Human Movement Science 67 (2019) 102509

Contents lists available at ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov

Human walk-to-run transition in the context of the behaviour of complex systems

M. Voigt*, M.K. Hyttel, L.S. Jakobsen, M.K. Jensen, H. Balle, E.A. Hansen

Sport Sciences, Department of Health Science and Technology, Aalborg University, Denmark

ARTICLE INFO

Keywords:
Gait transition
Bi-pedal gait
Stride rate
Walk-run transition
Behavioural attractors

ABSTRACT

This study had two main aims: 1) to investigate if the walk-to-run (WR-) transition occurs when the speed of locomotion is kept constant below the WR-transition speed (speed clamp) and the stride rate is increased monotonously using a metronome and 2) to investigate if diversion of attention and awareness from the locomotion process influences the position of the WR-transition in stride rate, stride length, and locomotion speed (SrSlLs) space.

Eighteen healthy individuals (13 men and 5 women) were recruited (age: 23.9 ± 1.5 years, height: 1.77 ± 0.10 m and body mass: 77.3 ± 12.8 kg). Stride-by-stride stride rates, stride lengths, locomotion speeds, and duty factors were determined on a treadmill in 4 different tests: 1) reference WR-transition, 2) preferred walking speed, 3) dual-task test including arithmetic calculations and 4) four speed clamp bouts with different initial velocities.

Walk-to-run transitions were elicited in all participants in the speed clamp bouts. When the stride rate ramp was clamped at preferred walking speed the WR-transition stride rate was not significantly different from the WR-transition stride rate during the reference test ($t = 2.2$, $p = 0.312$). However, in the SrSlLs space the speed clamp WR-transitions all deviated from the position of the reference WR-transition. Additionally, it was demonstrated that intensive attentional diversion using a dual-task paradigm had very little influence on the position of the WR-transition in the SrSlLs space.

It is argued that these observations can be explained in the context of the behavior of complex systems.

1. Introduction

Only a few studies have provided some evidence for the notion of the walk-to-run transition during human locomotion to be a consequence of the circumstance that the moving human body behaves like a complex dynamic self-organizing system (Diedrich & Warren, 1995, 1998). This type of systems were originally formally described by R.W. Ashby (see. e.g., Ashby, 1957; Ashby, 1962) and the behaviour of this type of systems can be described with Dynamic Systems Theory (Haken, 1983; Luenberger, 1979). Certain classes of complex self-organizing systems characteristically exhibit stable behavioral patterns (attractors) and instantaneous bifurcations, or phase transitions, in the behavioral patterns (Ashby, 1957, 1962; Thelen & Smith, 2007; van Kleef, 2015). An attractor is a stable position in state space (representing the variables describing the system's behavior) towards which a dynamical system returns following a perturbation (Haken, 1983). The transitions should occur in the absence of a central controller and does not

* Corresponding author at: Sport Sciences, Department of Health Science and Technology, Aalborg University, Niels Jernes Vej 12A, 9220 Aalborg, Denmark.

E-mail address: mv@hst.aau.dk (M. Voigt).

https://doi.org/10.1016/j.humov.2019.102509
Received 28 February 2019; Received in revised form 7 June 2019; Accepted 31 July 2019
Available online 12 August 2019
0167-9457/

simply assume organization at e.g. a neural level in humans, but is based on self-organization, i.e. organization based on spontaneous interactions, between the subcomponents of the system (Ashby, 1962; Heylighen, 2002; van Kleef, 2015). The behavior of a dynamic self-organizing system may be summarized in terms of one or more so- called *order parameter(s)*, which are low-dimensional collective variables that provide measures of the organizational state of the system (Haken, 1983). In relation to locomotion parameters like duty factor, stride rate, stride length that in many cases demonstrates an abrupt change in amplitude at the WR-transition, can be considered to be order parameters, because this abrupt change is a reflection of the change in system state and therefore can be used as a measure of the system state.

When continuous variation in a given parameter (a collective variable, system parameter, or a characteristic of the surroundings) induces a bi-furcation or phase transition, it is considered to be a *control parameter*. Locomotion speed and stride rate are examples of a control parameters in locomotion.

When the level of a control parameter is changed continuously a given system becomes successively more unstable, because dominance of negative feedback in the interactions caused by fluctuations in the behaviour of its subsystems changes towards dominance of positive feedback (Thelen & Smith, 2007). At a certain level of the given control parameter, a nonequillibrium state of the system is reached and a sudden bifurcation occurs in the behavior of the system, during which the system does not occupy intermediate states (Haken, 1983; Thelen & Smith, 2007). Many biological systems are dynamic self-organizing systems and are energetically open systems like the human body, and self-organizing behaviour of these only emerges if there is an unlimited energy supply (Thelen & Smith, 2007), which we will assume in the following. When the concepts reviewed above are applied to locomotion, the speed of locomotion, e.g. during treadmill walking, can be considered to be a control parameter, since a continuous increase in locomotion speed will at some value elicit the instantaneous transition from walking to running. The walk-to-run transition (WR-transition) can then be specified as the locomotion speed at the WR-transition.

