

# **The mechanics of human sideways locomotion**

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## **Abstract**

The purpose of this thesis was to clarify the sideways gait patterns and strategies to be adopted biomechanically. In the experiment of part II, I investigated the characteristics of sideways gait patterns at increasing speed on a treadmill. The times of foot contact and take-off were analyzed. At slow speeds, all of the subjects performed the walk-like pattern, which has double support phase and no flight phase. When the treadmill speed exceeded about 3.5 km/h, most subjects performed the gallop-like pattern, which has both double support phase and flight phase, while a few performed the run-like pattern, which has flight phase and no double support phase. It was revealed that at high speeds, gallop-like pattern, which is unfamiliar during forward locomotion was preferred.

In the experiment of part III, subjects stepped sideways on a ground at different speeds. Using a 3D optical motion capture system, the centre of mass (COM) displacements were calculated. From COM displacements and the centre of pressure (COP) data, each limb extension speed was evaluated. Joint works were calculated by standard inverse dynamics equations. As a result, during the walk-like pattern, trailing limb acted as an inverted pendulum, which transformed from the gravitational potential energy to kinetic energy.

On the other hand, leading limb acted as an inverted pendulum, which transformed kinetic energy to gravitational potential energy. During the gallop-like pattern, the trailing limb seemed dominantly extended and the leading limb flexed. However, attention to each joint, negative and positive work done at each ankle plantarflexion. These results suggested that the gallop-like pattern locally acted as spring-mass mechanism at each ankle.

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## **Part I General introduction**

The coordination of the movement of athletes' legs while performing sports is often impressive. Our legs allow us to move in various directions in the natural complex environment. They can produce several gait patterns with a broad range of motion and force production, but in general, only some limited patterns are performed. Many researchers have investigated the bipedal locomotion in humans and the reason it is preferred. For example, there are the energy-saving mechanisms of forward locomotion: the pendulum-like model of walking (Cavagna et al., 1976) and the bouncing model of running mechanisms (Cavagna et al., 1964). In addition, either walking or running is preferred depending on moving speed. These gaits are completely distinct; running is not simply a walk performed quickly (Alexander, 1989).

We step sideways frequently in daily life, e.g., to walk around an obstacle (Gilchrist, 1998) or to avoid a collision with others coming toward us. Sidestepping is also observed 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). However, no studies have investigated the pattern of human sideways locomotion. Sideways locomotion seems

entirely distinct from forward locomotion. During forward walking and running, the left and right legs can be used symmetrically because they are positioned laterally to the direction of movement. During sideways locomotion, in contrast, each leg is anteroposteriorly aligned. Because of these anatomical constraints, unique and complicated gait patterns may be preferred. Kuntze et al. (2009) investigated each joint kinetics during sidestepping and showed that the leading and trailing legs act as the distinct roles. This study suggested that the sideways locomotion require some specific gait patterns and that they are coordinated by distinct roles in each limb. These studies can shed light on how to move in all directions, coordinating each limb. However, how the sideways locomotion is accomplished is currently open question, hence, kinetic and kinematic approaches are required to identify the sideways gait patterns. The subsequent studies can also shed light not only on sideways locomotion but on coordinated movements in various directions.

In this thesis, I want to provide any evidences about human motor control in sideways locomotion. The goal of this thesis is to reveal sideways gait strategies to be adopted biomechanically. In the first experiment (Part II), I clarified the gait patterns in sideways locomotion at increasing speed on a treadmill. In the second experiment (Part III), I examined whether and how



the energy-saving pendular and bouncing mechanisms are adjusted during sideways locomotion, and investigated the contribution of joint kinetics at a wide variety of speeds.

## **1.1. Temporal pattern of human forward locomotion**

Forward gait patterns are generally defined according to the temporal patterns. Walking is defined by the existence of double support phase during stance, whereas running has a flight phase during which neither limb is in ground contact (Mercier et al., 1994, Getchell and Whitall, 2004, Van Caekenberghe et al., 2010).

Walking and running are also classified by the fraction of time for which each foot is on the ground called 'duty factor' (Alexander, 1989, Minetti, 1998a, Alexander, 2004). During normal walking, duty factor was about 0.6 (Alexander, 1980) and decreased with the increasing speed until 0.5. When duty factor becomes below 0.5, the gait pattern is defined running because there must be a flight phase.

Some other gait patterns have been researched. In 1998, Minetti (1998b) pointed out skipping as 'the third gait'. Skipping was a unilateral gait pattern in which the same foot was kept forward throughout and has both double support phase and flight phase. We rarely adopt skipping because of costly gait, however, Ackermann and van den Bogert (2012) suggested forward walking and skipping are preferred at low gravity using computational simulations. Whitall (1989) and Getchell and Whitall (2004) investigated the interlimb coordination in human galloping from early

childhood to adulthood. In these studies, galloping was defined as the gait pattern which has both double support phase and flight phase and also the asymmetrical landing pattern.

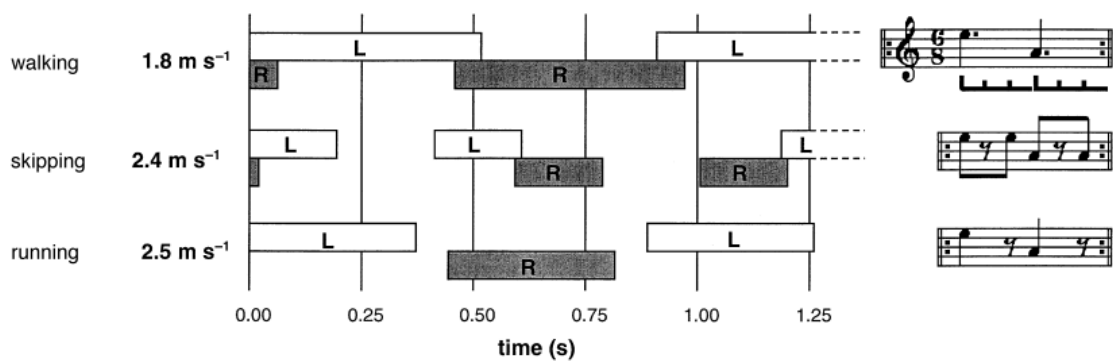


Fig. 1. Typical contact patterns for walking, skipping and running in humans.

The rhythmic transcription on the right shows the two-beat sequence of walking and running, and the three-beat pattern of skipping. L and R refer to left and right feet, respectively (Minetti, 1998b).

## 1.2. Displacement and mechanical energy of COM during forward walking and running.

During forward locomotion, studies in the displacements of the centre of mass (COM) have been mainly investigated by Cavagna's group. In 1963 and 1964, they investigated external work in walking and running. In these studies, they proposed two different models: "inverted pendulum" model in walking and "bouncing rubber ball" model in running. In walking, the kinetic energy of forward motion ( $E_{kf}$ ) is stored in part as gravitational potential energy ( $E_p$ ) when the point of contact with the ground is in front of COM. In running, on the other hand, as a leg strikes the ground, kinetic and gravitational potential energy is temporally stored as elastic strain energy in muscles, tendons, and ligaments and then is nearly all recovered during propulsive second half of the stance phase (Cavagna et al., 1963, Cavagna et al., 1964). They proved the presence of an elastic component in isolated frog muscle by using electrical stimulation (Cavagna et al., 1965, Cavagna et al., 1968).

In 1976, they assessed the effectiveness of pendulum-like energy savings by calculating the percentage recovery (Cavagna et al., 1976):

$$\text{Recovery (\%)} = \frac{W_v^+ + W_f^+ - W_{ext}^+}{W_v^+ + W_f^+} \times 100$$

where  $W_v^+$  represents the positive work calculated from one step of the positive increments undergone by  $E_p (= mgh$ , where  $m$  is the mass of the body and  $h$  is the height of the COM),  $W_f^+$  is the positive work of the positive increments undergone by  $E_{kf} (= 0.5mV_f^2$ , where  $V_f$  is the instantaneous forward velocity of the COM), and  $W_{ext}^+$  is the positive external work of the positive increments undergone by  $E_{com} (= E_p + E_{kf} + E_{kv}$ ,  $E_{kv} = 0.5mV_v^2$ , where  $V_v$  is the instantaneous vertical velocity of the COM). A 100 %recovery would require the  $(E_p + E_{kv})$  and  $E_{kf}$  curves (Fig. 2) to be exactly out of phase and of equal shape and amplitude; a 0 %recovery would require curves perfectly in phase. They found %recovery of about 65% in human walking and less than 5% in running. In 1977, they also showed %recovery of about 70 for turkeys and rheas, etc. at normal walking (Cavagna et al., 1977). In 2002, they used the within-step analysis of the  $E_p-E_k$  transduction;

$$r(t) = 1 - \frac{|\Delta E_{com}(t)|}{|\Delta E_p(t)| + |\Delta E_k(t)|}$$

where  $t$  is time. This analysis gave more information about pendulum energy transduction at each event during walking (Fig. 5) (Cavagna et al., 2002).

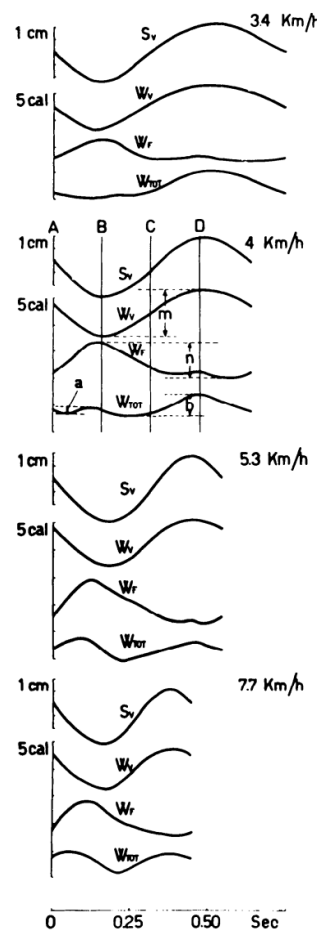


Fig.2. Work due to the speed changes of COM in forward direction ( $W_f$ ), work due to the vertical movements of COM ( $W_v$ ), and sum of the two ( $W_{tot}$ ). Displacements of COM in vertical direction ( $S_v$ ) (Cavagna et al., 1963).

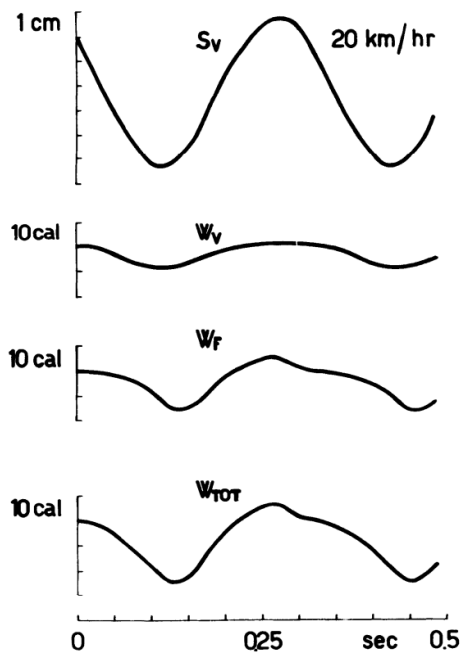


Fig.3. Work due to the speed change of COM in forward direction,  $W_f$ , and work due to the vertical displacement,  $W_v$ , on level running at 20 km/h;  $W_{tot}$  is the sum of the two. Displacement of COM in vertical direction is given by  $S_v$  (Cavagna et al., 1964).



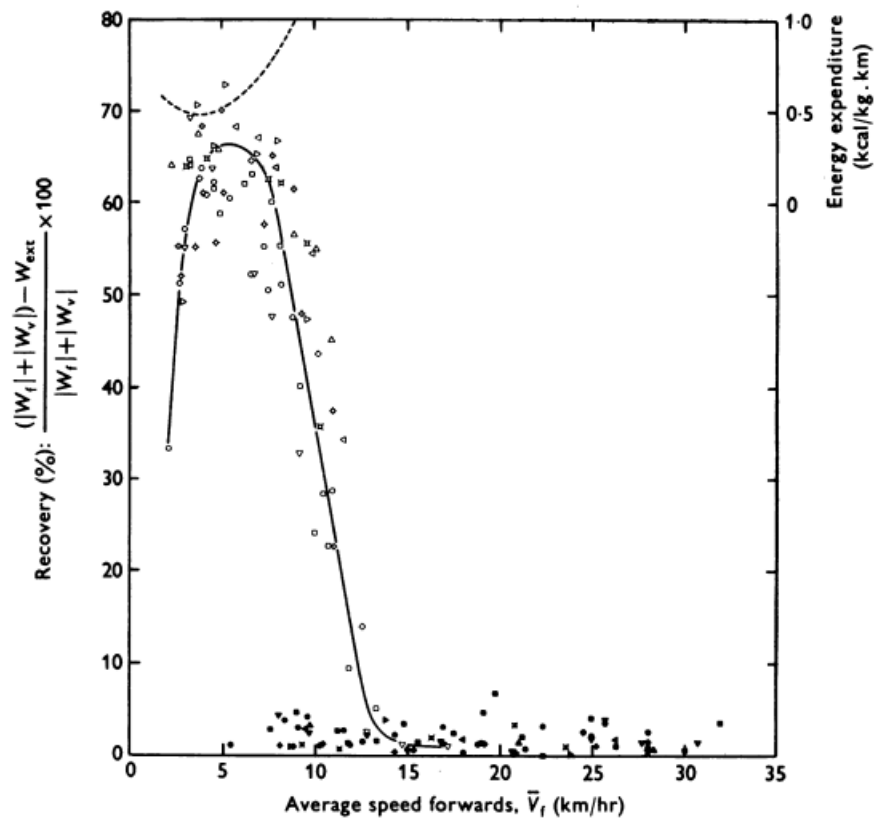


Fig.4. 'Recovery' of mechanical energy in walking (open symbols) and running (filled symbols) as a function of speed. The %recovery indicates the extent of mechanical energy re-utilization through the shift between potential and kinetic energy (elastic energy is not taken into account). The interrupted line gives the energy expenditure per unit distance (right-hand ordinate) (Cavagna et al., 1976).

