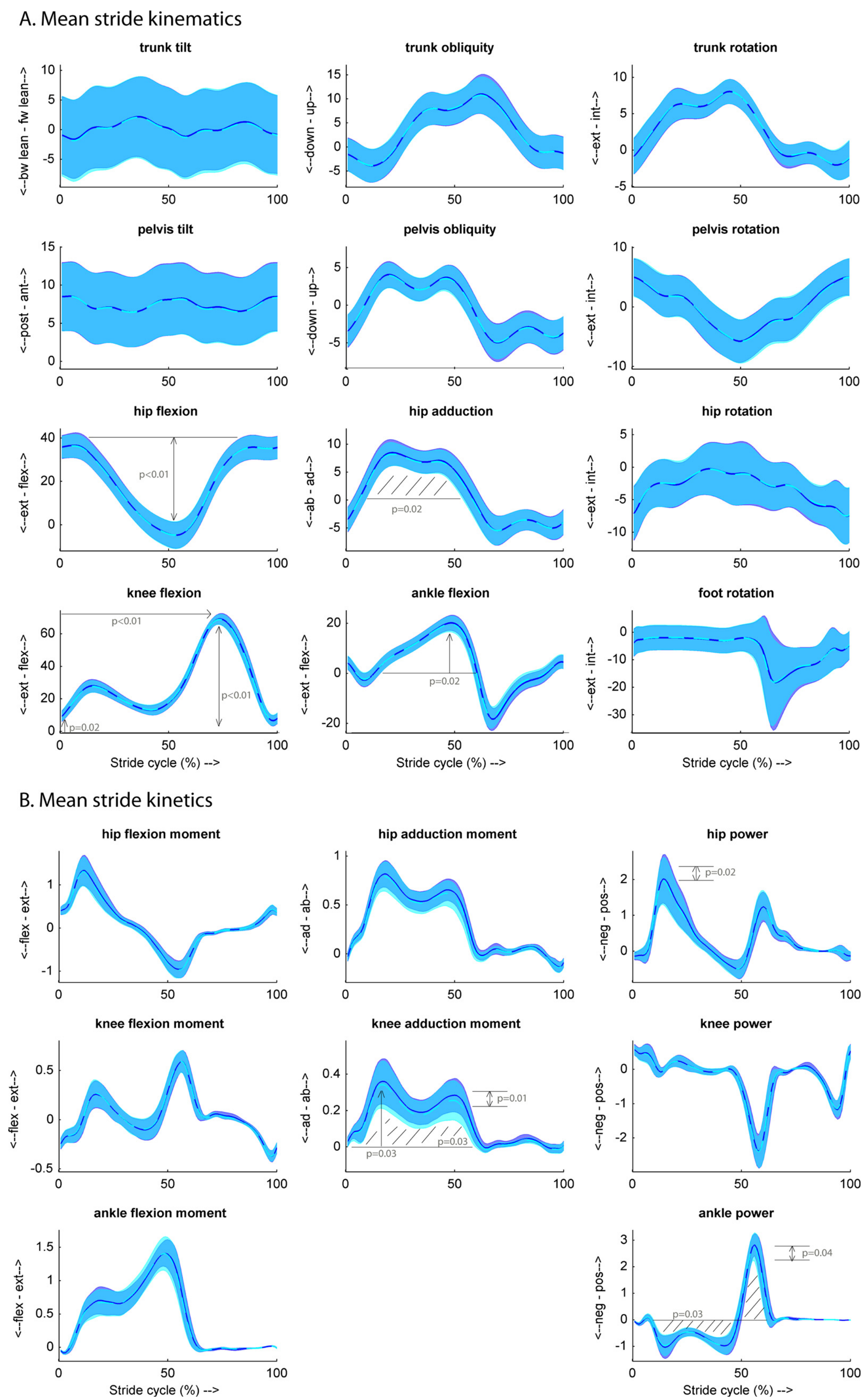

Fig. 2. Time-normalized ensemble averaged FS (blue) and SP (cyan) mean stride joint kinematics (A) and joint kinetics (B). One standard deviation is indicated as the light blue area, with non-overlapping areas in blue for FS and cyan for SP. The significant differences found for mean stride kinematic and kinetic parameters are indicated (see Table 1). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