In most of the recent literature dedicated to the study of human WR-transition, the speed of locomotion has been used as a control parameter for locomotion on treadmills to elicit transitions (see Kung, Fink, Legg, Ali, & Shultz, 2018 for a review). The dominance of this procedure may simply be a consequence of the fact that it is straight forward to do when a treadmill setup is applied. Triggers of WR-transitions have been discussed based on how the magnitude of the locomotion speed at WR-transition behaves following different manipulations of the situation of locomotion. As examples of manipulations, the following could be mentioned: body weight reduction (Ivanenko et al., 2011), treadmill inclination (Diedrich & Warren, 1998), and attentional diversion by dual-task experiments (Abdolvahab, 2015; Daniels & Newell, 2003). However, according to the ideas and definitions concerning the dynamic behaviour of self-organizing systems given above it can be assumed that the ultimate trigger for the WR-transition is a critical level of instability induced at a given magnitude of an arbitrary control parameter. Therefore, a search for a WR-transition trigger may not seem purposeful. No matter how the moving body, the surroundings, or the procedures are manipulated, the transition should always occur, when the moving body is driven to an unstable state by changing some parameter monotonously until a critical level. And the parameter in question is by definition classified as a control parameter. If the running situation is constant, i.e. if the surroundings, the procedures, and the state of the moving body are constant, then the critical speed where the transition occurs (i.e. the transition speed) will be stable/repeatable (Hansen, Nielsen, Kristensen, Madeleine, & Voigt, 2018). If the surroundings, the protocol, or the state of the moving body is changed, then the critical speed (transition speed) most likely also will change, as a consequence of the dynamics of the moving body or its interaction with the surroundings has been influenced by the changed conditions. This has been observed when e.g. the body weight is reduced during locomotion for example: 1) the transition speed will be lower than the transition speed during locomotion without body weight reduction (Ivanenko et al., 2011) and 2) when the treadmill inclination is increased, the WR-transition speed decreases as compared with the transition speed at horizontal locomotion (Diedrich & Warren, 1998).

To pursue an understanding of the WR-transition in terms of dynamic systems theory further, Hansen, Kristensen, Nielsen, Voigt, and Madeleine (2017) and Hansen et al. (2018) suggested that the stride rate should be considered a natural or fundamental control parameter for locomotion because the locomotion most likely is rate driven by central pattern generators (CPG's). Additionally, it was suggested that if the stride rates during preferred unrestricted human walking and running were considered to be behavioral attractors with *equal attraction*, the WR-transition should occur at the midpoint between the two attractor stride rates. We will refer to this as: "the attractor principle". This was confirmed by the collected data (Hansen et al., 2017, 2018). The same phenomenon could also be shown for ostriches based on the data from Daley, Channon, Nolan, and Hall (2016) (Hansen et al., 2017). When locomotion speed was considered, the relationship between behavioral attractor speeds and transition speed was not as clear (Hansen et al., 2017), indicating that the stride rate seems to play a special role in the transition process during bipedal vertebrate locomotion.

To explore the influence of stride rate on the WR-transition further, the main aim of the present study was to investigate how the WR-transition will behave if the locomotion speed is maintained constant (i.e. 'clamped'). This means that speed, in principle, is suppressed as control parameter, and the pattern of locomotion is subjected to continuous increase in stride rate ('rate ramp'). It was hypothesized that if the critical instability of the moving body, that elicits the transition, can be induced by the stride rate, independent of locomotion speed, then there should be no significant difference between the stride rate at the WR-transition elicited during speed clamp/rate ramp and the reference stride rate. This would indicate that the attractor principle still holds. Of note is that the reference stride rate is the stride rate at the WR-transition elicited by a monotonous increase in walking speed ('speed ramp') alone.

As mentioned above, if the behavior of the body during locomotion reflects the behavior of a complex system, the transition between behavioral states (walking and running) should not be controlled by a central controller. Rather, it should occur in a self-organized fashion without any involvement of conscious attention and awareness. It has been reported that the Rating of Perceived Exertion is increased during walking at speeds close to the WR-transition in comparison to running at the same speeds (Hreljac, 1993;

Minetti, Ardigo, & Saibene, 1994; Monteiro, Farinatti, De Oliveira, & Araújo, 2011), suggesting that some influence of attention and awareness might affect the transition process. To test this further, dual-task paradigms have been applied (Abdolvahab, 2015; Daniels & Newell, 2003). It has also been assumed that every single individual has a limited attentional capacity (Kahneman, 1973), and that a part of this capacity is involved in the WR-transition. Based on the latter, it may be predicted that if a procedure that diverts attention and awareness away from the process of locomotion is added in a WR-transition protocol, it could constitute a competition for attentional capacity and eventually cause a disturbance of the WR-transition. Using a dual-task paradigm (by asking participants to perform simple arithmetic during a WR-transition protocol) to divert conscious attention and awareness, Daniels and Newell (2003) found that the WR-transition speed on average increased by about 5%. This is in opposition to the idea that the human body acts as a complex system with a self-organizing behavior, because in the latter case the WR-transition should occur without the influence of a central controller. However in a similar dual-task experiment, Abdolvahab (2015) observed no change in the normalized WR-transition speed (Froude number) as well as a decrease in the running-to-walking transition point corresponding to an increased hysteresis between the transition points with increasing intensity of the diversion. In principle, these two latter studies overall support and oppose the idea of the involvement of conscious attention and awareness in the transition process. And these results are therefore considered to be inconclusive. As a consequence, our secondary aim was to provide more evidence concerning the likelihood of the influence of conscious attention and awareness on the WR-transition by adding a dual-task paradigm to the WR-transition protocol. The hypothesis related to this second aim was that diversion of conscious attention and awareness related to the locomotion process should have very little or no influence on the magnitude of the stride rate, stride length, and locomotion speed at WR-transition. A confirmation of the hypothesis would support the notion that the moving body acts dynamically as a complex system with self-organizing behavior.

2. Materials and methods

2.1. Participants

Eighteen healthy and injury free individuals (13 men and 5 women) volunteered for the present study. Average age, height, and body mass were 23.9 ± 1.5 years, 1.77 ± 0.10 m, and 77.3 ± 12.8 kg, respectively. All participants were accustomed to treadmill walking and running prior to data collection.

2.2. Experimental design

Each participant reported to the laboratory for a single test session, which in total lasted 75 min. Each test session included a standardized warm-up on a treadmill, determination of a reference WR-transition, determination of preferred walking speed (PWS), determination of a dual-task WR-transition protocol, as well as a protocol for determination of WR-transitions during 4 different 'speed clamps', i.e. 4 constant walking speeds superimposed with steadily increasing stride rates.