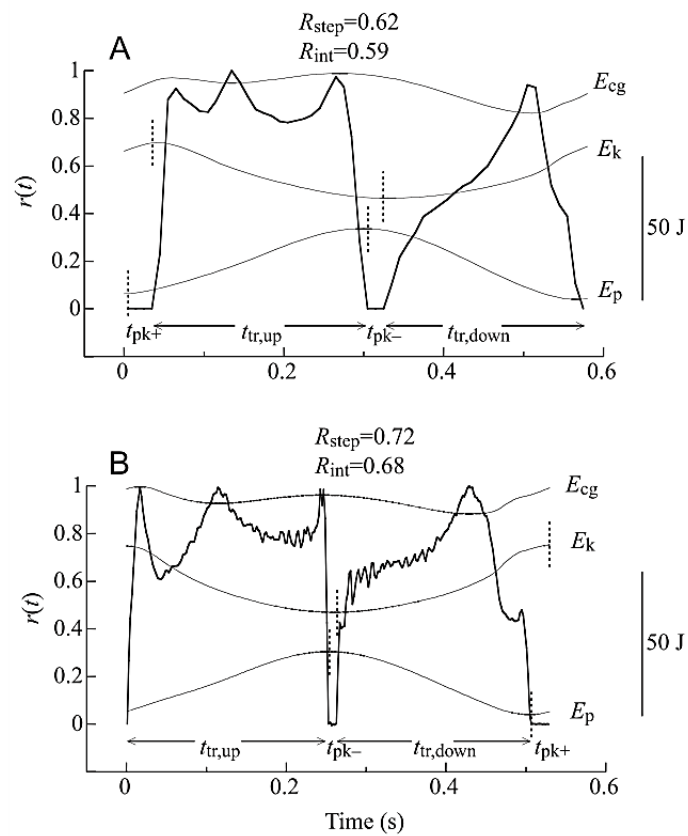


Fig. 5. Typical experimental recordings of loaded walking for (A) a European subject (male, 65.6 kg, 3.71 km/h, loaded with 19.3 kg) and (B) an African woman (Luo, 83.5 kg, 3.95 km/h, loaded with 19.5 kg). Note that in the African subject, loading results in a reduction in  $t_{pk-}$ , when  $E_p$  and  $E_k$  decrease simultaneously and in an increase in  $r(t)$  at the beginning of the descent of COM ( $t_{tr,down}$ ) (Cavagna et al., 2002).

### **1.3. Kinematics and kinetics of human locomotion**

In 1972, Winter et al., reported a television-computer tracking marker system for the kinematic analysis of locomotion (Fig. 6) (Winter et al., 1972). In 1974, they established low-pass digital filtering system to decrease the noise content in a raw coordinate data (Winter et al., 1974b), and showed two-dimensional (sagittal plane) joint kinematic parameter (Winter et al., 1974a), joint torque and energy flow (Winter and Robertson, 1978), power (Robertson and Winter, 1980) during walking, joint torque (Fig. 7) (Winter, 1980) and mechanical power (Winter, 1983) during running . They showed the ankle was primarily an energy generator, the knee an absorber, and the hip had relatively low power levels and no consistent patterns in power during jogging (Fig. 8) (Winter, 1983). The total amount of power generation increases with running speed, and relative contribution from each of these muscle group changes such that relatively more power is generated proximally as speed increases (Novacheck, 1998).

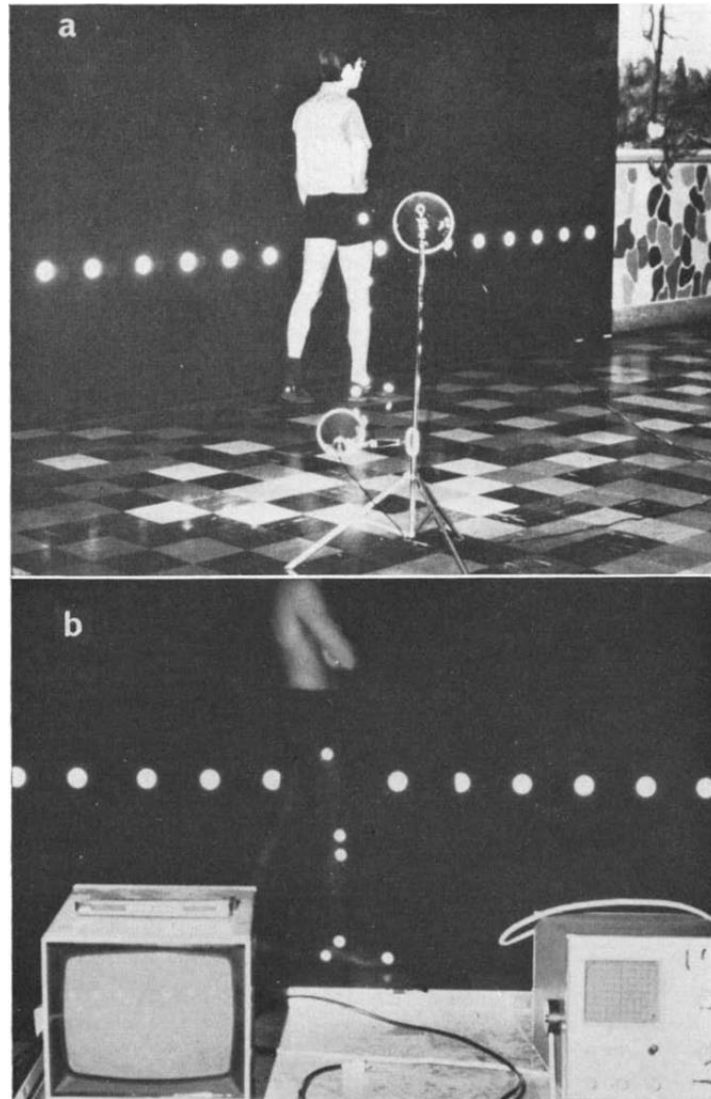


Fig. 6. (a) Subject on the “walkway” being tracked by a TV camera. Reflective markers on the body are placed on anatomical landmarks. Larger background markers serve as a yardstick so that absolute coordinates of each body marker can be calculated. (b) View of subject as seen by TV camera. Lightning is adjusted so that reflective markers have maximum contrast with the leg and the background (Winter et al., 1972).

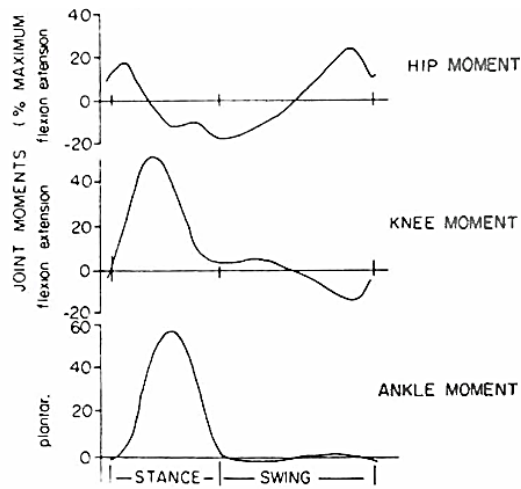


Fig. 7. Summary of moments of force patterns at the ankle, knee and hip for 11 trials in jogging (Winter, 1983).

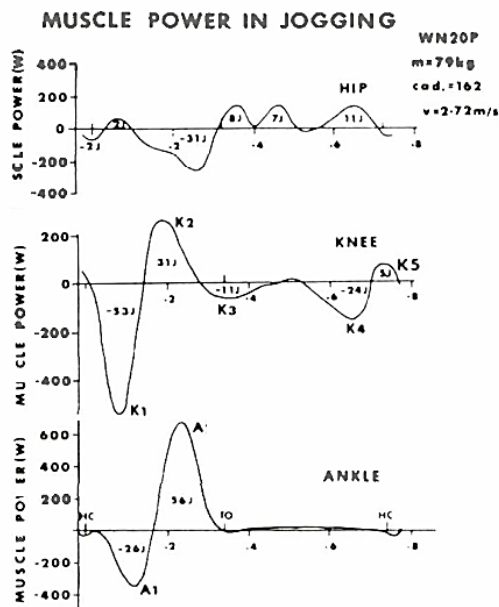


Fig. 8. Composite of power/work patterns at all three joints. Major generation of energy is done at ankle, with minor contribution at the knee. Power level at the hip is small, and when compared with other trials no pattern is evident (Winter, 1983).

#### **1.4. The study of lateral stepping**

Studies in lateral motion mainly focused on athletes. Most studies of lateral movement aimed to reduce risk of knee injury because non-contact the anterior cruciate ligament (ACL) injuries often occur during change in direction (Boden et al., 2000, Krosshaug et al., 2007). There here were few studies aimed to how to control of each limb to move sideways.

When basketball players perform lateral sliding task quickly, hip abductor velocity is not important, but faster hip extension is important (Shimokochi et al., 2013). Isokinetic tests of hip abduction and adduction cannot predict performance during side hop tests (Kea et al., 2001). Inaba et al. (2013) investigated kinetics and kinematics in lateral jump. They concluded extension torques and positive work done at hip, knee and ankle mainly contributed to the side step distances, on the other hand, hip abduction work did not contribute to propulsion. Kuntze et al. (2009) showed role-sharing during sidestepping; trailing limb has the roles of shock absorption and propulsive force generation, and leading limb act as braking and vertical force generation.

## **Part II Walk-, run- and gallop-like gait patterns in human sideways locomotion**

### **1. Introduction**

Human locomotion is not only forward and backward, but we can move sideways as well. People step sideways frequently in daily life, for example, to walk around an obstacle (Gilchrist, 1998) or to avoid a collision with others coming toward us. Sidestepping is also observed in various sports, such as football (Bloomfield et al., 2007). Some studies have investigated the characteristic of sidestepping. Williford et al. (1998) evaluated the metabolic and cardiovascular responses, and showed side stepping produced greater energy cost than forward locomotion at both slow (walking) and fast (running) speeds. Biomechanical study showed the leading and trailing leg act as the distinct roles during sidestepping (Kuntze et al., 2009). However, no studies have investigated the pattern of human sideways locomotion.

During forward locomotion, walking and running are mainly defined whether or not the existence of double support phase and flight phase. Walking has a double support phase and no flight phase, whereas running has a flight phase and no double support phase (Mercier et al., 1994, Getchell and Whitall, 2004, Van Caekenberghe et al., 2010) (Figure 1a and b). As the speed

increases, the transition from walk to run naturally occurs (Hreljac, 1995, Raynor et al., 2002). However, there is a significant difference to be taken into account when considering sideways locomotion. During forward locomotion, the left and right legs can be used symmetrically because they are positioned laterally to the direction of movement. In contrast, they are aligned back and forth during sideways locomotion. Because of these anatomical constraints, the leading and trailing legs show different joint moment patterns and must play different roles (Kuntze et al., 2009). This may be suggested that an asymmetrical gait patterns such as galloping, which has both double support phase and flight phase (Whitall, 1989, Minetti, 1998b, Getchell and Whitall, 2004) (Figure 1c), are preferred during sideways locomotion. Therefore, sideways gait patterns depending on moving speed should be different from forward walking and running. The purpose of this study was to examine the characteristics of gait patterns in human preferred sideways locomotion at increasing speeds.



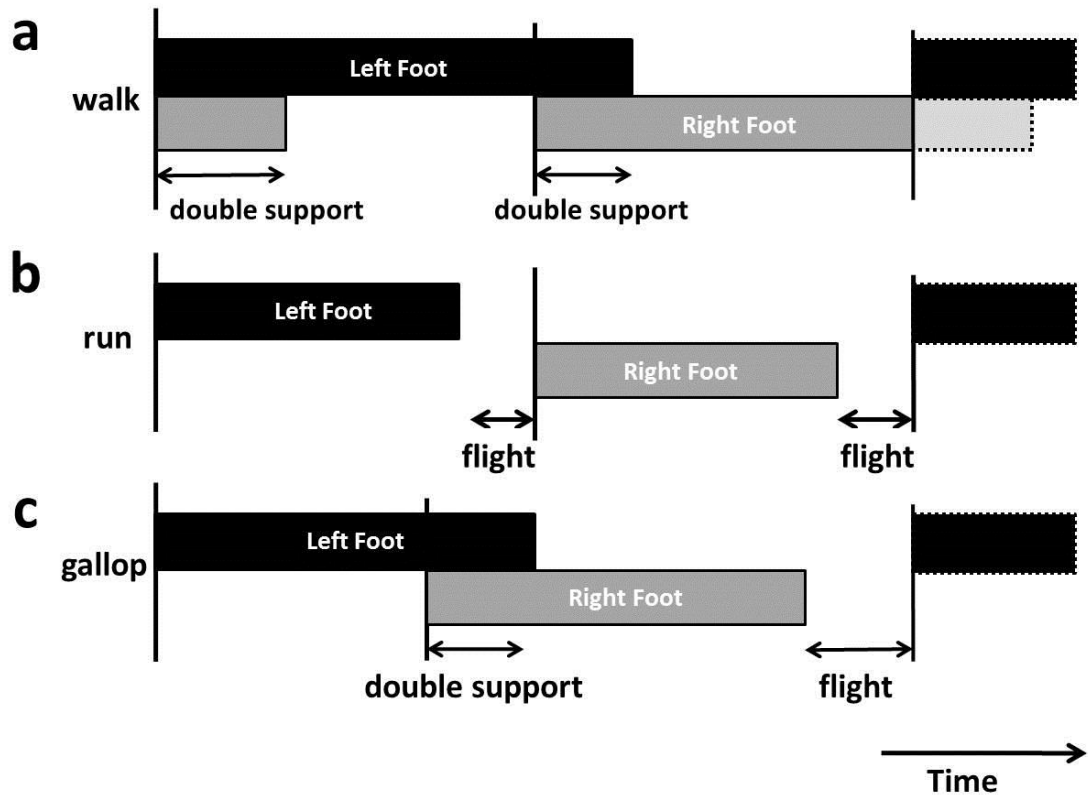


Fig. 1. Typical contact patterns for forward locomotion: walk, run and gallop. Time is represented horizontally from left to right, with periods of stance (solid bars) and swing (spaces).

## **2. Methods**

### **2.1. Subjects**

Fifteen healthy young male (age:  $22.6 \pm 0.7$  yrs, height:  $172.6 \pm 5.5$  cm, weight:  $65.9 \pm 7.5$  kg), with no history of major lower limb injury and neuromuscular disorders, participated in this experiment. They have never performed sidestepping on a treadmill. They provided informed consent to undergo the experimental procedures, which were conducted in accordance with the Declaration of Helsinki and approved by the ethics committee of the University (22-H-24).

### **2.2. Protocol**

The subjects were asked to step sideways on a treadmill using their own running footwear. Treadmill speed was increased from 1.3 km/h in steps of 0.3 km/h to 6.1 km/h every 20 s. Subjects repeated this procedure four times with the data from the final three times being used in the analysis. The subjects were instructed to use their preferred gait pattern at all times and not to cross their legs. No feedback was given on time or speed. Rest periods were provided between trials of at least 5 min or longer if requested, to prevent fatigue.