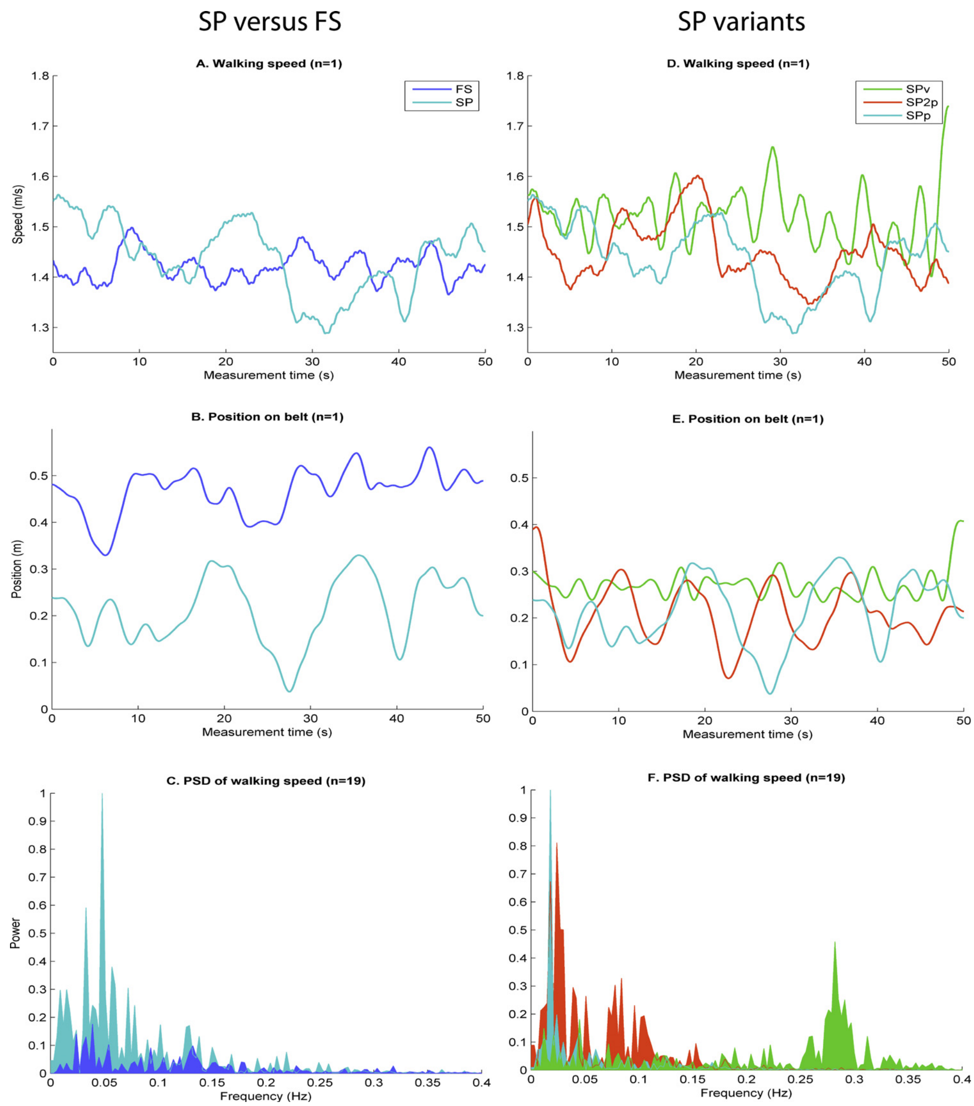

Fig. 3. Typical examples of the variation of the walking speed (A and D) and position of the pelvis on the belt (B and E) taken from one subject for the different conditions. In addition, the power spectral density (PSD) of the normalized walking speed from all subjects is given (C and F). SP and SP_p were the same for the subject, since SP_p was not repeated if it was scheduled directly subsequent to SP walking for a subject. Positive positions are frontwards of the middle (taken as zero) of the treadmill.