2.3. Preparation

Initially, age, height, and body mass (Tanita BWB-800 digital scale, Arlington Heights, IL, USA) of the participant were determined. Then, two pressure-sensitive sensors (Interlink electronics Inc., Westlake Village California, USA) were mounted with double adhesive tape at the underside of the insole of the right shoe. The two sensors were placed at positions corresponding to the midpoint of underside of the heel ('Heel Switch') and at the approximate midpoint between first and second metatarsal heads respectively ('Forefoot switch'). The sensors were used for determination of spatiotemporal stride characteristics. After that, a 10-min warm up and familiarization part was completed on the Woodway XL Pro treadmill (Woodway USA Inc., Waukesha, WI, USA). This part began with 1 min at 1 km h^{-1}, and continued with 1 min at 2 km h^{-1} etc., until 1 min at 10 km h^{-1} was completed. Subsequently, the participant rested for four min. During all the following testing, the signals from the two foot switches were recorded with a PC-based data acquisition system (National Instruments hardware and custom written Labview software: 'MrKick' by Knud Larsen, Aalborg University) applying a sampling frequency of 1000 Hz and stored for later analysis.

2.4. The test session

During all the following tests, the participant was blinded with respect to readouts of stride rate and treadmill belt speed.

The following was determined in chronological order:

2.4.1. Reference WR-transition

The participant was given the following instruction: "You now have to follow the speed of the treadmill belt. When it feels natural to run instead of walk, you simply do that". The treadmill belt speed was set at 5 km h^{-1} and the treadmill belt speed was increased every 10 s by 0.1 km h^{-1}, until 9 km h^{-1}. This resulted in test duration of approximately 7 min. In all cases, the WR-transition occurred within this speed interval. After this, the participant had four min of rest.

2.4.2. Preferred walking speed

The participant was given the following information: "You are now supposed to determine your preferred walking speed. It is supposed to be felt comfortably. You could for example imagine yourself walking at a path, without any particular purpose. You can control the speed by the buttons marked with plus and minus signs. Please take your time and make sure the speed is comfortable." When the participant had decided the PWS, walking was continued for one min. The total duration of this part of the test session did not exceed 5 min for any participant. The participant then had five min of rest.

2.4.3. Dual-task WR-transition

The protocol was basically the same as for determination of the reference WR-transition. However, in addition to the tasks of walking and following the treadmill belt speed, the participant had to perform arithmetic calculations, which should divert the participant's attention to and awareness of the process of locomotion. The protocol was designed in such a way, that we attempted to push the distraction of the participant's conscious attention and awareness of the process of locomotion to the limit of their capacity. The calculation tasks should begin with the number 911 and the number 7 should consecutively be subtracted. The participant should verbally announce each result. To maximize the intensity of attentional diversion on the participant, the experimenter constantly encouraged the participant to perform the calculations as fast as possible. Additionally, the experimenter noted if the answer was right or wrong. If the answer was wrong, the participant was asked to repeat the last calculation until it was correct, and then continue. The number of errors and the last number in the calculation sequence were noted as performance measures. The best performances were presented to the participant as a way of encouraging the participant. The participant then had 5 min of rest.

2.4.4. WR-transition at speed clamp/stride rate modulation

The next part of the test session consisted of four speed clamped bouts. Thus, each bout was performed at a pre-set speed combined with gradually increasing stride rate, guided by a metronome, until the WR-transition occurred. The WR-transition was determined in each bout. The four walking speeds were determined as 1) PWS, 2) PWS + 25% of the difference between the reference transition speed (RTS) and PWS, 3) PWS + 50% (RTS-PWS)) and 4) PWS + 75% (RTS-PWS). The order of the speed clamp bouts was randomized between participants. Before the first bout started, the participant was given the following information: "In this bout, you are now supposed to let your step rate follow the metronome. This means that each time you hear a metronome sound; a foot must hit the treadmill belt. By the following sound, the other foot must hit the belt, and so forth. The metronome will maintain a constant rate during the first 30 s. Hereafter, the metronome will gradually increase the rate. When it feels natural for you to run, you just do that. When you have started running, we turn of the metronome, and you simply continue to run in the way that you prefer". A bout started with 30 s of walking at a freely chosen stride rate at the pre-set speed. The stride rate was noted and the metronome was set at the noted rate. Then, the recording was started and the participant continued to walk at the initial speed at this constant rate for additional 30 s while adjusting to the metronome beat. Hereafter, the metronome's rate was increased with 4 beats min^{-1} every 15 s (corresponding to an increase of 2 strides min^{-1} every 15 s) until the participant shifted to running. To ensure that the locomotor pattern was stable after the WR-transition, the participant should run for a minimum of 1 min following the WR-transition.

2.5. Data recording and analysis

The analysis of the foot switch signals was performed with a custom written Matlab routine (Matlab 2015a, Mathworks, Natick MA, USA). The individual strides were isolated between consecutive offset times determined on the forefoot switch to include all types of foot strike patterns. From this information, the stride-by-stride (i.e. instantaneous) stride durations and the stride rates could be derived (see Fig. 1). Additionally for each stride, the time of first contact (heel or forefoot switch onset) was determined for each stride and the duty factor was calculated as the ratio between the contact time and the stride time in percent. The speed of the treadmill belt could not be recorded continuously since the treadmill had no analog or digital speed output channel. Still, a velocity signal for the analysis was needed to determine stride lengths of the individual strides. Therefore, velocity signals were generated in the Matlab scripts. This was straight forward at constant speed. However, the speed ramp signals from the reference transition tests had to be generated according to the strict time protocol during these test, i.e. starting the signal with 10 s of walking at 5 $km\,hr^{-1}$ followed by 0.1 $km\,hr^{-1}$ stepwise increases every 10th s, until 9 $km\,hr^{-1}$. The stride speed was calculated as the average speed over duration of each step. By including this information, both the instantaneous stride lengths and the average stride-by-stride speeds could be calculated. The WR-transitions were always clearly seen as abrupt decreases in the duty factor from about 50–60% to about 35–40% on the curves illustrating the time development of the instantaneous duty factor for each WR-transition test (Fig. 1). The WR-transition stride rate, speed, and stride length were determined as the magnitude of these three parameters during the last stride before the abrupt change in the duty factor occurred. All transitions occurred in all cases within one or two strides.