### 2.3. Data collection and data analysis

The motion during sidestep was captured from their back (i.e., from the side of the treadmill) using a high-speed video camera at 300 Hz (EXLIM PRO EX-F1; Casio Computer Co., Ltd., Tokyo, Japan). The times of foot contact and take-off were visually inspected on a frame-by-frame basis because the areas of sole at the instance of foot contact and take-off are variable within trial. Subjects performed the movement to the right. As illustrated in Figure 2, the motion consisted in the direction of the leading foot (right foot, shown in gray). We defined one step cycle duration as the time interval from foot contact of trailing foot (left foot, shown in black) to the subsequent trailing foot contact. To quantify the characteristics of sideways locomotion, five consecutive step cycles in the late 10 s within the 20 s data set were analyzed at each speed. We then analyzed four indices, step cycle frequency, proportion of the time between trailing foot contact and leading foot take-off relative to the entire stride duration ( $T_{on}-L_{off}$ ), proportion of time between leading foot contact and trailing take-off ( $L_{on}-T_{off}$ ) and relative timing ( $\phi$ ) (Figure 2). The step cycle frequency was calculated as the inverse of the duration of the step cycle. Positive values of  $T_{on}-L_{off}$  and  $L_{on}-T_{off}$  reflect the duration of a double support phase, and negative values indicate that there is a flight phase instead of double support.

The relative timing of trailing and leading foot contacts was evaluated by relative timing ( $\phi$ ), which was calculated as the time elapsed from the leading foot contact to the trailing foot contact relative to the entire stride period. The value denotes 0.5 if the trailing and leading foot contacts alternate in a perfect anti-phase coordination, whereas it has a value close to 0 or 1 if both feet hit the treadmill at the same time.

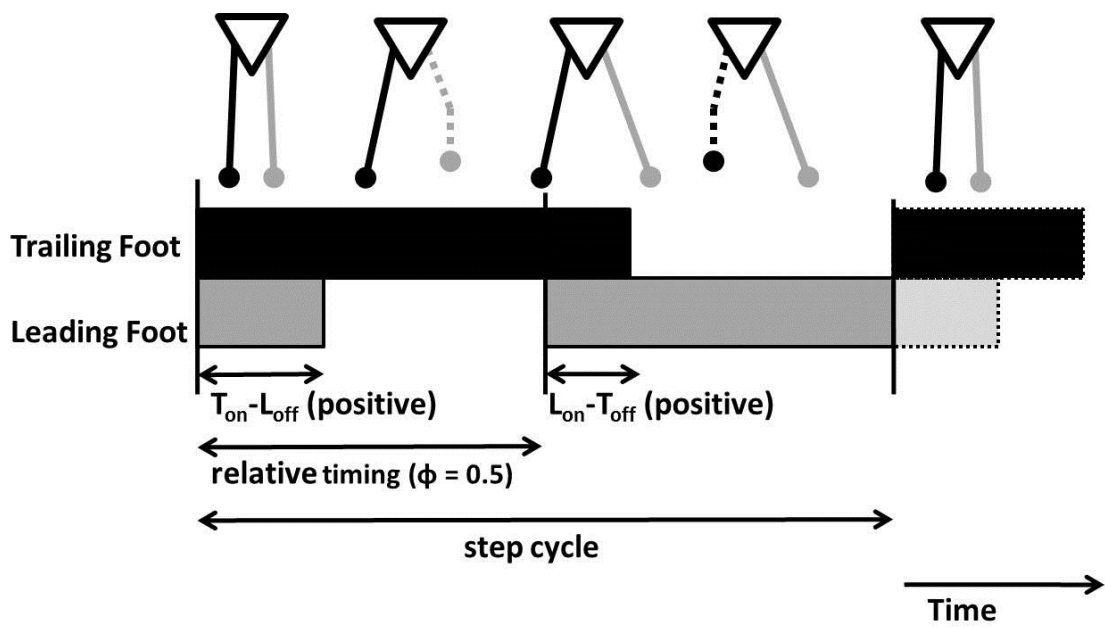


Fig.2. Definition of 1 step cycle,  $T_{on}-L_{off}$ ,  $L_{on}-T_{off}$  and relative timing ( $\phi$ ).

### 3. Results

At high speeds,  $L_{on}-T_{off}$  became negative only in subject 14 (at 3.4 km in average) and 15 (at 4.0 km/h in average), but remained positive in the other subjects (Figure 4). Therefore, subject 1–13 and subject 14, 15 were analyzed separately.

Figure 3 shows step cycle frequency as a function of gait speed. For most subjects, cycle frequency gradually increased as gait speed increased, but for subject 14 and 15, cycle frequency increased very little at high speeds.

Figure 4 shows  $T_{on}-L_{off}$  and  $L_{on}-T_{off}$  as functions of gait speed.  $T_{on}-L_{off}$  gradually decreased as gait speed increased for all subjects, and it became negative over  $3.5 \pm 0.5$  km/h (subject 1–13) and 2.5 km/h (subject 14) and 3.2 km/h (subject 15).  $L_{on}-T_{off}$  was continuously positive (i.e., there was a double support phase) for thirteen subjects. In contrast, it dropped into negative values (i.e., there was a flight phase) at the gait speeds of 3.4 km/h (subject 14) and 4.0 km/h (subject 15) for two subjects.

Figure 5 shows relative timing ( $\phi$ ) as a function of speed. In the majority of our subjects, the relative timing of the right and left foot contacts was organized in an anti-phase manner ( $\phi$  of approximately 0.5) at the low gait speeds, whereas it became asymmetric at the high gait speeds (ex.  $\phi$  of  $0.37 \pm 0.03$  at 6.1 km/h). The  $\phi$  of subject 15 remained at approximately 0.5 at

high speeds, and the  $u$  of subject 14 became asymmetric but was higher in value than that of the average in subject 1–13.

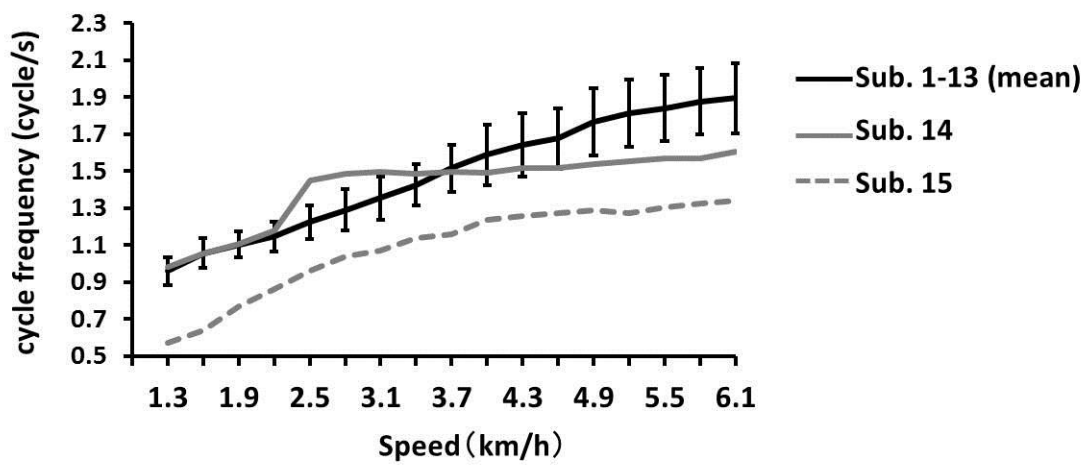


Fig.3. Step cycle frequency for fifteen subjects as a function of gait speed.

The data are represented for each speed as mean ( $\pm$ SD) of thirteen subjects (subject 1–13). Two subjects (subject 14, 15) were illustrated separately since qualitatively different patterns were observed.



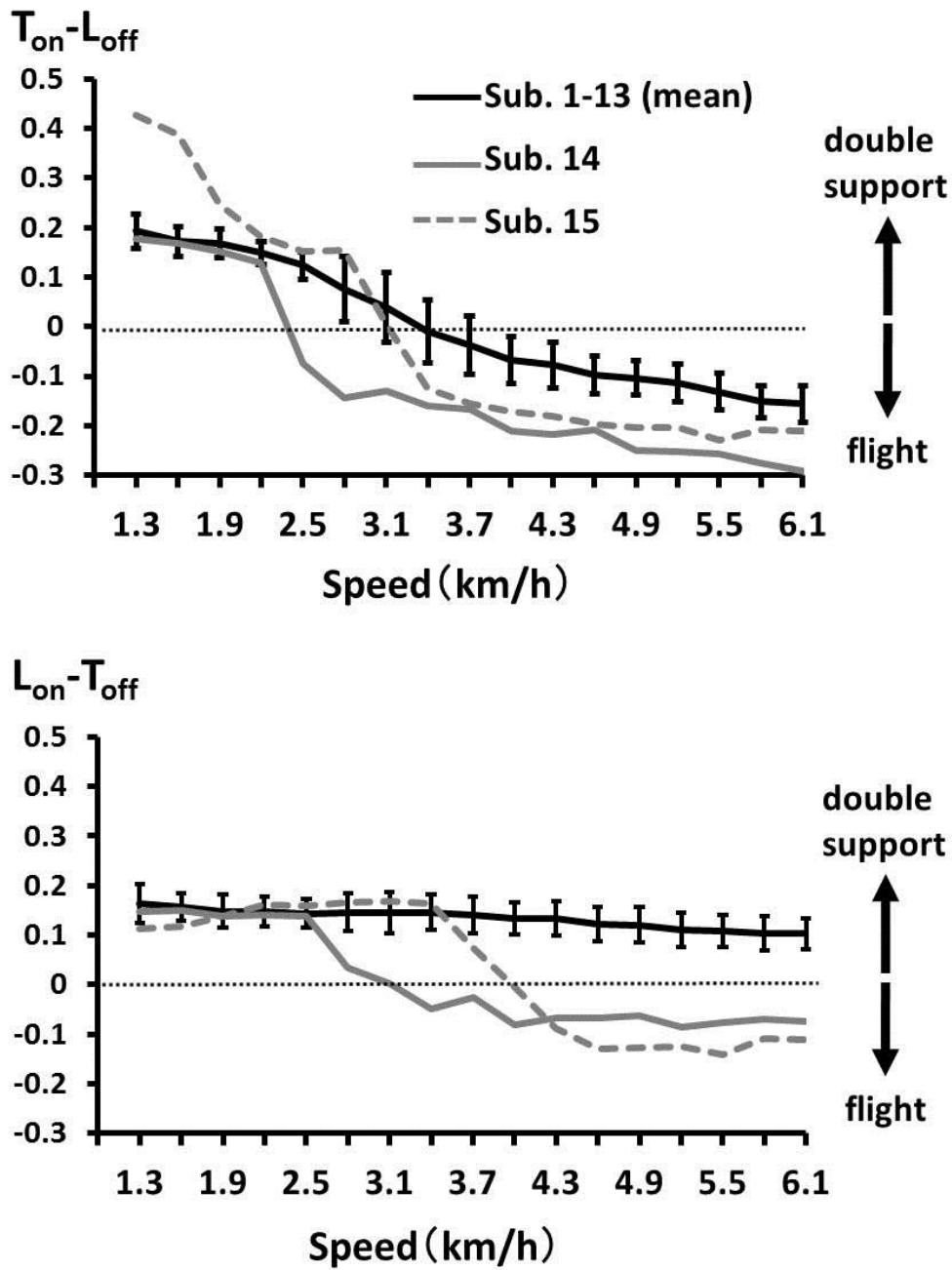


Fig.4.  $T_{on} - L_{off}$  (upper panel) and  $L_{on} - T_{off}$  (lower panel) for fifteen subjects as a function of gait speed. The data are represented for each speed as mean of thirteen subjects (subject 1–13). Two subjects (subject 14, 15) were illustrated separately since qualitatively different patterns were observed.

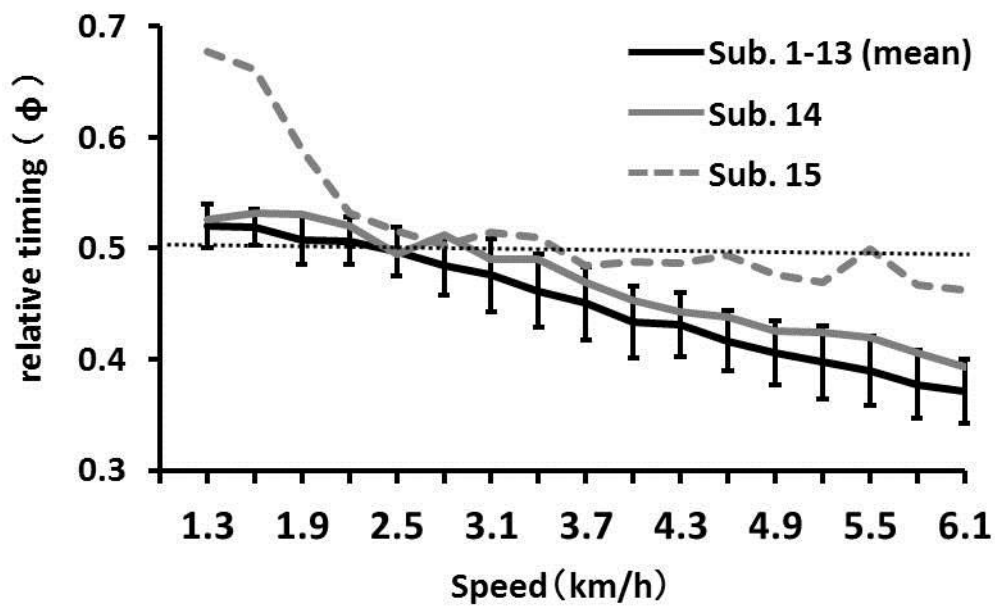


Fig.5. Relative timing of the trailing and leading foot contacts  $\phi$ . The values for subject 1–13, 14 and 15 were shown in separate lines. The horizontal dotted line indicates a value of 0.5 which represents a perfect anti-phase coordination.

#### 4. Discussion

Three different gait patterns were observed as a preferred style of sideways locomotion. At slow speeds, a double support phase and no flight phase (positive  $T_{on}-L_{off}$  and  $L_{on}-T_{off}$ ) with a symmetric foot contact rhythm ( $\phi$ ; 0.5) were observed in all of the subjects (Figure 6a). In contrast, at high speeds, two types of locomotion were observed. Two (13%) subjects showed a flight phase and no double support phase (negative  $T_{on}-L_{off}$  and  $L_{on}-T_{off}$ , Figure 6b). The other thirteen (87%) subjects showed both double support and flight phases (negative  $T_{on}-L_{off}$  and positive  $L_{on}-T_{off}$ ) and an asymmetric foot contact rhythm ( $\phi$ ; 0.37, Fig. 6c). These three patterns are similar to forward walking, running (Mercier et al., 1994, Van Caekenberghe et al., 2010) and galloping (Whitall, 1989, Minetti, 1998a, Getchell and Whitall, 2004). During sideways locomotion, most of our subjects naturally performed a gallop-like gait pattern at high speed, whereas forward galloping requires intentional adjustments (Getchell and Whitall, 2004). It is interesting that similar relative phase values were observed in sideways (0.35 in this study) and forward galloping (0.25–0.33 in (Whitall, 1989, Minetti, 1998b, Getchell and Whitall, 2004)).

