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Author contact	wouter.hoogkamer@faber.kuleuven.be + 32 (0)16 32 90 65
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Stride Length Asymmetry in Split-belt Locomotion

Wouter Hoogkamer¹, Sjoerd M. Bruijn^{1,2,3} and Jacques Duysens^{1,4}

¹Department of Kinesiology, KU Leuven, Belgium

²Department of Orthopedics, First Affiliated Hospital of Fujian Medical University, Fuzhou, Fujian, P.R. China

³MOVE Research Institute Amsterdam, Faculty of Human Movement Sciences, VU University Amsterdam, The Netherlands

⁴Department of Research, Development & Education, St. Maartenskliniek, Nijmegen, The Netherlands

Abstract The number of studies utilizing a split-belt treadmill is rapidly increasing in recent years. This has led to some confusion regarding the definitions of reported gait parameters. The purpose of this paper is to clearly present the definitions of the gait parameters that are commonly used in split-belt treadmill studies. We argue that the modified version of stride length for split-belt gait, which is different from the standard definition of stride length and actually is a measure of limb excursion, should be referred to as ‘limb excursion’ in future studies. Furthermore, the symmetry of stride length and stride time is specifically addressed.

Highlights We explain the calculation of spatial gait parameters for split-belt gait; The definition of stride length in split-belt gait is problematic; We argue that this measure should be referred to as ‘limb excursion’; Using standard definitions, stride time can never be asymmetric when not turning; Similarly, stride length can never be asymmetric when not turning

Key words Gait; Limb excursion; Split-belt walking; Symmetry; Treadmill walking

Correspondence: Wouter Hoogkamer, Department of Kinesiology, KU Leuven, Tervuursevest 101 bus 1501, 3001 Heverlee, Belgium, wouter.hoogkamer@faber.kuleuven.be

Introduction

Split-belt treadmills are used to study locomotor adaptation. After pioneering work in the 80 and 90ties, focusing on whether walking with two legs at different speeds is possible, this work has seen a huge boost recently (Fig. 1). A large part of this boost has come from the group of Amy Bastian, who explored locomotor adaptation, and its practical implications, in rehabilitation [7, 10]. In recent years ever more labs are using a split-belt to study gait adaptability. However, as the number of studies increases, definitions used for different gait parameters have become less clear in a substantial number of cases.

From our experience in discussing split-belt re-

Figure 1: Overview of the total number of split-belt publications and authoring labs. Only studies on split-belt gait in humans where belts run on different velocities were included.

Figure 2: Top view of foot placement in case of asymmetric stride lengths, which is only possible when turning.

search with clinicians, biomechanists and students, we see that concepts are often unclear, as a result of poor understanding of commonly used gait parameters, and the impossibility of applying these parameters to split-belt gait. Specifically, the definition of stride length in split-belt gait and its (a)symmetry is counterintuitive.

Paradoxical asymmetries

In split-belt studies, but also in studies on pathological gait, left-right asymmetry of gait parameters is often reported. It should be noted, however, that if we assume straight-ahead gait, some gait parameters can exhibit asymmetric behavior, while other variables, according to their common definitions cannot, irrespective of whether participants are healthy or not. This may only change when these parameters are defined differently. Specifically, as ‘stride’ commonly refers to a complete gait cycle, both stride time and stride length should be symmetric as they are summations of right and left step times and lengths, respectively. However, introduction of several alternative definitions of stride length and of asymmetry has resulted in mentioning asymmetric stride times and lengths [1, 5, 6, 7]. Such alternative definitions are not necessarily problematic, but when these definitions are not clearly addressed, the use of alternative definitions will result in confusion. For example, if we consider a stride length asymmetry of 1.4 and a stride length of 0.8m (both in the range of earlier reported values for split-belt gait [2, 5, 7]) and would interpret stride strictly as a complete gait cycle, we would erroneously think the participant is turning (Fig. 2). This exam-

ple already illustrates that it is good practice to not only report (a)symmetry values, but also values of the actual gait parameters, so that readers can judge the basis of the (a)symmetry.

The purpose of this paper is to clearly present the definitions of split-belt gait parameters and discuss the implications thereof. Furthermore, we advocate the use of ‘limb excursion’ as an alternative for ‘stride length’ in split-belt research.