2.6. Statistics

The differences between the reference WR-transition stride rate and each of the four WR-transition stride rates from the speed clamp tests were tested with four paired t-tests and a Bonferroni correction. Differences between the four WR-transition stride rates were tested with a One way Repeated Measures ANOVA. In case of a statistically significant main effect, a post hoc Bonferroni all pairwise multiple comparisons analysis was performed. The reference WR-transition and the dual-task WR-transition stride rates, as well as the reference WR-transition and the dual-task WR-transition speeds and the corresponding stride lengths were compared by two tailed paired t-tests. Confidence intervals were calculated for all comparisons. The cut off p-value was set at 0.05. The statistical analyses were performed using IBM SPSS Statistics (Version 25, SPSS Inc., Chicago, IL, USA).

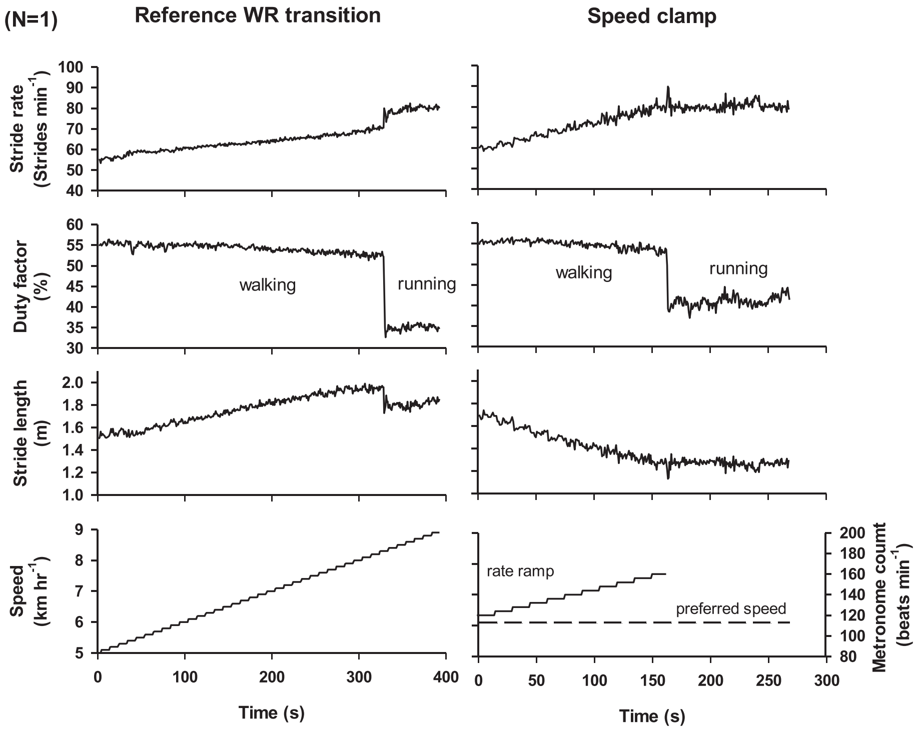

Fig. 1. Instantaneous stride rate, duty factor, stride length, and speed from a single participant (P7, male, 25 years, 1.81 m, 77.8 kg) performing a test for reference WR-transition (left column) and a speed clamp bout at preferred walking speed (right column). Stride rate, duty factor, and stride length were determined on a stride-by-stride basis using foot switch signals (see text for further details). During the speed clamp test, the stride rate was initiated with the self-selected stride rate followed by increases by 2 steps $\min^{-1}$ every 15 s controlled by a metronome (right column, bottom panel, solid line). The auditory feed-back was terminated as soon the experimenter observed that the transition had occurred. The WR-transitions were always visible as an abrupt decrease in the duty factor. The transition speed, stride rate and stride length were determined as the magnitude of these parameters during the last stride before the abrupt change in the duty factor.

3. Results

Fig. 1 shows representative examples (N = 1) of 'raw' data obtained from a test for determination of the reference WR-transition (left column) and a speed clamp bout starting at PWS (right column). The WR-transition is clearly seen from the duty factor signal, but abrupt changes are also seen at the reference WR-transition in the stride rate signal, which increases, and in the stride length signal, which consequently decreases.

The WR-transitions did not always occur as single events. Several participants shifted forth and back between walking and running a few times before the WR-transition was stable (not illustrated). In these cases, the last transition followed by a minimum of 1 min of continuous running was defined as the WR-transition. This was most prominent during the speed clamp bouts.

3.1. WR-transitions the reference test and the speed clamp bouts

Fig. 2 illustrates the WR-transition speeds stride rates and stride lengths from the determination of the reference WR-transition and the WR-transitions during the speed clamp bouts. The results of the statistical analysis of these results are presented in Table 1. The reference WR-transition stride rate was not significantly different from the WR-transition stride rate from the PWS speed clamp bout. The confidence interval for this comparison included zero, and therefore it cannot be ruled out that there is no difference between these two situations. The reference WR-transition stride rate was also not significantly different from the WR-transition stride rate at the speed clamp +25% bout. However, for this comparison the confidence interval did not include zero and the p-value ($p = 0.052$) was very close to the cutoff value of 0.05, which indicate a tendency for a significant difference. The WR-transition stride rates from the +50% and +75% speed clamp bouts were significantly different from the reference WR-transition stride rates.