Why is an asymmetric gallop-like gait pattern preferred in sideways, but not in forward, human locomotion? The main explanation would be the

alignment of the legs and the movement direction. In sideways locomotion, the two legs are positioned back and forth along the movement direction, whereas in forward locomotion, they are positioned laterally to the movement direction. Because of this restriction, the trailing limb must be the only leg to produce major propulsive forces. Humans need to change gait patterns from walking to running as velocity increases in forward locomotion, biomechanically understood as a transition from a pendulum mechanism to a bouncing mechanism because the maximum velocity during walking is determined by natural pendular frequencies: if the centrifugal force of the body exceeds gravity, the feet actually leave the ground (Minetti, 1998b, Saibene and Minetti, 2003, Usherwood, 2005). The velocity at which gait transition was observed in our experiment (i.e., walk to gallop: 3.5 km/h, walk to run: 3.4 km/h in subject 14 and 4.0 km/h in subject 15) is much slower than that observed in human forward (7.71 km/h in Mercier et al., 1994, 7.45 km/h in Diedrich and Warren, 1995, 7.16 km/h in Hreljac et al., 2005) and backward (6.65 km/h in Terblanche et al., 2003, 5.69 km/h in Hreljac et al., 2005) gait. This discrepancy might be because inverted pendulum mechanisms only around the trailing limb, not around the leading limb, contribute to the movement in sideways locomotion. Furthermore, because the subjects were not allowed to cross their feet, they could not have a longer stride. Therefore,

a flight phase is needed at a slower speed compared with forward locomotion.

In bouncing locomotion, the limbs must play roles of shock absorption and braking, propulsive and vertical force generation. Both legs can play both roles in forward running by flexing and extending the knee joint: shock absorption and braking force generation after a foot contact and propulsive and vertical force generation before the same toe-off. In contrast, this strategy works less efficiently in sideways locomotion because the knee joint has very limited degrees of freedom along the movement direction, although the hip and ankle joints might compensate for the knee joint's function. Instead, in the gallop-like side stepping, the roles of shock absorption and propulsive force generation, on the one hand, and braking and vertical force generation, on the other hand, appear to be distributed to the trailing and leading limbs, respectively, to a certain extent (Kuntze et al., 2009). In terms of role-sharing, the two legs in human sideways locomotion ought to be regarded as fore and hindlimbs rather than as left and right limbs. During quadrupedal locomotion, Kimura (1992) reported that forelimbs mainly produce braking forces and hindlimbs are dominant in acceleration force production. During galloping, which quadrupeds choose at the highest speeds, the foot force pattern showed initial acceleration (produced by a hindlimb) and a successive deceleration (by a forelimb) before the flight phase (Minetti, 1998b). This sequence was

the opposite to that used in forward locomotion.

In sideways locomotion, a run-like locomotion seems less efficient because the leading leg must play both roles of shock absorption while deceleration and the trailing must play the same roles while acceleration. However, why two subjects performed a run-like gait pattern? Anthropometric characteristics may not influence their gait patterns (subject 1–13: 167–182 cm in height, subject 14: 174 cm and subject 15: 169 cm). One possibility is that two subjects have no idea of galloping and intentionally switch to a run-like gait pattern because of no instruction about sideways gait patterns. They might intentionally perform a run-like pattern using some cue. For example, subject 14 might perform it in a consistent step frequency and subject 15 might in a consistent relative timing intentionally. So both  $T_{on-L_{off}}$  and  $L_{on-T_{off}}$  were suddenly decreased in the transition for two subjects, while gradually decreased for the other thirteen subjects (Fig. 4).

The practical importance of this study is that sideways gait patterns are selected naturally depending on moving speed. This indicates that suggested gait patterns are different during walking around an obstacle in daily life and evade a defender in some sports. Therefore, in the practical situation such as training and rehabilitation, we should consider sidestepping as not merely ‘sidestepping’ but three different gait patterns. Because this

study has only examined the characteristics of gait patterns in sideways locomotion, further study is needed about sideways walk-to-run and walk-to-gallop transition biomechanically and metabolically.

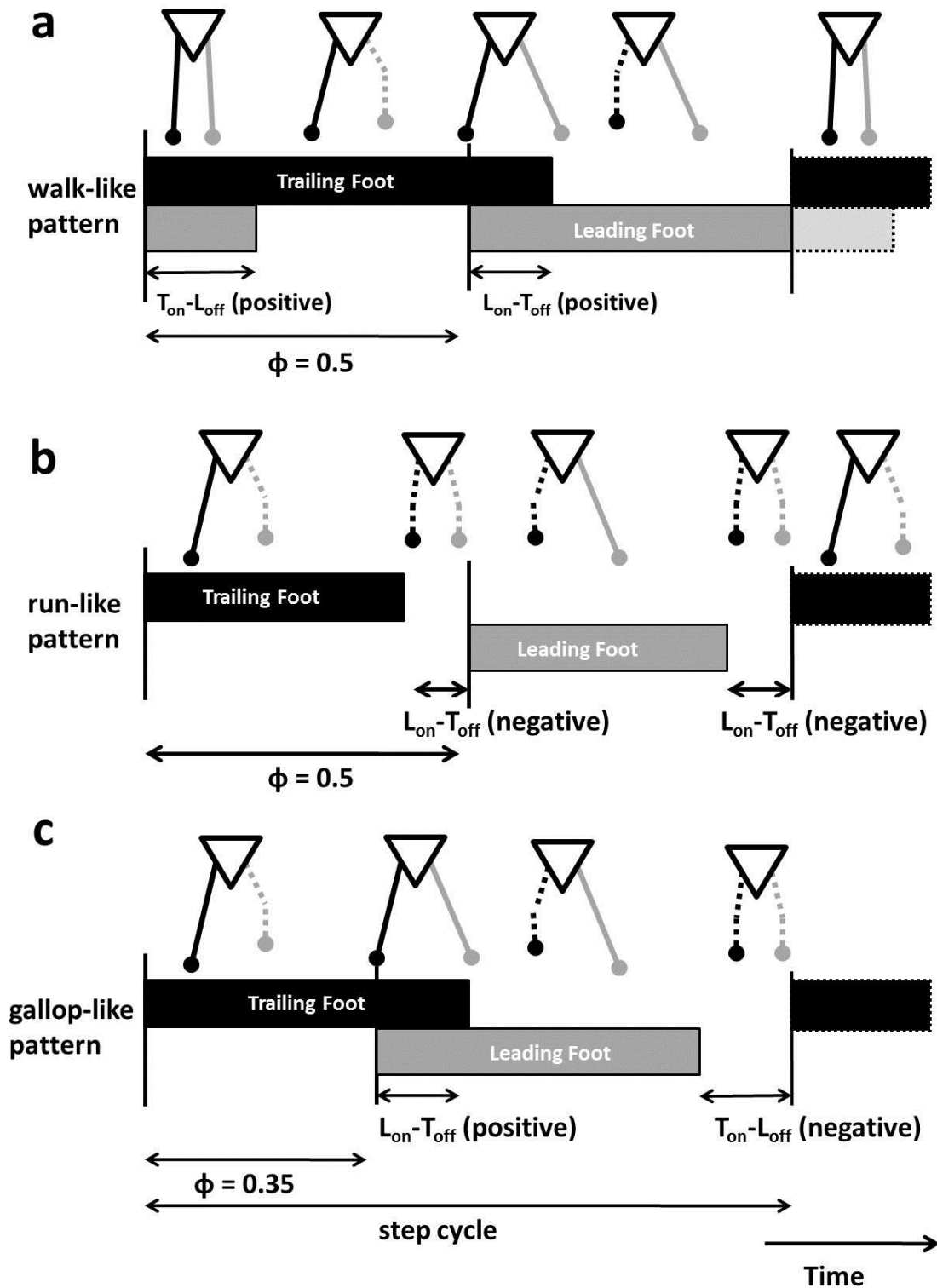


Fig.6. Typical examples for walk (a), run (b) and gallop-like (c) sideways locomotion.



## **5. Conclusion**

Our study revealed that there are three gait patterns in side- ways locomotion. At slow speeds, all of the subjects performed a walk-like pattern. Gait transition was observed as speed increased. At higher speeds, thirteen out of fifteen subjects preferred an asymmetric, gallop-like gait pattern, and only two subjects preferred a run-like gait pattern. In the gallop-like side stepping, the trailing and leading limbs might separately play roles of shock absorption and propulsive force generation, and braking and vertical force generation, respectively.

## **Part III Kinematics and kinetics of sideways gait pattern at different speeds**

### **1. Introduction**

Activities in daily life and sports require sideways movement in a wide variety of speeds. Continuous adjustment of gait parameters is required to produce lateral velocity. In part II of the present study, I analyzed temporal parameters, such as the timing of foot contact and take-off, during sideways locomotion and clarified the gait patterns in such movements. These results showed that at slow speeds, a walk-like pattern, which has a double support phase and no flight phase, is preferred. On the other hand, at high speeds, a gallop-like gait pattern that has both double support and flight phases is preferred. However, it is unclear how these patterns are organized.

To clarify the mechanisms in both walk- and gallop-like patterns, I considered that these gait patterns are guided by the energy-saving processes in sideways locomotion. The pendulum-like model for forward walking and the bouncing model for forward running are generally accepted as fundamental energy-saving mechanisms of forward locomotion. In walking, the kinetic energy of COM of forward motion is partially stored as gravitational potential energy when the point of contact with the ground is in

front of COM. In running, on the other hand, as a lower limb strikes the ground, kinetic and gravitational potential energy is temporarily stored in elastic components, such as muscles, tendons and ligaments, and is recovered during the propulsive second half of the stance phase (Cavagna et al., 1963, Cavagna et al., 1964). Minetti (1998b) suggested that pendular and elastic mechanisms concurrently operate during forward skipping in humans and forward galloping in quadrupedal animals. Thus, I hypothesized that these energy-saving mechanisms are also used in sideways locomotion.

To individually understand the function of the trailing and leading lower limbs, it is important to measure joint kinetics and kinematics. Inaba et al. (2013) showed that extension torques and work at the hip, knee and ankle joints mainly contribute to single-leg side-jump distance, but showed that hip abduction work does not produce sufficient power. Shimokochi et al. (2013) also suggested hip extensor function is important in lateral cutting movements, but not in hip abductor movement. Kuntze et al. (2009) suggested that the trailing and leading limbs have distinct roles in locomotion; the trailing limb is involved in shock absorption and propulsive force generation, whereas the leading limb is involved in braking and vertical force generation. However, they measured joint torque at a single speed (3 m/s); hence, it is still unclear how joint kinetics at each limb contribute in sideways gait patterns at

different speeds.

The purpose of the present study is twofold: (1) to examine adjustments in the energy-saving pendular and bouncing mechanisms are made, with the clarification of the underlying mechanisms; (2) to investigate the contribution of joint kinetics during sideways locomotion at a wide variety of speeds.

## **2. Methods**

### **2.1. Subjects**

Twelve healthy young males (age:  $22.6 \pm 3.3$  yrs; height:  $172.8 \pm 5.7$  cm; weight:  $68.9 \pm 6.5$  kg), with no history of major lower limb injury or neuromuscular disorders, participated in this experiment. They provided informed consent to undergo the experimental procedures, which were conducted in accordance with the Declaration of Helsinki and approved by the ethics committee of the university (H25-H-19).

### **2.2. Protocol**

The experiment was performed along a straight walkway, which consisted of an 10-m acceleration segment and 6-m measurement segment, placed on five force platforms ( $0.6 \text{ m} \times 0.4 \text{ m}$ , TF-4060-B, Tec Gihan, Japan) (Fig. 1). Subjects performed sideways locomotion barefoot to the right at different speeds ( $0.6\text{--}3.0$  m/s and more, if possible). They were instructed to use their preferred gait pattern, keep the speed as constant as possible and not to cross their lower limbs. They stepped over three step cycles before passing the first photocell. Before trials, each start position was freely chosen to allow sufficient acceleration. Speed of locomotion was measured using two photocells aligned to the measurement segment at waist height. One step cycle

was composed of three consecutive foot contacts; the trailing foot contact (left foot in this experiment), the leading foot contact (right foot) and the subsequent trailing foot contact. The successful trial was defined as when the three foot contacts were made on the separate force plates. Before recordings, subjects practised for a few minutes to get accustomed to the movements. After each trial, verbal feedback about foot contact and the measured time was provided by the experimenters.

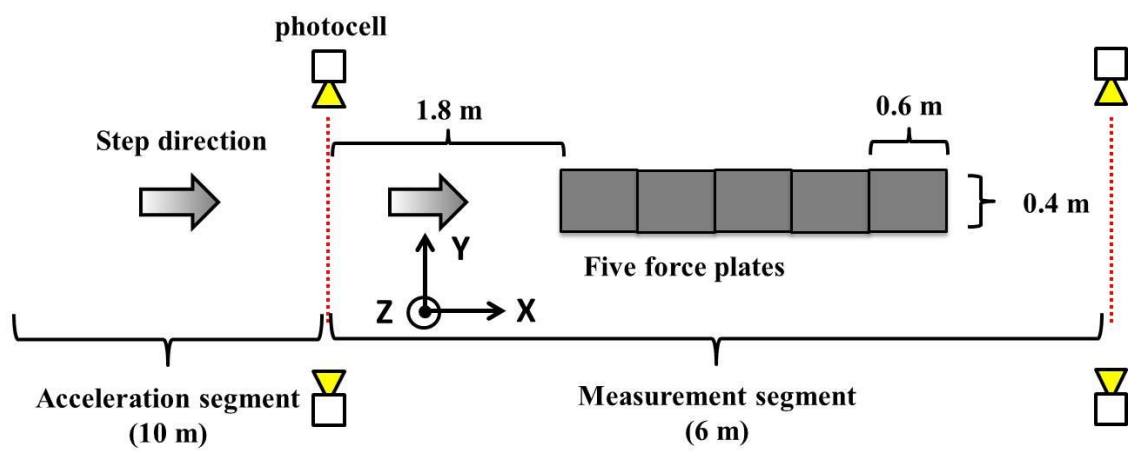


Fig. 1. Experimental set-up.