Spatial parameters in treadmill gait

One commonly applied method to calculate spatial gait parameters during treadmill gait is based on the timing of gait events combined with belt speed. Stride length is equal to stride time multiplied by belt speed; step length is equal to step time multiplied by belt speed. Note that both length measures should be corrected for displacements in the global frame of reference, as these calculations are only precise when subjects do not drift on the treadmill and when foot placement relative to the center of mass is constant. The latter will not be the case in asymmetric gait with different swing speeds between limbs (see the work of Roerdink et al. [8, 9]).

To avoid problems with displacements on the belt, spatial parameters can be calculated based on the positions of the feet [7]. In this case step length is best determined based on toe positions just before lift-off, because in healthy gait at this gait event the toes of both feet are on the floor. More often step length is estimated based on the inter ankle distance at initial contact [7], which slightly deviates from the overground definition of step length, as the heel of the trailing limb is already raised at this time. Stride length is then calculated as the summation of left and right step length.

Unlike normal treadmill gait, in split-belt gait, temporal parameters and belt speeds cannot be used easily to calculate spatial parameters, as both belts run at different speeds. Thus, spatial parameters need to be calculated from feet positions directly. For step length, this is done by taking the anterior-posterior distance between the ankle marker of each leg at initial contact of the leading leg. Fast step length refers to the step length measured at initial contact of the fast leg (leg which makes contact with the fast moving belt); slow step length refers to step length measured at slow leg initial contact [7] (Fig. 3). It is important to cal-

culate these distances at initial contact, as the feet will move closer together (or apart) during double support, since the belts move at different speeds (Fig. 3).

Stride length or limb excursion

For stride length, the situation is more complex, since stride length includes both left and right steps. Logically, one would define stride length as the sum of left and right step lengths, similar to normal gait. However, in their influential paper on split-belt adaptation Reisman et al. [7] introduced a modified version of stride length, which is calculated as the distance travelled by the ankle marker in the anterior-posterior direction from initial contact to lift-off of one limb (Fig. 3). The advantage of this method is that it allows assessing asymmetry in ‘stride lengths’ between fast and slow legs. However, this type of stride length is not comparable to ‘normal’ stride length, which can never be asymmetrical on a treadmill (c.f. Fig. 2). Instead, this definition of ‘stride length’ is closer to a measure of limb excursion, or distance travelled during stance. While the group who introduced this measure [7] moved away from the use of stride length and focused on other spatial parameters based on limb excursion [4], we, and other groups, initially adopted their definition of stride length to be consistent [2, 5]. However, we have to acknowledge that stride length is not the most appropriate name for this gait parameter, since in any other condition ‘stride’ refers to a complete gait cycle. Alternatively, we argue that in future research this measure is best referred to as ‘limb excursion’; this to avoid any confusion with ‘true’ stride length.

Furthermore, limb excursion can easily be related to other excursion measures that previously have been shown to be important in the control of gait, such as limb angles at initial contact and lift-off [4] and hip excursion [3]. For instance, from work in cats it is well-known that the hip extension at lift-off is a crucial factor in the automatic switching from stance to swing [3]. Hence it is conceivable that subjects automatically try to maintain these hip excursions at a relatively constant level in order to profit from this automatic switching. Thus, the use of limb excursion measures, including limb angles at initial contact and lift-off may lead to novel insights in the control of gait.

Figure 3: Definitions of spatial gait parameters for split-belt gait. A: Side view during initial contact of the slow leg (full lines) and during lift-off of the fast leg (dashed lines). B: Side view during initial contact of the fast leg (full lines) and during lift-off of the slow leg (dashed lines). A ‘fast step’ occurs when moving from the dashed lines in panel A to the full lines in panel B, while a ‘slow step’ occurs when moving from the dashed lines in panel B to the full lines in panel A. The interval between initial contact of the leading leg (full lines) and the lift-off of the trailing leg (dashed lines) consists of the double support phase. Step length is calculated by taking the anterior-posterior distance between the ankle marker of each leg at initial contact of the leading leg; fast step length refers to the step length measured at fast leg initial contact and slow step length refers to step length measured at slow leg initial contact. Stride length is calculated as the distance traveled by the ankle marker in the anterior-posterior direction from initial contact to lift-off of one limb.

Conclusions

We strongly advice to report gait parameters for both sides and not just symmetry values. Additionally, when using ambiguous gait parameters, we encourage addressing their definitions and calculation procedures clearly to prevent wrong interpretations. Lastly, the use of ‘limb excursion’ measures for split-belt gait should be preferred over stride lengths, since this nomenclature is more correct, and such measures may lead to novel insights.

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