The mean stride length obtained from the reference tests was 1.86 ± 0.11 m. In Table 2, the percentage mean changes in WR-transition stride rates and stride lengths, in relation to the reference test, are presented. Increasing WR-transition walking speed between the speed clamp bouts was accompanied by increases in the WR-transition stride rates, and expectedly concomitant decreases in stride lengths were observed (Fig. 2 and Table 2). The statistically insignificantly higher value of merely 4.5% in the WR-transition stride rate compared to the WR-transition stride rate during the speed clamp bout at PWS was accompanied with a considerable 38% decrease in the WR-transition stride length (Table 2, Fig. 2b).

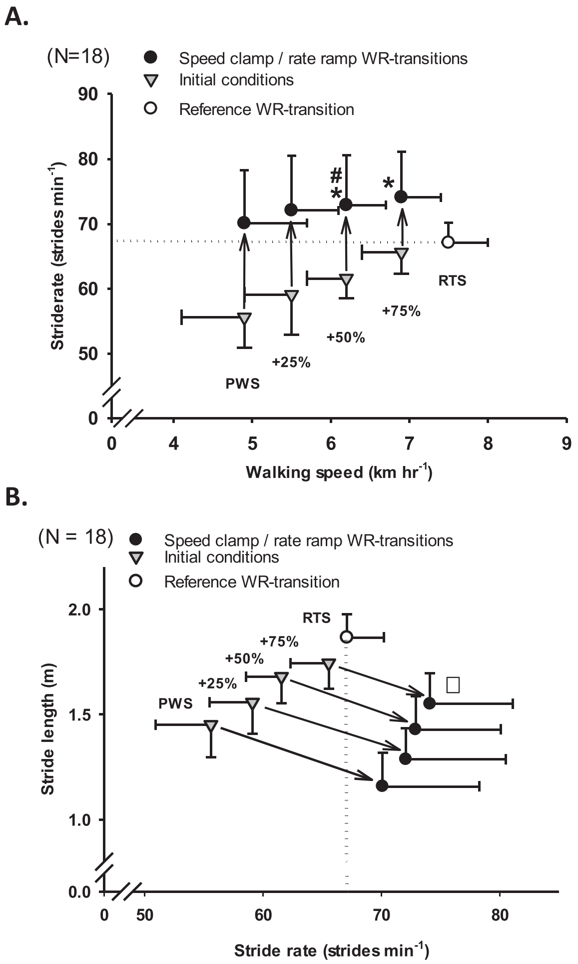

Fig. 2. A Locomotion speed and stride rate space: The figure illustrates the reference walk-to-run transition (WR-transition) and the speed clamp WR-transitions starting at: 1) preferred walking speed (PWS), 2) PWS + 25%, 3) PWS + 50%, and 4) PWS + 75% of the difference between the reference WR-transition speed (RTS) and PWS. The order of the initial conditions was randomized between bouts. Error bars indicate standard deviations. *Significantly different from the reference WR-transition stride rate ($p < 0.004$). # Significantly higher than the WR-transition stride rate at PWS ($p = 0.04$). The arrows indicate changes in stride rate from the starting point to the transition point for each of the speed clamp bouts. B Stride rate – stride lengh space. As above but in a different space. *: different form each other ($p < 0.001$).

3.2. Dual task WR-transition

In sixteen of the participants, a WR-transition in the dual-task situation was elicited. The last two participants continued to walk until 9 km h^{-1}, which constituted the end of the test, and consequently they had to be excluded from the analysis. In Fig. 3, the WR-transition stride rates, stride lengths, and locomotion speeds from the reference test and from the dual-task test are illustrated. An average 2.1% increase of the WR-transition stride rate, an average 0.2% increase of the stride length, and an average 1.3% increase of the WR-transition speed were seen.

Table 1 shows that no statistical difference was found between the reference WR-transition stride rate and the WR-transition stride rate during the dual task test ($p = 0.135$) and the confidence interval includes zero. Besides, the reference WR-transition speed and the WR-transition speed from the dual task test were not significantly different ($p = 0.072$) and zero was included in the confidence interval. Finally, the reference WR-transition stride length and the WR-transition stride length from the dual task test were not significantly different ($p = 0.824$) and zero was included in the confidence interval.

4. Discussion

Two important observations were made in the present study. Firstly, when walking speed was kept constant at the PWS, and the stride rate was monotonously increased from the preferred stride rate, a WR-transition occurred at a stride rate not significantly different from the reference WR-transition stride rate. This was in favor of our first hypothesis, and it supports the idea that the stride rate has a special influence on the WR-transition. However, the hypothesis was only partly confirmed since when the stride rate ramp

Table 1
Statistical analyses of the walk-to-run transition stride rates from the speed clamp/rate ramp experiments, and the walk-to-run transition stride rates, stride lengths and locomotion speeds from the dual task experiments. *Statistical significance. No test: There was no difference between +25% and +75%. As a consequence, comparisons with the enclosed mean of +50% were not performed.

		95% Confidence interval limits			
Speed clamps (N = 18)	diff	Lower	Upper	*t*-value	P-value
WR-transition stride rates	Strides min^{-1}	Strides min^{-1}	Strides min^{-1}		
Speed clamp vs reference					
PWS vs reference	3.00	−0.58	6.58	1.77	0.380
+25% vs reference	4.97	1.19	8.74	2.78	0.052
+50% vs reference	5.79	2.82	8.76	4.11	0.004*
+75% vs reference	5.13	4.01	10.00	4.93	< 0.001*
Speed clamp vs speed clamp					
+25% vs PWS	1.97	−1.18	5.11		0.478
+50% vs PWS	2.79	−0.09	5.48		0.040*
+75% vs PWS	3.99	−0.76	8.79		0.136
+50% vs + 25%	0.82	−2.67	4.31		No test
+75% vs + 25%	2.03	−1.51	5.57		0.631
+75% vs + 50%	1.21	−2.20	3.63		No test
Dual Task (N = 16)	diff	Lower	Upper	*t*-value	P-value
WR-transition stride rates	Strides min^{-1}	Strides min^{-1}	Strides min^{-1}		
Reference vs dual task	−1.46	−3.432	0.512	−1.58	0.135
WR-transition speed	km hr^{-1}	km hr^{-1}	km hr^{-1}		
Reference vs dual task	−0.18	−0.381	0.072	−1.9 4	0.072
WR-transition stride length	m	m	m		
Reference vs dual task	0.003	−0.033	0.026	−0.23	0.824