### **2.3. Data Collection**

Three-dimensional coordinates of the anatomical landmarks were acquired using a 3D optical motion capture system with 16 cameras taking measurements at a frequency of 200 Hz (Raptor-EDigital Real Time System, Motion Analysis Corporation, Santa Rosa, CA, USA). Thirty-one reflective markers were placed on each subject's body (Fig. 2). The anatomical landmarks defined 14 landmarks: head, trunk, upper arms, forearms, hands, thighs, shanks and feet. Ground reaction forces (GRFs) data were recorded at a frequency of 1000 Hz and low-pass filtered using a fourth-order Butterworth filter with a cut-off frequency of 75 Hz (Hunter et al., 2004). All numerical calculations, including the analyzes below, were performed using MATLAB 2007b (The MathWorks, Inc., MA, USA).



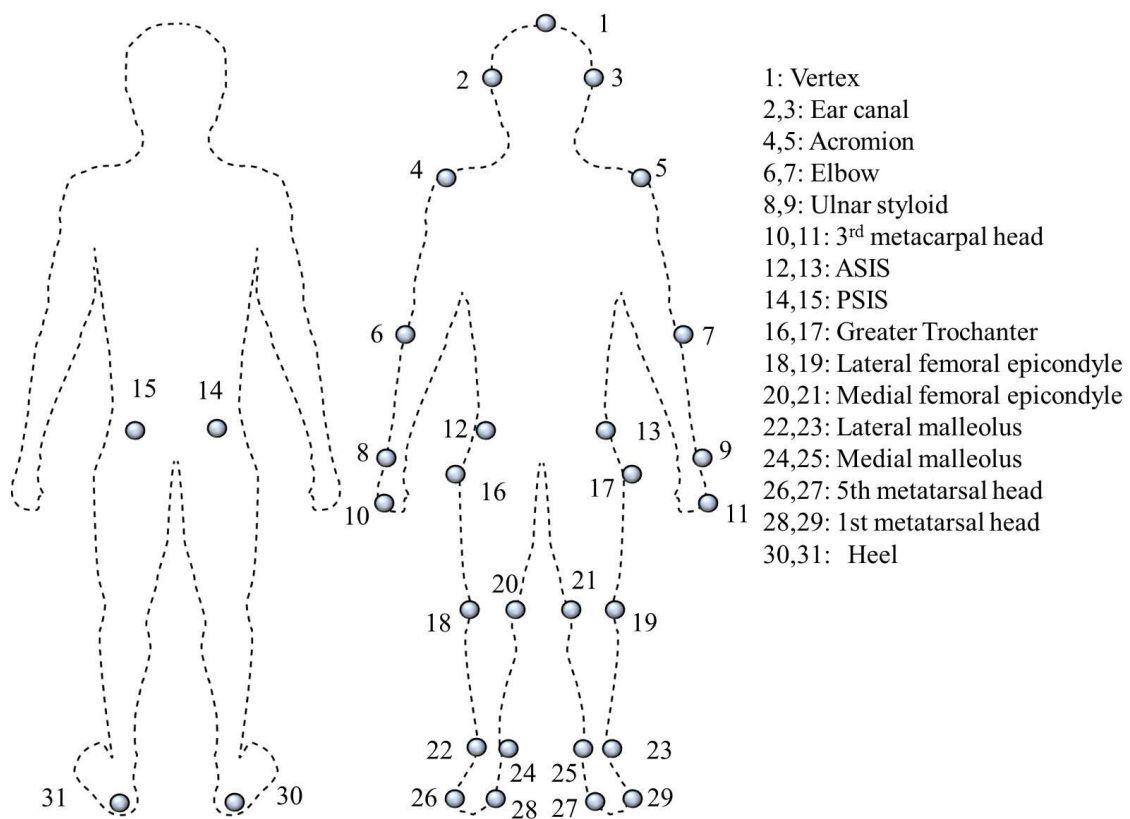


Fig. 2. An illustration of the configuration.

## **2.4. Data Analysis**

### **2.4.1. Kinematic data**

I defined one-step-cycle duration as the time interval from the trailing foot contact to its subsequent contact. Landing and take-off were determined from the vertical GRF with a cut-off value of 3% of the body mass. The step-cycle frequency was calculated as the inverse of the duration of the step cycle.

The directions of the global reference system axes are fixed in the laboratory (Fig. 1) where X is the medial–lateral axis, Y is anterior-posterior axis and Z is the vertical axis. The obtained positional data of markers attached to the body were smoothed using a fourth-order zero phase shift Butterworth low-pass filter at the cut-off frequency of 4.6–7 Hz performing a residual analysis (Winter, 2009). The segment mass and moment of inertia were derived on the basis of the body segment inertia parameter; COM displacements were then calculated on the basis of their segment parameters (Ae et al., 1992).

The pelvis, thigh, shank and foot anatomical coordinate systems (ACSSs) were almost the same as those used by Inaba et al. (2013) (Fig. 3). They were all right-handed orthogonal systems determined using the cross products of unit vectors defined by anatomical landmarks on each segment.

The pelvis ACS was defined as follows; the x-axis was the unit vector from the left anterior iliac spine (ASIS) to the right ASIS, the z-axis was the cross product of the x-axis and the unit vector from the midpoint of a line connecting right and left posterior iliac spine (PSIS) to the midpoint of a line connecting right and left ASIS, and the y-axis was the cross product of the z- and x-axes.

The right thigh ACS was defined as follows; the z-axis was the unit vector from the knee joint centre to the hip joint centre; the x-axis was the cross product of the unit vector defined by the cross product of the vector from the hip joint centre to the lateral femoral epicondyle, and the vector from the hip joint centre to the medial femoral epicondyle and the z-axis; and the y-axis was the cross product of the z- and x-axes.

The right shank ACS was defined as follows (Fig. 3); the z-axis was the unit vector from the ankle joint centre to the knee joint centre; the x-axis was the cross product of the unit vector defined by the cross product of the vector from the knee joint centre to the lateral malleolus and the vector from the knee joint centre to the medial malleolus and the z-axis; and the y-axis was the cross product of z-axis and x-axis.

The right foot ACS was defined as follows; the y-axis was the unit vector from the ankle joint centre to the midpoint between the line connecting

the heads of the first and fifth metatarsals (Collins et al., 2009); the z-axis was the cross product of the unit vector from the head of the first metatarsal to the head of the fifth metatarsal and y-axis; and the x-axis was the cross products of the y- and z-axes. The left thigh, shank and foot ACSs were defined in the same way as the right ACSs.

The local coordinate system of a proximal segment of a joint was used as a rotation axis. Joint angles were calculated as the relative position of distal segments with respect to proximal segments using the Cardan angle definition (x-y'-z'' sequence) (Winter, 2009). The rotation angle around the x-axis was defined as hip and knee extension/flexion and ankle plantarflexion/dorsiflexion; around the y'-axis as hip abduction/adduction, knee valgus/varus and ankle eversion/inversion; and around the z''-axis as hip, knee and ankle external/internal rotation. To eliminate the influence of inter-subject variance in body mass, the joint moment components were normalized to the body mass.

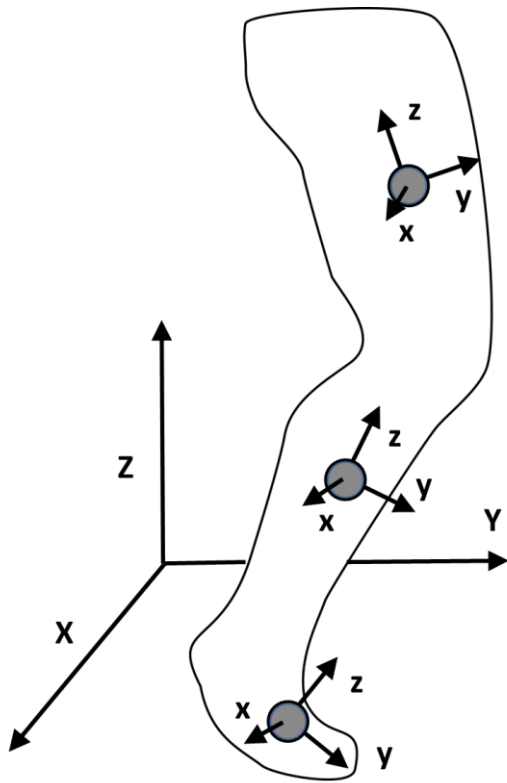


Fig. 3. Anatomical coordinate system in the right thigh, shank and foot.

### **2.4.2. Kinetic Variable**

The GRF signals were down-sampled to 200 Hz and synchronized in time with kinematic data. Joint torques were calculated using standard inverse dynamics equations (Winter, 2009). Joint power was calculated by multiplying the joint torque with the joint angular velocity. The amount of work at each joint was calculated for each power phase as the time integral of the power curve (Bezodis et al., 2008).

### **2.4.3. Displacements of COM**

Step speed was calculated by averaging the speed of COM within the step. The mechanical energy changes of COM on the body were calculated from the positional data of markers. Rotational kinetic energy of the body and the anterior-posterior motion of COM was neglected, only the motion in the frontal plane was considered when calculating the mechanical energy of COM (Cavagna, 1975). The gravitational potential energy of COM ( $E_p$ ) is defined as follows:

$$E_p = mgh$$

where  $m$  is the mass of the body,  $g$  is the acceleration of gravity and  $h$  is the height of COM. The kinetic energy to the horizontal and vertical movement of COM ( $E_{kf}$  and  $E_{kv}$ , respectively) is defined as follows:

$$E_{kf} = \frac{1}{2}mV_f^2, E_{kv} = \frac{1}{2}mV_v^2$$

where  $V_f$  and  $V_v$  is the instantaneous horizontal and vertical velocity of COM.

The total kinetic energy of COM ( $E_k$ ) is equal to

$$E_k = E_{kf} + E_{kv}$$

The total energy of COM ( $E_{com}$ ) is equal to

$$E_{com} = E_p + E_k$$

The recovery of mechanical energy at each instant,  $r(t)$  was calculated as follows:

$$r(t) = 1 - \frac{|\Delta E_{com}(t)|}{|\Delta E_p(t)| + |\Delta E_k(t)|}$$

where  $t$  is time (Cavagna et al., 2002). Mean  $r$  of mechanical energy at entire step ( $R_{step}$ ), trailing single stance ( $R_{trail}$ ) and leading single stance ( $R_{lead}$ ) were calculated.

To measure steady-state locomotion, the regularity of the selected steps was assessed from the ratio between positive and negative work: only steps where  $0.8 < W_v^+/W_v^- < 1.2$ ,  $0.6 < W_{kf}^+/W_{kf}^- < 1.5$  and  $0.8 < W_{ext}^+/W_{ext}^- < 1.2$  were used for analysis (Cavagna et al., 2011).  $W_v^+$  and  $W_v^-$  represent the work of the positive and negative increments undertaken by  $E_p + E_{kv}$ . Whereas  $W_{kf}^+$  and  $W_{kf}^-$  are the work of the positive and negative increments undertaken by  $E_{kf}$ ; and  $W_{ext}^+$  and  $W_{ext}^-$  are the external work of the positive increments

undertook by  $E_{com}$ . In a perfect steady gait on a level surface, the ratio between the absolute values of positive and negative work in an integer number of steps should be equal to one.

Each limb length ( $l_{trail}$  and  $l_{lead}$ ) was defined as the distance between COM and mean  $COP_x$  at each foot contact, because  $COP_x$  displacement after landing and before take-off was very large. To measure the leg extension parameter, maximum and minimum extension speed of  $l_{trail}$  ( $\dot{l}_{trail}$ ) and  $l_{lead}$  ( $\dot{l}_{lead}$ ) during each single-stance phase were calculated.

## **2.5. Statistics**

Multiple regressions were used to determine the variations between the specific variables (i.e., the recovery, limb extension speed and a joint work) and step speed within the subject. Subject was treated as categorical factor using dummy variable with 11 degrees of freedom. The  $p$  value from the  $t$  test for the regression slope of the variables was used to determine the probability of the analysis.



### **3. Results**

#### **3.1. Acquired data and temporal characteristics of sideways locomotion**

According to the results of part II of the experiment, all acquired gait cycles were defined as walk-, run- and gallop-like patterns. The walk-like pattern comprised 124 steps at speeds ranging from 0.53 to 1.35 m/s, the gallop-like pattern comprised 95 steps at speeds ranging from 0.96 to 4.60 m/s; and the run-like pattern comprised 4 steps at speeds ranging from 0.95 to 4.49 m/s (Fig. 4). I excluded the run trials as explained below. Figure 5 shows step-cycle frequency as a function of speed. Determining the variations within the subject, the strong positive correlations were found between step speed and step-cycle frequency in both walk- and gallop-like patterns ( $r = 0.94$ ,  $p < 0.001$  and  $0.88$ ,  $p < 0.001$  in the walk- and gallop-like patterns, respectively). In particular, stride frequency was very high during the walk-like pattern at the same speed range in the gallop-like pattern.

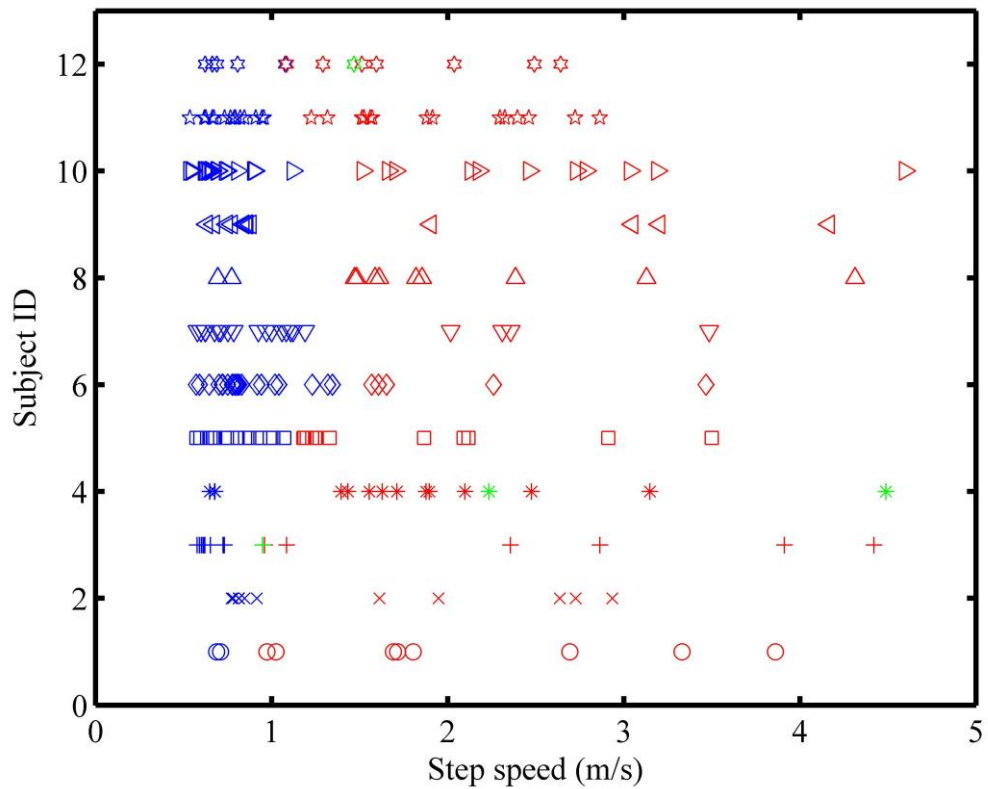


Fig. 4. Acquired data for 12 subjects. Blue, red and green colours represent each trial in the walk-, gallop- and run-like patterns, respectively. Each symbol represents each subject's result.