correlations in stride interval have been found to occur naturally [14,15]. The fluctuation in walking speed we observed also took place over multiple steps (see Fig. 3). It is therefore unlikely that these fluctuations resulted from active foot placement to control for balance, but rather that they were associated with the spontaneous long-term variation as seen in over ground walking. In contrast to the increased variability in the sagittal plane, some frontal and transversal plane kinematic and kinetic parameters were found to be more constant during SP. This might be due to 'freezing' of these degrees of freedom by the subjects, to lower the complexity of the task while still learning SP walking [16]. It should be noted, however, that only a few of these measures were significantly different and some coincidental significant results are expected to occur. Besides fluctuations during SP, we also found some long-term fluctuations in walking speed during FS walking, indicating that fixed speed treadmill walking is not 'fixed'. The variation during FS walking is achieved by varying the position on the belt and is thus limited by the length of the belt.

When comparing the SP modes, differences were mostly found between SP_p/SP_{2p} and SP_v, all being larger than between FS and SP walking -up to 120% of the stride-to-stride variability. In addition, walking speed variability was significantly reduced during SP_v. These walking speed changes occurred at a shorter time-scale during SP_v, and on a smaller range of the belt. Therefore, it appears that SP_v overcompensated for changes in walking speed. Subjects preferred SP_p over SP_{2p} as being most similar to comfortable walking. This may be attributable to the fact that subjects were better familiarized to SP_p walking, although the ratings between the first SP and second SP_p did not differ. SP_p was preferred over SP_{2p}, likely because the lower gain of SP_p resulted in a smoother adjustment of the belt speed. It can be concluded that the SP mode affects stride speed variance, and that SP_p appears to be the most comfortable of the three SP modes.

Since FS-trials were set to match the SP speeds in order to eliminate effects of differences in walking speed, the order of FS and SP was not randomized. To minimize order effects, at least 3 min were allowed for acclimatization to each condition. However, we still found small differences between the SP/SP_p conditions; subjects walked faster during the latter trial and showed slightly increased stride variability. This suggests a small learning effect that may affect the representativeness of the first SP trial and the comparison between SP and FS conditions. In addition, since SP and FS walking always occurred prior to the other SP variations, subjects may have become more familiarized with SP_p walking compared to the other

Table 2
Mean values and standard deviations for the three different SP modes.

	SP_p	SP_{2p}	SP_v
Mean stride			
Spatio-temporal parameters			
Walking speed (m/s)	1.37 ± 0.09	1.37 ± 0.14	1.39 ± 0.13
Stride length (m)	1.47 ± 0.08	1.47 ± 0.12	1.49 ± 0.11
Step width (m)	0.11 ± 0.03	0.12 ± 0.03	0.11 ± 0.03
Stride time (s)	1.08 ± 0.05	1.08 ± 0.06	1.07 ± 0.05
Stance percentage (%)	63.2 ± 1.20	63.4 ± 1.22	63.6 ± 1.37
Kinematic/kinetic parameters[a]			
Hip flexion offset (°)	0.548 ± 0.13	0.597 ± 0.15[3]	0.525 ± 5.22[2]
Hip rotation moment RMS (N m/kg)	0.175 ± 0.06[3]	0.177 ± 0.07[3]	0.204 ± 0.07[1,2]
Hip rotation moment gain (N m/kg)	0.97 ± 0.27[3]	0.97 ± 0.31[3]	1.08 ± 0.29[1,2]
Knee rotation moment RMS (N m/kg)	0.080 ± 0.04[3]	0.082 ± 0.05[3]	0.111 ± 0.06
Knee rotation moment gain (N m/kg)	0.89 ± 0.50[3]	0.88 ± 0.58[3]	1.11 ± 0.58[1,2]
Stride variance			
Spatio-temporal parameters			
Walking speed (m/s)	0.061 ± 0.03	0.069 ± 0.03[3]	0.047 ± 0.02[2]
Stride length (m)	0.056 ± 0.04	0.062 ± 0.03[3]	0.037 ± 0.02[2]
Step width (m)	0.020 ± 0.00	0.021 ± 0.00	0.021 ± 0.00
Stride time (s)	0.017 ± 0.00	0.020 ± 0.01	0.018 ± 0.00
Stance percentage (%)	0.016 ± 0.01	0.019 ± 0.01	0.023 ± 0.01
Kinematic/kinetic parameters[a]			
Peak hip extension (°)	0.698 ± 0.15[2]	0.815 ± 0.24[1,3]	0.678 ± 0.15[2]
Peak hip abduction during swing (°)	0.686 ± 0.12[2]	0.785 ± 0.21[1]	0.757 ± 0.19
Hip abduction moment gain (N m/kg)	0.063 ± 0.01[2]	0.070 ± 0.02[1]	0.068 ± 0.02
Hip rotation moment RMS (N m/kg)	0.026 ± 0.01[3]	0.032 ± 0.01[3]	0.028 ± 0.01[1,2]
Hip rotation moment gain (N m/kg)	0.144 ± 0.05[2]	0.176 ± 0.06[1,3]	0.132 ± 0.05[2]
Knee rotation moment RMS (N m/kg)	0.021 ± 0.01[3]	0.026 ± 0.02[3]	0.025 ± 0.01[1,2]
Ankle flexion moment gain (N m/kg)	0.052 ± 0.01[2,3]	0.061 ± 0.01[1]	0.060 ± 0.02[1]