Table 2
The mean percentage changes in the mean walk-to-run (WR) transition stride rates and WR-transition stride lengths during the four different speed clamp/rate modulation bouts in relation to the reference test. Reference: WR-transition determined during a speed ramp (0.1 km h^{-1} every 15 s, starting at 5 km h^{-1}) PWS: preferred walking speed, +25%: PWS + 25% of the difference between the reference WR-transition speed and PWS, +50%: PWS + 50% of the before mentioned speed interval, and + 75%: PWS + 75%.

Test (N = 18)	Delta WR-transition stride rate %	Delta WR-transition stride length %
Reference	0.0	0.0
PWS	4.5	−38.0
+25%	7.5	−31.0
+50%	8.6	−23.5
+75%	10.4	−17.1

was initiated at higher speeds than the preferred (and consequently at higher stride rates), the observed WR-transition stride rates successively increased to values, which became significantly higher than the reference WR-transition stride rate. The second important observation was that the application of a dual-task procedure to divert the attention from the process of locomotion during walking with monotonous increasing walking speed did not change the WR-transition speed, stride rate, or stride length significantly. This was in favour of our second hypothesis and it supports the idea that the human body during walking can be considered to act dynamically as a complex system in a self-organized manner, without influence of a specific control center.

4.1. Speed clamp test

Interestingly during all the speed clamp/rate ramp tests performed in this study, a WR-transition was elicited in spite of the fact that the influence of locomotion speed changes was eliminated. As mentioned earlier, it is well known that continuous increase in locomotion speed will elicit a WR-transition (Kung et al., 2018). However, since the locomotion speed is the product of stride rate and stride length, and when the locomotion speed increases the stride rate in parallel, it is suggested that it is a critical value of stride rate that elicits WR-transition, not a level of locomotion speed per se. This suggestion is in accordance with the observation of the finding

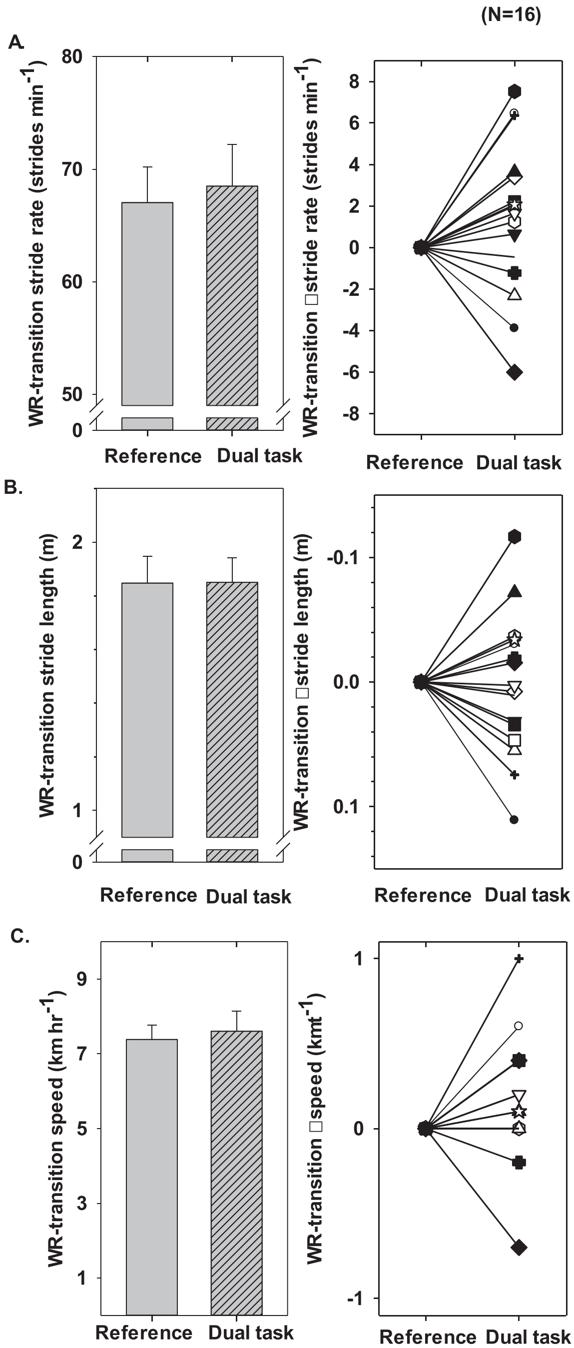

Fig. 3. Comparison of reference and dual-task WR-transition stride rates (A), WR-transition stride lengths (B), and WR-transition speeds (C). Left panels show the mean values (error bars: +SD) while the right panels show intra-individual differences. None of the difference between the reference and dual task tests where significant and zero was included in the confidence intervals the tests (Table 1). Therefore, it cannot entirely be ruled out that are no differences between the reference and the dual-task tests.

that the stride rate appears to play a special role in eliciting the WR-transition (Hansen et al., 2017, 2018). An experiment including stride rate clamps and speed ramps, where the stride length will have to be chosen freely like in the speed clamp/ramp rate experiments in the present study, could further provide support for the special role of the stride rate for the WR-transition. If WR-transitions would not be elicited in a rate clamp/speed ramp experiment, it would be a strong indication of the stride rate to play a special role as control parameter in the process of eliciting WR-transitions.

Our first hypothesis was partially confirmed, since when the speed was clamped at PWS it could not be ruled out that there was no difference between the stride rate at the WR-transition during the PWS speed clamp bout and reference WR-transition stride rate.

However when the clamp speeds were increased, the position of the corresponding WR-transitions changed (Fig. 2a and b). In the following we will, based on the findings by Diedrich and Warren (1998) and Hansen et al. (2017), argue that these changes in position of the WR-transitions in stride rate – stride length space are caused by interrelationship between the behavioral attractors for walking and running and the WR-transition.

Diedrich and Warren (1998) suggested, in the context of the behaviour of self-organizing complex systems, that for human locomotion there may be a rather fixed relationship between the behavioural attractors for running and walking and the WR-transition due to 'competition between attractors'. In other words, that the positions of the attractors for walking and running and the WR-transition in state space are linked. They hypothesized that due to this fixed relationship, if the WR-transition, for dynamic reasons, changes position in stride rate – stride length space, then the positions of the corresponding attractors should change place with approximately the same amount as the WR-transition as well. They also found that when extra load was added to the ankles, both the WR-transition and the attractor for walking changed place in stride rate-stride length space in relation to the same parameters measured in an undisturbed reference situation. The change mainly occurred down the rate axis (see their Fig. 6). Additionally, they found that when the speed was kept constant (clamped) at preferred walking speed and a positive inclination ramp was imposed on the participants, both the WR-transition and the attractor for walking changed place in stride rate-stride length space in parallel in relation to the same parameters measured in a reference situation. In this case the change occurred mainly down the stride length axis (see their Fig. 8). No information concerning the behaviour of the attractors for running was presented by Diedrich and Warren (1998), however they suggested that these should also change in parallel with the attractor for walking and the WR-transition in both situations. Both of their results indicate rather fixed relations between the behavioural attractors during walking and running and the WR-transition under different dynamic circumstances, but that the relation may be different between dynamic situations. This is in line with the findings reported by Hansen et al. (2017, 2018) i.e. the attractor principle, however, this in the case of undisturbed locomotion and speed ramp the attractor principle was most prominent in rate space.

In relation to the present study it is claimed that during each of the speed clamp bouts, the dynamic situations of locomotion are different between bouts (and also different from the reference situation). A speed clamp can in this context be compared with e.g. loading of the ankles. Thus, in both situations the moving body must adapt, or behave, differently dynamically in the process of organizing itself to the specific circumstances. When the ankles are loaded the inertia of the legs will change. Further during the speed clamp/rate ramp, adaptations can only occur by changes in stride length. This may in turn also have an influence on the position of the WR-transition in parameter space.

In each specific speed clamp condition, the initial conditions (the given speed clamp, self-selected stride rate and stride length) can be considered to be the walking attractor for this specific condition. Therefore, Fig. 2a and b illustrates how the speed clamp walking attractors (grey triangles) and the corresponding transitions (filled circles) behave both in locomotion speed – stride rate space and in stride rate – stride length space. Focusing on the latter (Fig. 2b), it can be seen that when the attractors change place between the speed clamp situations, the WR-transitions change places in the same direction. Between PWS and +75% clamp speed, the attractor stride rates and lengths increases and the same pattern is seen for the WR-transitions. This observation corresponds to the observations of Diedrich and Warren (1998) and confirms the idea about a more or less fixed interrelationship between a given walking attractor and its corresponding WR-transition. It is well known that stride rate and stride length increases with locomotion speed. Consequently, the changes in positions of the speed clamp attractors are consequences of the increases in the magnitude of clamp speeds due to the simple relationship: locomotion speed = stride rate × stride length. It follows that the changes in the speed clamp WR-transitions should be a consequence of changes in the dynamics of walking caused by the increased magnitude of the speed clamps. For the reference situation, the PWS attractor is also the walking attractor in the reference transition. In Fig. 2b it can clearly be seen that the PWS WR-transition and the reference WR-transition have very different positions in stride rate – stride length space, and most likely this difference in position is mainly caused by the change in walking dynamics caused by the speed clamp. The change in position of the WR-transition in stride rate – stride length space mainly occurs along the stride length axis (Fig. 2b), while the change along the rate axis is insignificant (Fig. 2b), which indicates that the attractor principle is valid in both situations. Still, attractors for running were not determined in the present study and more direct evidence for validation of the attractor principle is needed.

4.2. Dual-task

Our results demonstrated that there was no, or just a very little, change in the position of the WR-transition in stride rate – stride length – locomotion speed (SrSlLs) space when intensive attentional diversion was added as compared to the reference test situation. In the perspective of self-organization, and according to the dynamic framework described above, very little conscious attention should be involved to in the transition from walking to running. For treadmill locomotion, the locomotor drive needs to be set in the CNS to initiate locomotion. This can be governed by a conscious decision. When the locomotion then has been initiated the body should then just react on a subconscious level according to sensory inputs induced by the moving treadmill belt on the feet and the related changes in the dynamics of the body itself induced by the friction between the foot and the treadmill belt. Our results support this idea, because the addition of intensive attentional diversion only demonstrated a subtle deviation in the average position in the WR-transition SrSlLs space as compared to the position of the WR-transition in the reference situation (Fig. 3). We consider the reference situation to be the condition in this study with the highest level of self-organization. In the dynamic framework explained above, any conscious or emotional influence on the instantaneous state of locomotion can be considered to be influences from a central controller which should violate the self-organizing process. Therefore, the influence of the parts of the CNS that are involved in conscious attention and awareness should be as small as possible to preserve possible advantages of self-organization during locomotion.