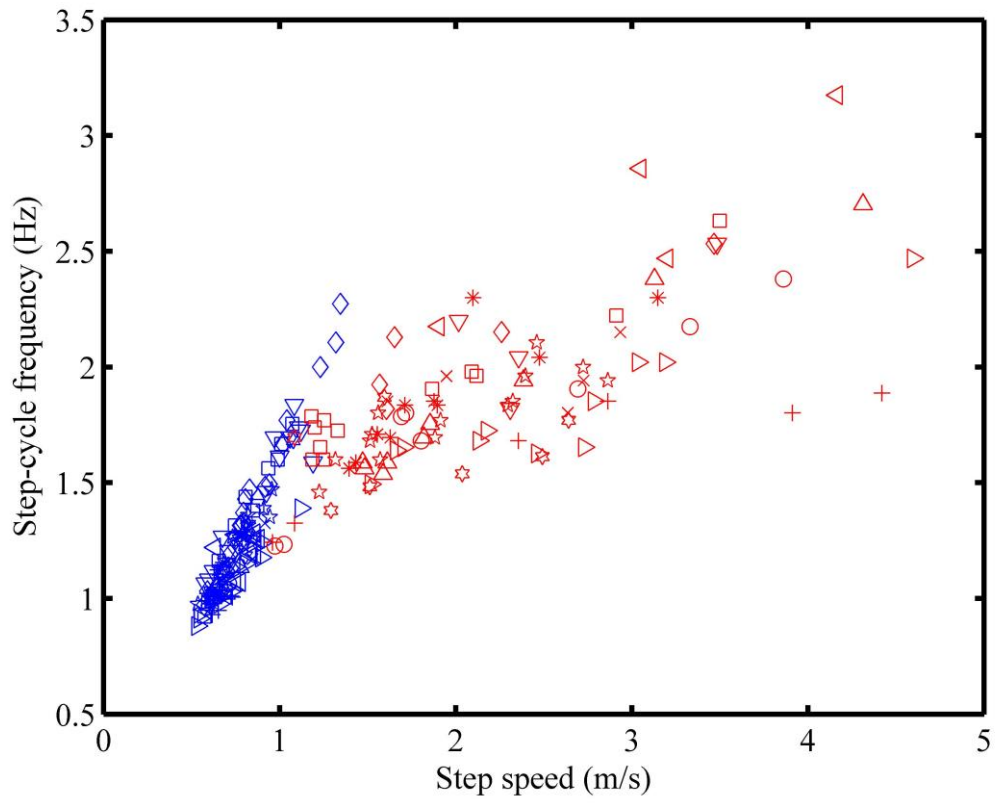


Fig. 5. Step-cycle frequency as a function of speed. Blue and red colours represent each trial in the walk- and gallop- like patterns, respectively. Each symbol represents each subject's result.

### 3.2. The COM trajectory

During the walk-like pattern, the  $E_p$  and the  $E_k$  curves were out of phase (Fig. 6, left). When the trailing limb was landing, the  $E_p$  gradually decreased and the  $E_k$  increased; the opposite occurred during leading limb contact. The  $E_{com}$  increased before the push-off phase and the  $E_{com}$  and  $E_{kf}$  reached a local minimum during the double support phase. During the gallop-like pattern (Fig. 6, right), at the first part of the trailing foot contact the  $E_{com}$ ,  $E_{kf}$  and  $E_p$  curves decreased in phase. During the second part of the trailing foot contact, the  $E_{com}$  and  $E_{kf}$  increased whereas the  $E_p$  was low. During the double support phase, the  $E_{com}$  and  $E_{kf}$  reached a peak. After take-off of the trailing foot, the  $E_{com}$  and  $E_{kf}$  decreased whereas the  $E_p$  increased.

Figure 7 shows the recovery ( $R_{step}$ ,  $R_{trail}$  and  $R_{lead}$ ) as a function of speed. Determining the variations within the subject, the weak correlations were found between step speed and  $R_{step}$ ,  $R_{trail}$  and  $R_{lead}$  in the walk-like patterns ( $r = 0.20$ ,  $p = 0.03$ ,  $r = 0.35$ ,  $p < 0.001$  and  $r = -0.35$ ,  $p < 0.001$ , respectively). On the other hand, the strong negative correlations were found between step speed and  $R_{step}$ ,  $R_{trail}$  and  $R_{lead}$  in the gallop-like patterns ( $r = -0.77$ ,  $p < 0.001$ ,  $r = -0.67$ ,  $p < 0.001$  and  $r = -0.69$ ,  $p < 0.001$ , respectively).

Figure 8 shows maximum and minimum  $\dot{l}_{trail}$  and  $\dot{l}_{lead}$  during each

single-stance phase during the walk-like pattern (top panel). Determining the variations within the subject, the correlations were found between step speed and maximum  $\dot{l}_{trail}$  and minimum  $\dot{l}_{lead}$  ( $r = 0.91, p < 0.001, r = -0.87, p < 0.001$ , respectively). Minimum  $\dot{l}_{trail}$  and maximum  $\dot{l}_{lead}$  were not correlated with step speed. Also, these variables were not significantly correlated ( $r = -0.12, p = 0.21$ ) (Fig. 8, bottom).

Figure 9 shows maximum and minimum  $\dot{l}_{trail}$  and  $\dot{l}_{lead}$  during each single-stance phase during the gallop-like pattern (top panel). Determining the variations within the subject, the correlations were found between step speed and maximum  $\dot{l}_{trail}$  and minimum  $\dot{l}_{lead}$  ( $r = 0.95, p < 0.001, r = -0.86, p < 0.001$ , respectively). Minimum  $\dot{l}_{trail}$  and maximum  $\dot{l}_{lead}$  were not correlated with step speed. However, these variables were significantly correlated ( $r = -0.53, p < 0.001$ ) (Fig. 9, bottom).

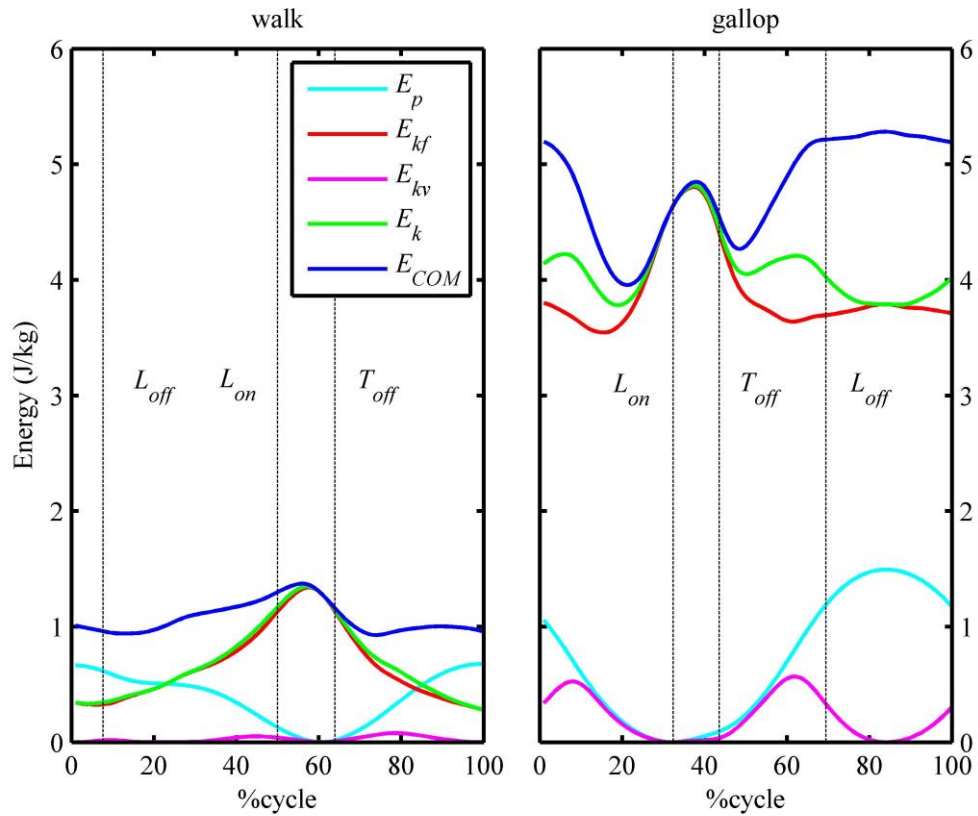


Fig. 6. Mechanical energy of COM of the body during walk at 0.62 m/s and gallop at 2.79 m/s in subject 10. The horizontal time scale is normalized to the step cycle. In each panel, the curves show the gravitational potential energy ( $E_p$ ), the kinetic energy of motion in the sagittal plane ( $E_k$ ) and the total translational energy of COM in the sagittal plane ( $E_{com}$ ). The zero line corresponds to the minimum attained by the  $E_p$  curve.  $L_{off}$ : leading foot take-off,  $L_{on}$ : leading foot landing,  $T_{off}$ : trailing foot take-off.

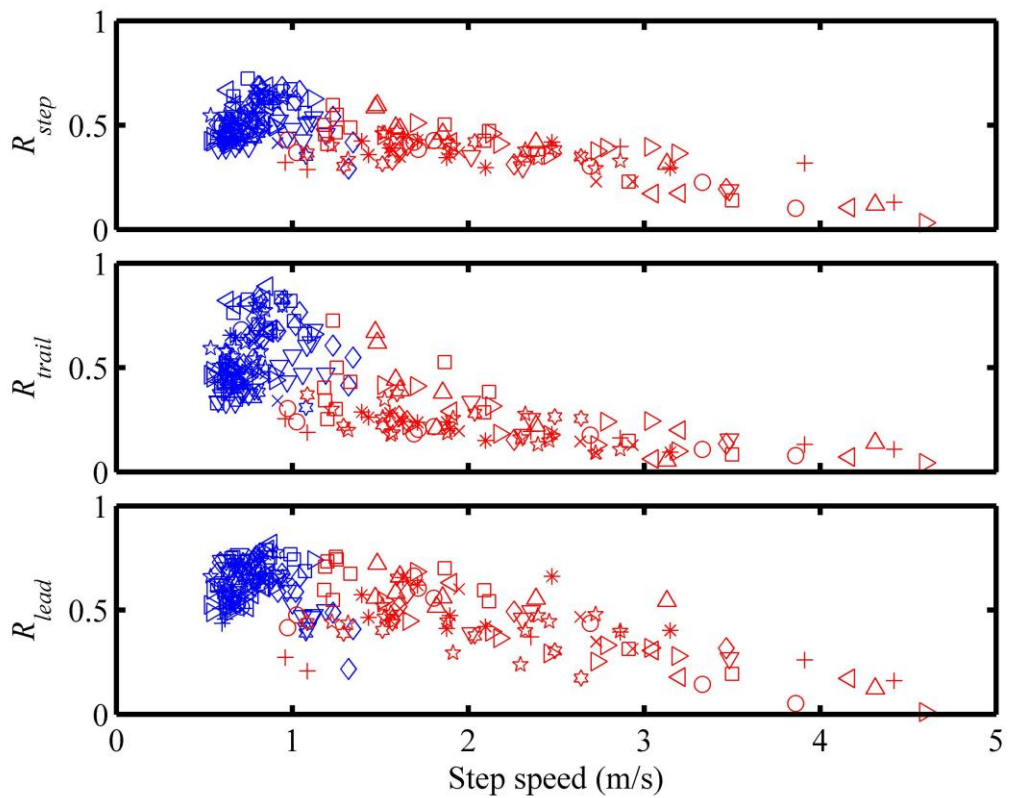


Fig. 7.  $R_{step}$  (upper),  $R_{trail}$  (middle) and  $R_{lead}$  (bottom) as a function of speed.

Blue and red colours represent each trial in the walk- and gallop- like patterns, respectively. Each symbol represents each subject's result.

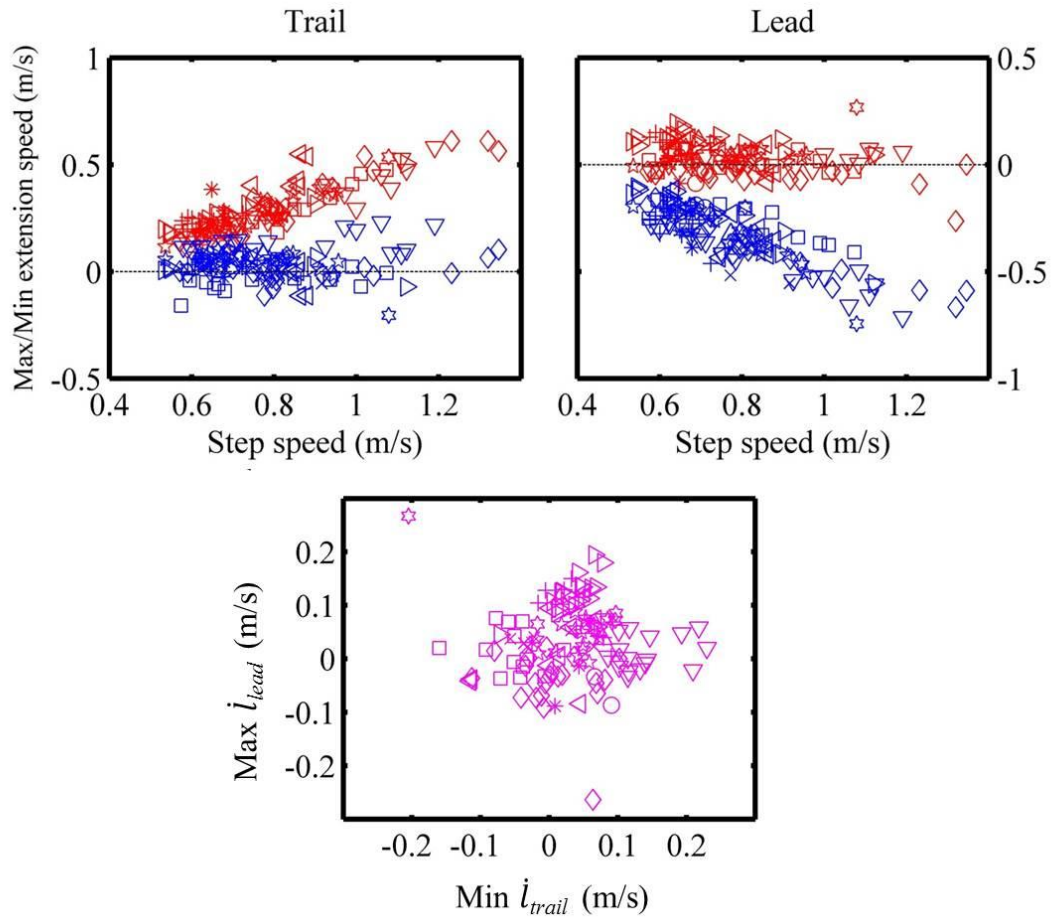


Fig. 8. Top: Maximum (red) and minimum (blue) speed of  $l_{trail}$  ( $\dot{l}_{trail}$ ) and  $l_{lead}$  ( $\dot{l}_{lead}$ ) during each single-stance phase during the walk-like pattern.