[a] Note that only the significant kinematic and kinetic parameters are given, for a complete overview of all parameters we refer to Appendix B. Also note that Kinetic gains are expressed as the ratio of SP mode versus FS. Significant differences resulting from the post hoc multiple comparison are indicated ([1] significantly differs from SP_p; [2] from SP_{2p}; [3] from SP_v). *Abbreviations*: IC, initial contact; rot, rotation; ext/flex, extension/flexion; abd, abduction; RMS, root-mean-square value.

variations. This possible bias may have been tempered, however, since only the last minute of each trial was used for analysis and subjects were given at least 5 min to become accustomed to SP walking, a figure close to the 6 min of habituation time normally advised for fixed speed treadmill walking [17,18].

One of the suggested advantages of SP walking is that it would offer a natural way of controlling and varying walking speed, leading to a more natural gait and possibly better resembling over ground gait compared to FS treadmill walking. We did find some indication that the variation of walking speed indeed seems to better resemble over ground walking, in terms of increased fluctuations over multiple strides [14,15]. On the other hand, the mean stride pattern of SP walking did not seem to come closer to the over ground gait pattern, with even further reduced stride length, joint range of motion and increased step width compared to FS walking [1,2]. It should be noted, however, that these differences were small and that a small learning effect was found between the first and second SP trial (SP_p), with increased stride length and joint range of motion and decreased stride time during the second trial. More importantly, the small differences in mean stride pattern between SP and FS treadmill walking indicate that the accelerations and decelerations of the treadmill during SP walking do not seem to interfere with the stride pattern. However, consecutive measurement of different SP algorithms and over ground walking should be performed in future studies to allow a more direct comparison between SP and over ground walking.

In conclusion, SP walking can be considered similar to FS treadmill walking for clinical gait analysis, in the absence of any clinically relevant differences in gait patterns. The resembling FS and SP gait patterns seem to indicate that interactions with the treadmill during SP walking do not notably affect the kinematics and kinetics. Moreover, SP walking allows for more freedom in stride variability. Subjects are able to select and change their own preferred walking speed, resulting in long-term stride fluctuations that resemble those as seen during over ground walking. In addition, SP walking offers several practical advantages, such as the measurement of long-term stride variability or endurance, while reducing measurement time due to the inherent selection of the preferred walking speed. The next step should be to assess whether or not SP walking could be an effective alternative to over ground walking in gait analysis.

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Conflict of interest

The authors declare that they have no competing interests.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gaitpost.2013.08.022.

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