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Prediction of walk-to-run transition using stride frequency: A test-retest reliability study

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ABSTRACT

The transition from walking to running has previously been predicted to occur at a point where the stride frequency starts getting closer to the running attractor than to the walking attractor. The two behavioural attractors were considered to be represented by the freely chosen stride frequencies during unrestricted treadmill walking and running. The aim of the present study was to determine the relative and absolute test-retest reliability of the predicted walk-to-run transition stride frequency. Healthy individuals ($n = 25$) performed walking and running on a treadmill in a day-to-day test-retest design. The two behavioral attractors were determined during walking and running at freely chosen velocities and stride frequencies. Subsequently, the walk-to-run transition stride frequency was predicted using camera recordings and a previously reported equation for prediction. The walk-to-run transition occurred at a velocity of 7.7 ± 0.5 km h^{-1} at day 1 as well as at day 2. Besides, the predicted walk-to-run transition stride frequencies were 69.7 ± 3.3 strides min^{-1} and 70.5 ± 3.4 strides min^{-1} on day 1 and day 2, respectively ($p = 0.08$). A further comparison between the predicted walk-to-run transition stride frequencies at day 1 and day 2 showed an $ICC_{3,1}$ of 0.89, which indicated almost perfect relative reliability. The absolute reliability was reflected by a%-value of the standard error of the measurement (*SEM*%) of 1.6% and a%-value of the smallest real difference (*SRD*%) of 4.4%. In conclusion, the predicted walk-to-run transition stride frequency can be considered reliable across days.

1. Introduction

Walking and running constitute fundamental characteristics of human movement behaviour. Consequently, the ability to effectively perform walking and running is central to human function and well-being. It further follows, that our understanding of the control and behaviour of walking and running is of great importance. As an example of a reason for that, one could point to the field of assistive solutions for individuals with walking disability. The better our understanding is of the control and behaviour of walking and running, the better we can develop neuroprosthetic solutions that can assist individuals with impaired walking and running abilities [1]. Examples of solutions could involve exoskeletons, robot-based systems, or systems applying electrical muscle or epidural stimulation [2]. A prerequisite for such solutions is a thorough understanding of the control and behaviour of natural walking and running.

One aspect that throughout decades, in particular, has challenged our understanding of the control and behaviour of natural walking and running is the walk-to-run transition [3,4]. In other words, the reason or reasons for humans to shift from walking to running at progressively increased velocity remains unclear. For example, it is suggested in the literature that the walk-to-run transition is triggered by increased sensed effort due to exaggerated biomechanical loading in the form of increased activation of the tibialis anterior, rectus femoris, and hamstring muscles during the swing phase [5,6]. It has also been suggested that the transition is made with minimal attention demand [7]. Overall, the body of the existing literature concerning the walk-to-run transition does not provide any clear-cut explanation of the reason for the transition [8]. In a recent contribution to the existing literature on the topic, it was suggested that the central aspect of walk-to-run transition in humans might be influenced by behavioural attractors [9,10] in the form of stride frequencies spontaneously occurring during behaviourally unrestricted gait conditions of walking and running [11]. The suggestion was formulated based on the experimental finding that gait shift from walking to running could be predicted to occur at a point when the stride frequency starts getting closer to the running attractor than to the walking attractor. In other words, the agreement between a predicted and an independently calculated walk-to-run transition stride frequency was reported [11].

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The purpose of the present study was to investigate the test-retest reliability of the predicted walk-to-run transition stride frequency since that would add to our understanding of the walk-to-run transition. In line with previously published guidelines for reporting reliability and agreement studies [12], both relative and absolute measures of reliability are reported in the present article.

2. Methods

2.1. Participants

A total of 25 individuals, including 19 men and 6 women, volunteered for the present study. The individuals had to be asymptomatic with respect to musculoskeletal injuries of the lower limbs. It turned out that 24 of the participants were recreationally active sports science students. One participant was a former sports science student. Most of the participants were recreationally active sports science students. The participants were characterized by the age of 26.6 ± 4.2 years, a height of 1.77 ± 0.08 m, a body mass of 77.4 ± 11.6 kg, and a leg length of 0.97 ± 0.06 m. Fourteen of the participants had also participated in our previous study [11]. Prior to testing, written informed consent was obtained from each participant. The study conformed to the standards set by the Declaration of Helsinki, and the procedures were approved by The North Denmark Region Committee on Health Research Ethics (N-20160003).

2.2. Experimental design

A test-retest design was applied. Each participant reported to the laboratory on two days, which were separated by 4 to 8 (6.3 ± 1.2) days. The times of the day at which each participant reported to the laboratory were similar (53 ± 88 min difference between day 1 and day 2) to avoid a possible influence of circadian rhythm [13]. The participant was instructed to continue a usual lifestyle between the two days. The test session on the first day was replicated on the second day.