Bottom: the relationship between minimum  $\dot{l}_{trail}$  and maximum  $\dot{l}_{lead}$ . Each symbol represents each subject's result.



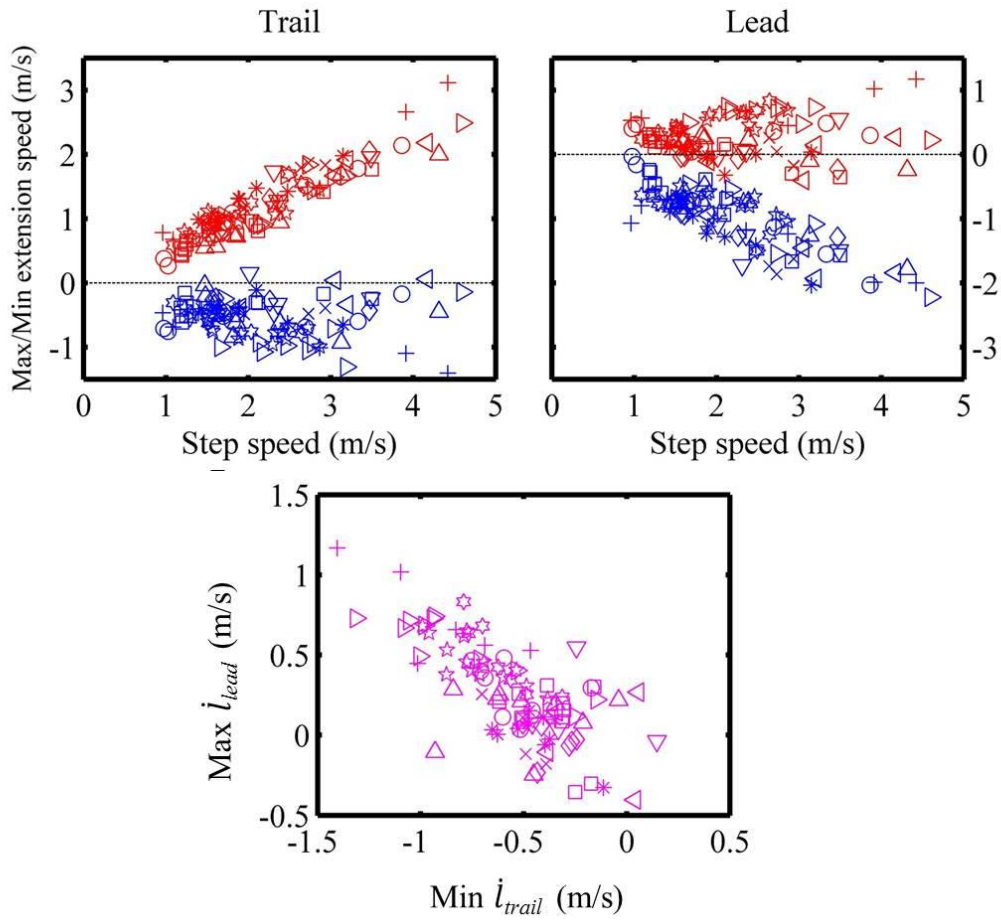


Fig. 9. Top: Maximum (red) and minimum (blue) speed of  $l_{trail}$  ( $\dot{l}_{trail}$ ) and  $l_{lead}$  ( $\dot{l}_{lead}$ ) during each single-stance phase during the gallop-like pattern.

Bottom: the relationship between minimum  $\dot{l}_{trail}$  and maximum  $\dot{l}_{lead}$ . Each symbol represents each subject's result.

### **3.3. Kinetic parameters**

Because of the anatomical constraints in sideways locomotion, I mainly analyzed hip, knee and ankle extension/flexion and hip abduction/adduction movements. The typical pattern of peak joint extension torque, joint angle velocity and power data are shown in Figure 10. During walk- and gallop-like patterns, the large hip and knee extension torque and ankle plantarflexion torque were observed. However, the hip and knee joints produced positive and negative power to a lesser extent. During the walk-like patterns, the trailing ankle power was produced around the double support phase and the power was absorbed at the leading ankle. During the gallop-like pattern, the negative and subsequent positive powers were produced at both the ankle joints and sometimes at the trailing knee joint.

To understand how the joint works contribute to generate lateral velocity, I calculated joint work; the integral of the power generated and absorbed at each joint. During the walk-like pattern, positive work for push-off was mainly performed at ankle plantarflexor muscles in the trailing limb (Fig. 11, left). Simultaneously, negative work was performed mainly at the ankle plantarflexor muscles in the leading limb (Fig. 11, right). The hip and knee joints did not perform positive or negative work.

During the gallop-like pattern in the trailing limb, positive work was

observed mainly at the ankle and knee joints and negative work was observed at the ankle joint (Fig. 12, left). In the leading limb, positive work was observed at the ankle and negative work at the knee and ankle joint (Fig. 12, right).

Figure 13 shows hip abduction work at the trailing limb (left) and adduction (right) work at the leading limb during the walk- (blue, top panel) and gallop-like patterns (red, bottom panel). Determining the variations within the subject, the correlations were found between step speed and hip abduction work at the trailing limb during both walk- and gallop-like patterns ( $r = -0.30$ ,  $p < 0.001$ ,  $r = -0.71$ ,  $p < 0.001$ , respectively) and hip adduction work at the leading limb during the gallop-like pattern ( $r = 0.22$ ,  $p = 0.04$ ).

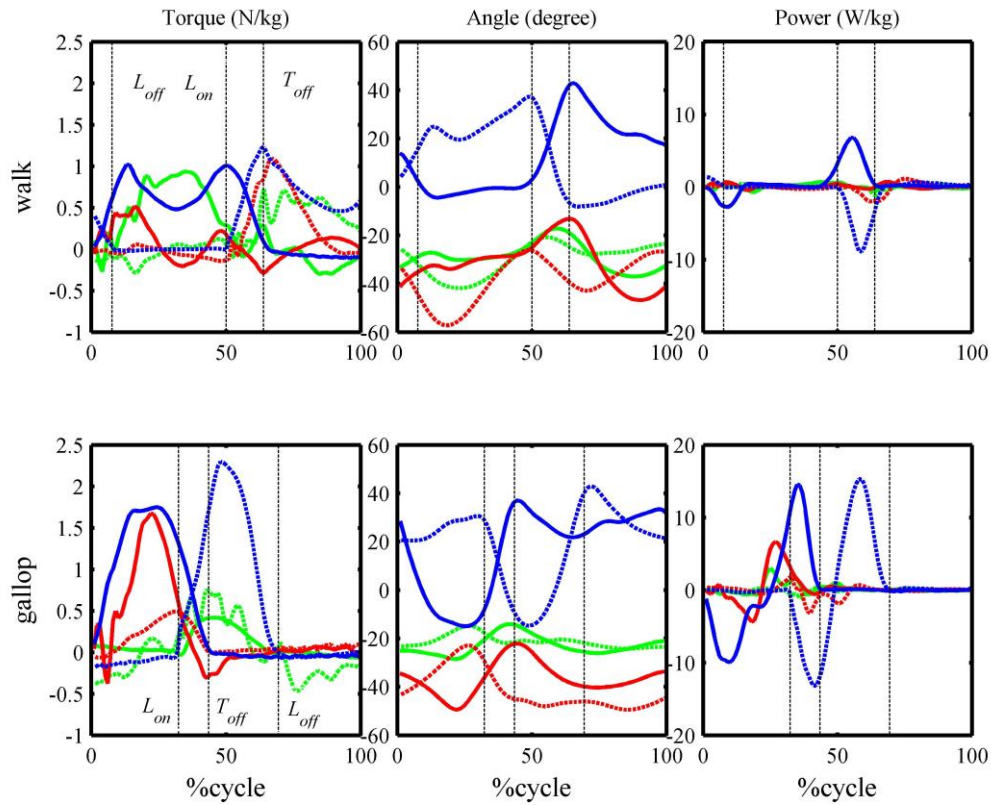


Fig. 9. Typical pattern of peak joint torque, joint angle velocity and power at ankle (blue), knee (red) and hip (green) in walk at 0.62 m/s (top) and gallop at 2.79 m/s (bottom) in subject 10. The horizontal time scale is normalized to the step cycle. Solid and dotted curves represent the trailing and leading limb, respectively.  $L_{off}$ : leading foot take-off,  $L_{on}$ : leading foot landing,  $T_{off}$ : trailing foot take-off.

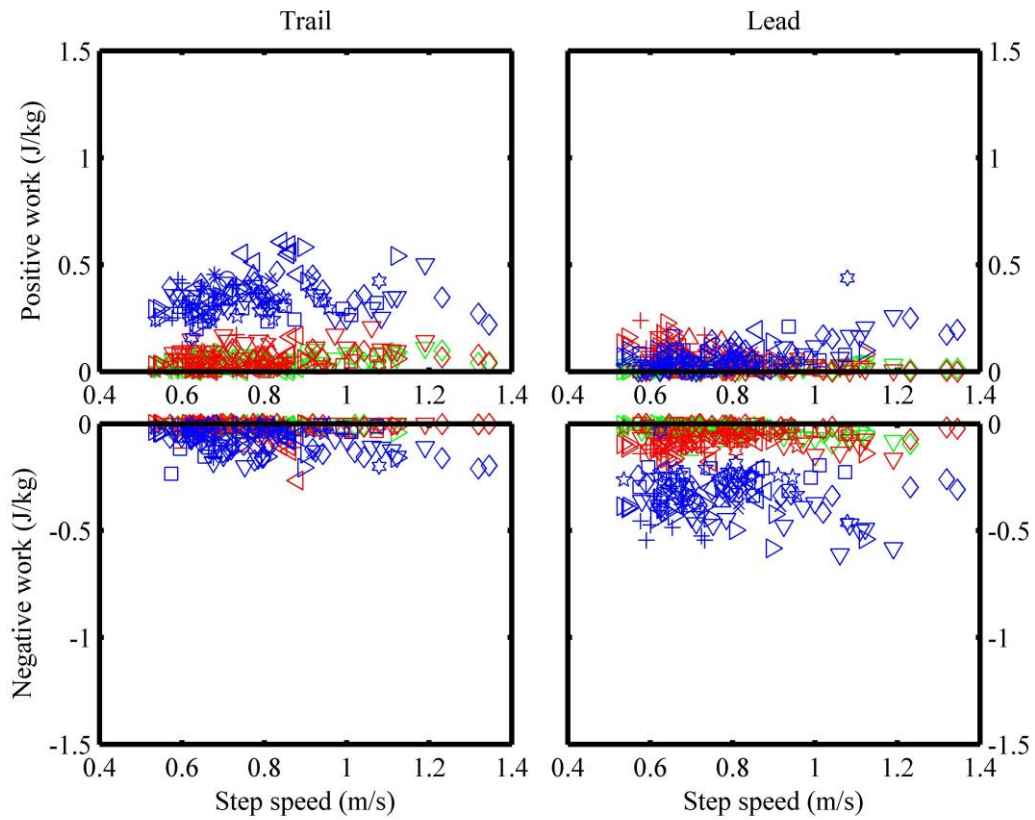


Fig. 11. Positive and negative work at each stance phase as a function of speed during the walk-like pattern. Blue, red and green colours represent the ankle, knee and hip, respectively. Each symbol represents each subject's result.

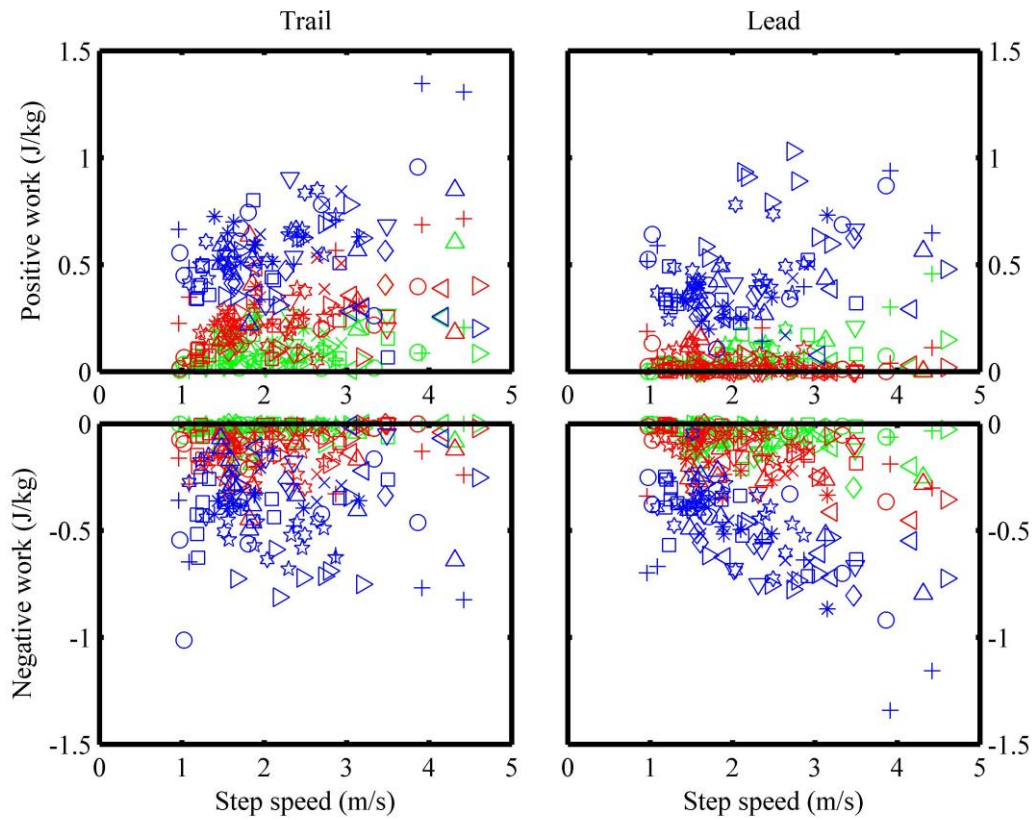


Fig. 12. Positive and negative work at each stance phase as a function of speed during the gallop-like pattern. Blue, red and green colours represent the ankle, knee and hip, respectively. Each symbol represents each subject's result.