There was a tendency for a change in the position of the WR-transition in SrSlLs space (Table 1) towards a higher WR-transition speed. However, for two participants the WR-transition never occurred in the dual-task situation. We speculate that both phenomena may be related to the interplay between attention and arousal (Kahneman, 1973). If good performance in the dual-task situations is defined as the ability not to interfere with the locomotion process under the influence of intensive attentional diversion, the main part (N = 16) of the participants performed WR-transitions as expected. However, two participants dib not perform a WR-transition witnin the speed interval used in the experimental protocol. Attention and arousal co-varies and the Yerkes-Dodson law states that performance has an inverse U-shaped relation with the level of arousal (Yerkes & Dodson, 1908). At high arousal levels, arousal interferes with attention so that important clues necessary to perform optimally are lost and the dominant and most obvious aspects of the situation will begin to dominate (Kahneman, 1973). Therefore, sixteen participants assumedly had a near optimal level of attention/arousal relationship with respect to uphold the self-organizing behaviour of the body, and only a very little influence on the WR-transition was found. The two participants who performed badly were supposedly over-aroused. In the dual-task situation with over-arousal, the primary (dominant) task (of walking) was therefore maintained to be dominating, most likely since the rather few attentional resources even on subconcious levels, which may be needed to not to interfere with the self organizing process, were lost in competition with the high arousal levels. As a result, the WR-transition process was overridden.

5. Conclusion

It was demonstrated that walk-to-run transitions can be elicited when participants are asked to walk at a constant speed (speed clamp) and the stride rate is monotonously increased using a metronome. Additionally, it was demonstrated that intensive attentional diversion using a dual-task paradigm had very little influence on the position of the WR-transition in the stride rate, stride length, and locomotion speed space. It is argued that these observations can be explained in the context of the dynamic behavior of complex systems. Finally, it is suggested that for human locomotion the specific position of a given WR-transition in parameter space is determined by the positions of the two behavioral attractors in this space, one for walking and one for running observed under the same circumstances as the WR-transition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

Participants are thanked for their participation.

Funding

No external funding was available for this project.

Data availability

Relevant data will be available electronically if the work is published.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2019.102509.

References

Abdolvahab, M. (2015). Gait transition dynamics are modulated by concurrent cognitive activity. *Attention Perception Psychophysics, 77*, 2502–2506.

Ashby, W. R. (1957). *An Introduction to Cybernetics.* London: Chapman & Hall LTD.

Ashby, W. R. (1962). *Principles of the self-organizing system.* Illinois, USA: Pergamon Press225–278.

Daley, M. A., Channon, A. J., Nolan, G. S., & Hall, J. (2016). Preferred gait and walk-run transition speeds in ostriches measured using GPS-IMU sensors. *Journal of Experimental Biology, 219*, 3301–3308.

Daniels, G. L., & Newell, K. M. (2003). Attentional focus influences the walk-run transition in human locomotion. *Biological Psychology, 63*, 163–178.

Diedrich, F. J., & Warren, W. H., Jr (1995). Why change Gaits? Dynamics of the walk-run transition. *Journal of Experimental Psychology: Human Perception and Performance, 21*, 183–202.

Diedrich, F. J., & Warren, W. H., Jr (1998). The dynamics of gait transitions: Effects of grade and load. *Journal of Motor Behavior, 30*, 60–78.

Haken, H. (1983). *Synergetics, An Introduction* (3rd ed.). Berlin: Springer.

Hansen, E. A., Kristensen, L. A. R., Nielsen, A. M., Voigt, M., & Madeleine, P. (2017). The role of stride frequency for walk-to-run transition in humans. *Science Report, 7*(1), https://doi.org/10.1038/s41598-017-01972-1.

Hansen, E. A., Nielsen, A. M., Kristensen, L. A. R., Madeleine, P., & Voigt, M. (2018). Prediction of walk-to-run transition using stride frequency: A test-retest reliability study. *Gait and Posture, 60*, 71–75.

Heylighen, F. (2002). The science of self-organization and adaptivity. In L. D. Kiel (Vol. Ed.), *Knowledge Management, Organizational Intelligence and Learning, and*

Complexity: Vol. 3. Abu Dhabi, U.A.E.: EOLSS Publishers Co Ltd.
Hreljac, A. (1993). Preferred and energetically optimal gait transition speeds in human locomotion. *Medicine and Science in Sports and Exercise, 25*, 1158–1162.
Ivanenko, Y. P., Labini, F. S., Cappellini, G., Macellari, V., McIntyre, J., & Lacquaniti, F. (2011). Gait transitions in simulated reduced gravity. *Journal of Applied Physiology, 110*, 781–788.
Kahneman, D. (1973). *Attention and Effort.* Englewood Cliffs, New Jersey: Prentice-Hall Inc.
Kung, S. M., Fink, P. W., Legg, S. J., Ali, A., & Shultz, S. P. (2018). What factors determine the preferred gait transition speed in humans? A review of the triggering mechanisms. *Human Movement Science, 57*, 1–12.
Luenberger, D. G. (1979). *Introduction to Dynamics – Theory, Models and Applications.* New York: John Wiley and Sons.
Minetti, A. E., Ardigo, L. P., & Saibene, F. (1994). The transition between walking and running in humans: Metabolic and mechanical aspects at different gradients. *Acta Physiologica Scandinavica, 150*, 315–323.
Monteiro, W. D., Farinatti, P. T. V., De Oliveira, C. G., & Araújo, C. G. S. (2011). Variability of cardio-respiratory, electromyographic, and perceived exertion responses at the walk-run transition in a sample of young men controlled for anthropometric and fitness characteristics. *European Journal of Applied Physiology, 111*, 1017–1026.
Thelen, E., & Smith, L. B. (2007). Dynamic systems theories. In R. Lerner (Vol. Ed.), *Handbook of Child Psychology: Vol. 1*. Hoboken, New Jersey, USA: John Wiley and Sons.
van Kleef, E. A. (2015). Engineering strategy: A holistiv view on the design of complex systems. In 6th Resilience Engineering International Symposium, vol. 6, pp. 1-6. Lissabon: Resilience Engineering association.
Yerkes, R. M., & Dodson, J. D. (1908). The relation of strength of stimulus to rapidity of habit-formation. *Journal of Comparative Neurology of Psychology, 18*, 459–482.