2.3. Test sessions

Each test session consisted of four parts. The first part consisted of 10 min familiarization during which the participant walked on a motorised WOODWAY Pro XL treadmill (WOODWAY Inc., Waukesha, WI, USA) at 1 km h^{-1} for 1 min. Subsequently, the velocity was increased by 1 km h^{-1} each min, ending at 10 km h^{-1}. This first part of the session was completed by 10 min of rest. During the rest period, height and body mass were measured. In addition, the leg length was measured from the top of the anterior superior iliac spine to the bottom of the lateral malleolus [14,15]. The second part of the test session constituted the main part. This part was initiated by a bout of locomotion commenced at 3 km h^{-1} at which the participant walked for 30 s. After that, the experimenters increased the velocity by a predetermined magnitude of 0.5 km h^{-1} every 30 s. The part ended with 30 s at 10 km h^{-1} followed by 5 min rest. In advance, the participant had been instructed to shift from walking to running whenever it felt natural during the bout. With respect to the data analysis, the first velocity at which the participant eventually chose to run was considered the individual transition velocity. The justification for this particular procedure, as well as for applying a discrete treadmill protocol, was that it was consistent with many previous studies [3,16,17]. In the third and fourth part of the test session, the participant performed bouts of unrestricted walking and running at freely chosen velocity and freely chosen stride frequencies. These two bouts occurred in counterbalanced order and were separated by 5 min of rest. In order to standardize the procedure, all participants received the same instructions. The instruction for the walking bout was as follows, "*You are now supposed to walk in a preferred and comfortable way. For example, you could imagine yourself walking on the road without any particular purpose*". The instruction for the running bout was as follows, "*You are now supposed to run in a preferred and comfortable way. For example, you could imagine yourself running on the road without any particular purpose*". The participant was instructed to adjust the treadmill velocity according to preference and was blinded to the velocity. The bouts lasted until the participant had chosen the treadmill velocity; however, maximally 5 min and an additional 30 s for data recording. The participants wore their own running shoes and comfortable clothes. The test procedure was identical to the one applied in a previous study [11]. All the bouts of locomotion, except those for familiarization, were recorded with a GoPro Hero 4 silver edition camera (GoPro Inc., San Mateo, CA, USA) from the sagittal plane.

2.4. Data analysis

The raw data from each predetermined velocity and locomotion bout consisted of 30 s camera recordings. These recordings were analysed by the VLC version 2.1.2 software (VideoLAN organization, Paris, France). The first and the final 5 s of each recording were disregarded from the analysis. The number of strides in the remaining 20-s period was rounded to the nearest quarter of a stride. The initial contact between a heel and the treadmill belt defined the beginning of a stride cycle. Subsequently, the number of strides performed in the 20 s period was expressed in strides $\min^{-1}$. Similarly to a previous study [11], two different methods were applied for the determination of individual transition stride frequencies. The method of primary interest in the present study is termed the prediction method. A method of secondary interest is termed the calculation method.

For the prediction method, an individual transition stride frequency was determined based on the theories and justification described in the introduction, in Fig. 1, as well as in more details recently [11]. The individual predicted transition stride frequency (d) was determined from the following equation:

$$d = 0.5(b - a) + a,$$

where a denotes the freely chosen stride frequency (in strides $\min^{-1}$) during unrestricted walking at freely chosen velocity. b denotes the freely chosen stride frequency (in strides $\min^{-1}$) during unrestricted running at freely chosen velocity. a, b, and d are illustrated in Fig. 1. As an example, an individual with freely chosen stride frequencies during unrestricted walking and running of 60.0 and 82.5 strides $\min^{-1}$, respectively, would have a predicted transition stride frequency (d) of 71.3 strides $\min^{-1}$ as determined from the following calculation:

$$d = 0.5(82.5 \text{ strides} \min^{-1} - 60.0 \text{ strides} \min^{-1}) + 60.0 \text{ strides} \min^{-1}$$

For the calculation method, the individual stride frequencies during walking at the predetermined velocities were first plotted as a function of velocity. Then, a linear regression (Excel 2011, Microsoft Corporation, Bellevue, WA, USA) was applied to the plotted data. The obtained regression equation was used to calculate the individual stride frequency at the transition velocity. The reason for applying this approach was that the protocol did not provide data for walking at the actual transition velocity at which running per definition was performed. The linear regression equation had the following form:

$$y = \alpha x + \beta,$$

where y denotes the calculated transition stride frequency (in strides $\min^{-1}$), and x denotes transition velocity (in km h^{-1}). As an example, an individual with the regression equation of

$$y = 6.35x + 25.5$$

for the predetermined velocities and a transition velocity of 7.5 km h^{-1}, would have a calculated transition stride frequency (y) of 73.1 strides $\min^{-1}$ as determined from the following calculation: