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Asymmetric interlimb role-sharing in mechanical power during human sideways locomotion

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ABSTRACT

Sideways movement at a wide variety of speeds is required in daily life and sports. The purpose of this study was to identify the characteristics of asymmetry in power output between lower limbs during sideways gait patterns. Seven healthy men performed steady-state sideways locomotion at various speeds. The mechanical external power of each limb was calculated and decomposed to the lateral and vertical components by the center of mass velocity and ground reaction force. We acquired data from 126 steps of sideways walking at 0.44–1.21 m/s, and from 41 steps of sideways galloping at 1.04–3.00 m/s. The results showed asymmetric power production between the limbs during sideways locomotion. During sideways walking, the trailing limb predominantly produced positive external power and the leading limb produced predominantly negative external power, and these amplitudes increased with step speed. In contrast, during sideways galloping, negative and subsequent positive power production was observed in both limbs. These differences in asymmetric interlimb role-sharing were mainly due to the vertical component. During sideways galloping, the trailing limb absorbs vertical power produced by the leading limb due to the longer flight time. This characteristic of vertical power production in the trailing limb may explain the presence of a double-support phase, which is not observed during forward running, even at high speeds. Our results will help to elucidate the asymmetric movements of the limbs in lateral directions at various speeds.

1. Introduction

The coordination of the movement of the legs allows people to move in various directions within a naturally complex environment. Most gait research has focused on straightforward walking and running, which are executed by symmetric role-sharing of leg movement. However, people often move sideways using asymmetric leg movements at a wide variety of speeds in daily life (Glaister et al., 2007), e.g., to walk around an obstacle (Gilchrist, 1998), or in various sports such as football (Bloomfield et al., 2007), basketball (Shimokochi et al., 2013), tennis (Uzu et al., 2009), and badminton (Kuntze et al., 2009). To understand the basic mechanics of such asymmetric interlimb role-sharing of leg movement, it is first necessary to understand the energetics of the individual legs during sideways movement at a variety of speeds. However, there have been considerably fewer studies of sideways locomotion compared with forward locomotion.

A previous study showed that during sideways locomotion, spatiotemporally unique gait patterns that are different from those associated with forward locomotion were spontaneously preferred depending on the speed of movement (Yamashita et al., 2013). At slower speeds (<1 m/s), sideways walking, which has a double-support phase and no flight phase, is preferred (Fig. 1a). It is the same pattern as that of forward walking (<2.2 m/s in Mercier et al. (1994)). In contrast, at faster speeds (>1 m/s), sideways galloping, which has both double-support and flight phases, is preferred (Fig. 1b). It is the same pattern as that in forward galloping, which requires intentional effort during forward locomotion (>1.7 m/s in Getchell and Whitall (2004)). A previous study suggested that the trailing and leading limbs act asymmetrically in

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Nomenclature

Notation

COM center of mass
$F_{res,trail}$, $F_{res,lead}$ resultant ground reaction force of the trailing and leading limb, N
$F_{lat,trail}$, $F_{lat,lead}$ lateral ground reaction force of the trailing and leading limb, N
$F_{ver,trail}$, $F_{ver,lead}$ vertical ground reaction force of the trailing and leading limb, N
GRF ground reaction force
L_{on}–T_{off} proportion of time between the leading foot's contact and the trailing foot's take-off relative to the entire stride duration
$P_{ext,trail}$, $P_{ext,lead}$ mechanical external power generated by the trailing and leading limb, W
$P_{lat,trail}$, $P_{lat,lead}$ mechanical external power of the lateral component generated by the trailing and leading limb, W
$P_{ver,trail}$, $P_{ver,lead}$ mechanical external power of the vertical component generated by the trailing and leading limb, W
T_{on}–L_{off} proportion of time between the trailing foot's contact and the leading foot's take-off relative to the entire stride duration
t_{step} step duration, s
V_{com}, V_{lat}, V_{ver} resultant, lateral, and vertical COM velocity, m s^{-1}
W^{+}_{ext}, W^{-}_{ext} mechanical positive and negative external work calculated from COM velocity, J
W^{+}_{lat}, W^{-}_{lat} mechanical positive and negative external work of the lateral component calculated from COM velocity, J
W^{+}_{ver}, W^{-}_{ver} mechanical positive and negative external work of the vertical component calculated using COM velocity, J
$MP^{+(-)}_{ext,trail}$, $MP^{+(-)}_{ext,lead}$ mean positive (negative) mechanical external power generated by the trailing and leading limb per body mass, W kg^{-1}
$MP^{+(-)}_{lat,trail}$, $MP^{+(-)}_{lat,lead}$ mean positive (negative) mechanical external power of the lateral component generated by the trailing and leading limb per body mass, W kg^{-1}
$MP^{+(-)}_{ver,trail}$, $MP^{+(-)}_{ver,lead}$ mean positive (negative) mechanical external power of the vertical component generated by the trailing and leading limb per body mass, W kg^{-}

sidestepping at a single speed (3 m/s) in comparison to symmetric movement (running) at the same speed (Kuntze et al., 2009). However, it remains unknown whether the asymmetric roles of the limbs are applicable at a wide variety of speeds and during different gait patterns.

To increase the understanding of the role of the limbs during locomotion, external power, which is the amount of center of mass (COM) energy change per unit of time, has been used to evaluate forward walking (Donelan et al., 2002) and running (Arampatzis et al., 2000). The mode of forward locomotion (i.e. walk or run) is determined mainly by the movement speed, and these movement types have distinct gait modes with different mechanics. Forward walking is generally characterized by an inverted pendulum, absorbing power at foot contact and producing power at push-off to redirect the COM velocity (Donelan et al., 2002). Forward running is roughly characterized by a spring-mass, absorbing and recovering energy (Cavagna et al., 1963, 1964). In addition to walking and running, an energy curve analysis applied to forward skipping and galloping suggests that the body behaves like a spring-mass in forward galloping (Fiers et al., 2013) and as a spring-mass and an inverted pendulum in forward skipping (Minetti, 1998; Minetti et al., 2012).

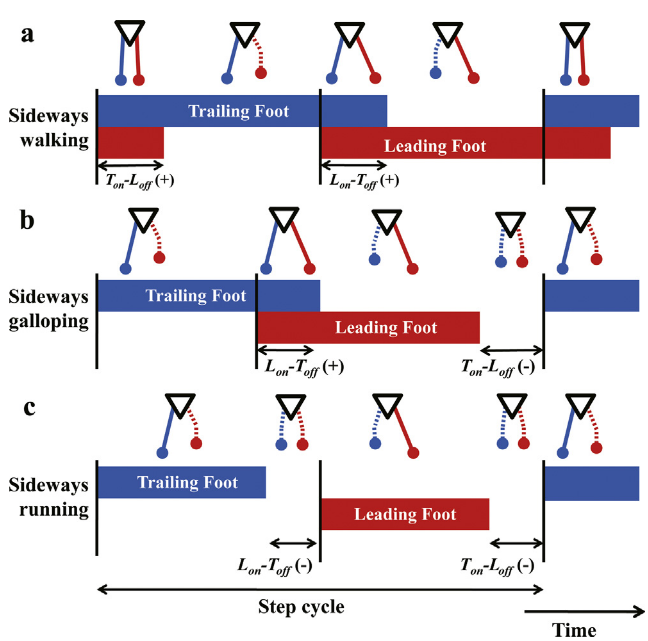

Fig. 1. Typical contact patterns for sideways walking, galloping, and running (Figure created based on Yamashita et al., 2013). Time is represented horizontally from left to right, with periods of stance (solid bars) and swing (spaces).

The decomposition of external power to the horizontal and vertical components needs be elucidated in order to increase the understanding of asymmetric interlimb role-sharing during sideways gait patterns at a variety of speeds. Mauroy et al. (2013) demonstrated interlimb role-sharing between the final step and the previous step when jumping over an obstacle during forward running. Both legs behaved like spring-masses, but they contributed differently to horizontal and vertical power output. We hypothesized that the role of each limb during sideways walking and galloping can be clearly understood by calculating external power and its decomposition to the lateral and vertical components and quantifying them with step speed. The purpose of the present study was to identify the characteristics of asymmetrical power production in each limb during sideways gait patterns at various speeds.

2. Methods

Seven healthy young men (age: 23.3 ± 1.8 years; height: 1.74 ± 0.06 m; mass: 70.7 ± 5.0 kg) with no history of major lower limb injury or neuromuscular disorders participated in this study. They provided written informed consent to undergo the experimental procedures. This study was conducted in accordance with the Declaration of Helsinki and was approved by the ethics committee of our university (23-H-8).

The experiment was performed on a straight walkway consisting of a 10-m acceleration segment and an 8-m measurement segment placed on five force platforms (0.6 × 0.4 m, TF-4060-B, Tec Gihan, Japan) (Fig. 2). Participants performed sideways locomotion to the right while barefoot. The time required to perform the task was measured using two photocells aligned to the measurement segment at waist height. Participants were asked to pass these photocells at a variety of time settings (from 11 s to 3 s with 1-s decrements and shorter, if possible). The order of trials was not randomized to confirm the gait transition with increasing speed, and participants were able to adjust to the subsequent faster time setting. Participants were instructed to use their preferred gait pattern, to keep their speed as constant as possible, and not to cross their lower limbs during movement. They were not given any information about gait patterns or advised to use a particular way of moving. Before each trial, the starting position was chosen freely in the acceleration segment of the track by the participant to allow sufficient acceleration. One "step