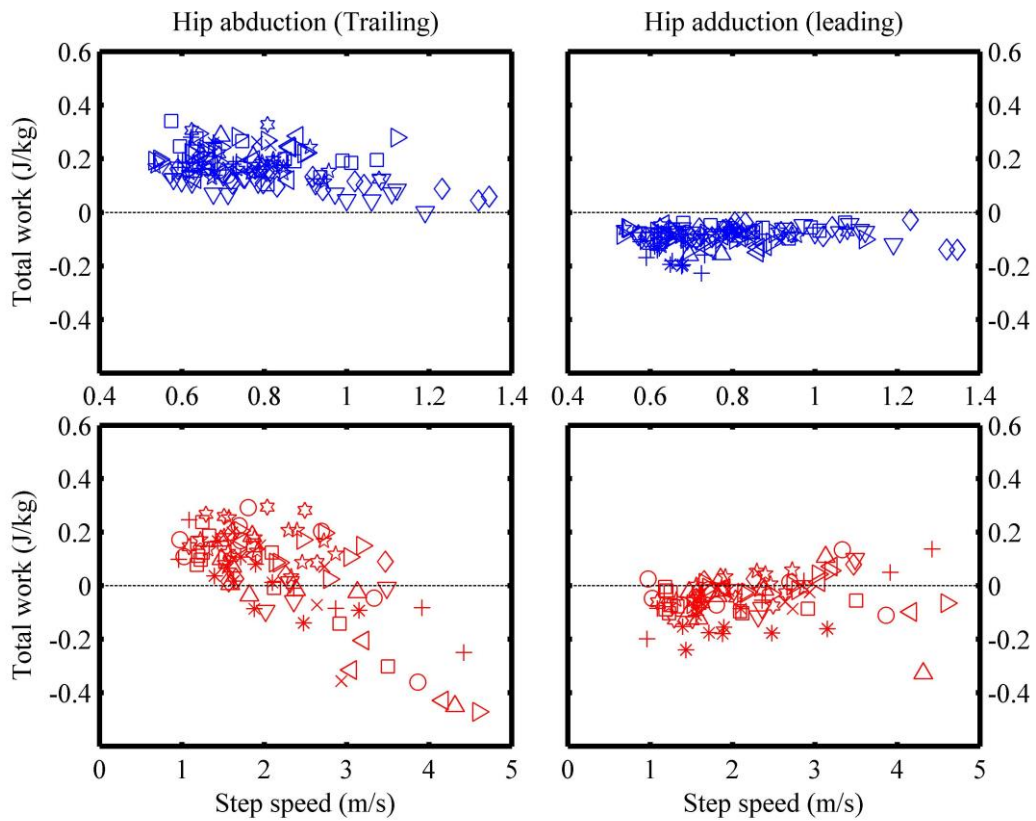


Fig. 13. Hip abduction work at the trailing limb (left) and hip adduction work at the leading limb (right) during the walk-like pattern (top, blue) and the gallop-like pattern (bottom, red) as a function of speed. Each symbol represents each subject's result.

## 4. Discussion

### 4.1. The mechanics of a walk-like pattern

During a walk-like pattern in sideways locomotion,  $R_{step}$ ,  $R_{trail}$  and  $R_{lead}$  showed around 0.5–0.7 (Fig. 7). These results of the present study were similar to those of a previous study (Cavagna et al., 2002) that showed about 0.6 during forward walking. During the walk-like pattern, the  $E_p$  and the  $E_k$  curves were out of phase (Fig. 6, left). These results indicate that the walk-like pattern had a similar energy exchange manner to the forward walking.

At the trailing foot contact, extension was the primary movement, even in the double support phase, and there was simultaneously flexion of the leading limb (Fig. 8). During the double support phase in forward walking, each transition to a new stance limb requires redirection of COM velocity from an inverted pendulum arc to the next (Donelan et al., 2002; Kuo, 2002a, b; Soo and Donelan, 2012). During the redirection, negative collision work by the leading limb and the positive push-off power of the trailing limb were produced (Donelan et al., 2002, Kuo, 2002a, b; Soo and Donelan, 2012). In the walk-like pattern, the power production at the trailing ankle, and the power absorption at the leading ankle and were observed (Figs. 10 and 11). This result showed that the walk-like pattern has the similar mechanism as the



pendulum-like behaviour of forward walking. Therefore, these results suggest that specific role sharing of both limbs acting as an inverted pendulum with different energy formations:  $E_k$  to  $E_p$  and  $E_p$  to  $E_k$ , respectively in the walk-like gait pattern.

## 4.2. The mechanics of the gallop-like pattern

Compared with the walk-like pattern,  $R_{step}$ ,  $R_{trail}$  and  $R_{lead}$  showed relatively lower values of approximately  $< 0.5$  during the gallop-like pattern, and this decreased with speed (Fig. 7). These results contradict those of a previous study, which revealed that the recovery during running as explained by the spring-mass mechanism was  $< 0.05$  (Cavagna et al., 1976). In contrast, recovery during forward skipping was approximately 0.5, and it was modelled as an inverted pendulum with an elastic component, ‘the combined energy-saving model’ (Minetti, 1998b). Forward skipping looks similar to the sideways gallop in that they both have double support and flight phases. Therefore, the gallop-like pattern appears to be represented as a combined energy-saving model like forward skipping, but there is an essential difference between them. The difference is that the leading limb becomes the subsequent trailing limb in skipping. This means that the leading limb can rotate more in the skipping phase than in the gallop-like pattern. The very high potential energy range in skipping indicated that the leading limb can extend to accelerate COM. In a gallop, however, the leading limb did not extend as much, and the trailing limb did not flex as much (Fig. 8).

During forward running, the spring-mass model generally supposes that a limb is flexed at the beginning of the stance phase and extended to the

same extent before take-off (Mauroy et al., 2013). In detail, both ankle and knee act as spring-like behaviour; negative work at each joint is stored as elastic energy (Hof, 2003). Moreover, running speed influences the ankle and knee stiffness (Arampatzis et al. 1999). On the other hand in this study, the trailing lower limb appeared predominantly extended and the leading limb appeared predominantly flexed (Fig. 9). Attention to joint kinetics, ankle plantarflexor negative and positive power at both trailing and leading limb was observed (Fig. 10). Knee extensor positive and negative power at trailing limb was also observed to a lesser extent and the power patterns at both hips were inconsistent. However, these joint works varied to step speed (Fig. 12). Therefore, unlike forward running, which has ankle and knee spring stiffness, the gallop-like pattern acts locally as a spring-mass mechanism at each ankle and the spring stiffness do not contribute to control step speed.

### 4.3. Speed control strategies in walk- and gallop-like patterns

According to a simple sprinter model with rotation and extension components (Jacobs and Schenau, 1992), it is easy to comprehend the speed control strategies of locomotion. A simple sideways locomotion model is shown in Figure 14; in this model the rotational component is affected by  $\sin \theta$ , whereas the extensional component is affected by  $-\cos \theta$ . In this experiment,  $\theta_{trail}$  ranged from about  $90^\circ$  to  $130^\circ$  and  $\theta_{lead}$  was from  $50^\circ$  to  $90^\circ$ . Therefore, at the beginning of the trailing stance phase, COM velocity is mainly determined by the rotational component. Previous research has suggested that it is better to extend the limb at the end of the stance phase, including the double support phase, as a push-off strategy in sprinting (Jacobs and Schenau, 1992). In my study, however, the extension vector almost always produced a braking component in the case of the leading limb (Fig. 14). Moreover, during the gallop-like pattern, the horizontal velocity became almost its lowest at take-off ( $E_{kf}$  in Fig. 6). Thus, decreasing the duration of flight phase appears to be a better strategy.

During walk- and gallop-like pattern, hip abduction work of the trailing limb decreased with step speed (Fig. 13, left). Hip abductor muscles can generate a medially directed GRF and adductor muscles can generate a laterally directed GRF (Rogers and Pai, 1993). Inaba et al. (2013) also

indicated that hip abduction work contributed to COM acceleration laterally in the earlier stance phase. Therefore, the hip abduction work on the trailing limb may contribute to the acceleration of the rotation velocity during sideways locomotion. In the same way, hip adduction work on the leading limb may contribute to assisting the rotation velocity. During the gallop-like pattern, however, the hip abduction work decreased with step speed. This may be because the hip adduction torque should be produced on the trailing stance phase to the subsequent foot contact. Therefore, the hip abduction work cannot contribute to lateral velocity.

The minimum  $\dot{l}_{trail}$  and maximum  $\dot{l}_{lead}$  were not correlated with step speed during the gallop-like pattern (Fig. 9). Moreover, these variables ranged widely, especially in moderate speeds; however, these variables were significantly correlated with each other (Fig. 9). This indicates that the higher the flexion speed of the trailing limb at landing, the higher extension speed of the leading limb at take-off. These results suggest that although the role and dynamics of each limb was totally different, the kinematics of the two limbs were tightly coordinated. The inter-limb coordination in sideways locomotion should be examined in future by the combined limb model, probably by implementing the concept provided in Figure 14.

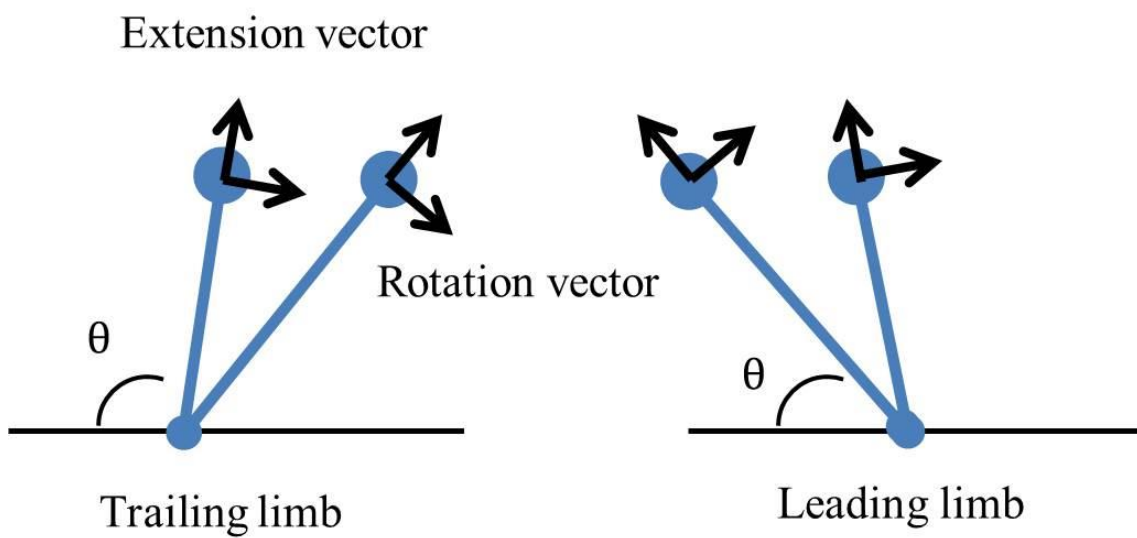


Fig. 14. A simple sideways locomotion model based on Jacobs and Schenau (1992).

## **5. Conclusion**

During the walk-like pattern, the trailing limb acted as an inverted pendulum, which transforms the gravitational potential energy to kinetic energy. Conversely, the leading limb acts as an inverted pendulum, which transforms kinetic energy to gravitational potential energy. During the gallop-like pattern, the trailing limb appears to predominantly extend, along with the flexion of the leading limb. Attention to joint kinetics, ankle plantarflexor negative and positive power at both trailing and leading limb was observed. These results suggested that the gallop-like pattern acted locally as a spring-mass mechanism at each ankle.

## **Part IV General Discussion**

### **1. The mechanics of the run-like pattern**

In part II of the experiment, with increment of gait speed, two out of fifteen subjects preferred a run-like pattern on a treadmill. In part III of the experiment, only 4 run-like steps were observed in contrast to 95 gallop-like steps on the ground. These results suggest that the run-like pattern is not preferred both on the treadmill and the ground, and there are some differences between running on the treadmill and on the ground.

The run-like pattern, which has flight phase and no double support phase, showed less step cycle frequency and longer flight phase than the gallop-like pattern did (part II). According to the simple sideways locomotion model (Fig. 14), the orientation of the trailing limb at take-off may be more vertical for the subsequent flight phase. This strategy makes it difficult to produce propulsive velocity. At the leading stance phase, braking component must be produced because of the extension for the flight phase. Therefore, the run-like pattern might not be preferred at high speeds on both a treadmill and ground. On the one hand, there seems to be some advantages of the run-like pattern. At the beginning of the leading stance phase, the limb may be flexed as the same as walk- and gallop-like pattern (see Figs. 8 and 9). Then, the



limb seems to more extend before the flight phase as mentioned above. Attention to the trailing limb, the flexion speed at landing becomes larger because longer flight time makes larger downward speed. Then, the limb extends for the flight phase. Thus, the run-like pattern can be performed like a spring, utilizing more stored elastic energy than the gallop-like pattern, in which trailing limb predominantly extended and the leading limb predominantly flexed. Therefore, two subjects might prefer the run-like pattern in part II of the experiment and efficiency achieve the sideways locomotion for 6 min on the treadmill.

## **2. The differences in the walk–gallop transition speed during sideways locomotion on the treadmill and the ground**

The walk–gallop transition speed was 0.97 m/s (3.5 km/h) on a treadmill (part II). Speculating the acquired data in part III of the experiment, the transition speed was about 1–1.5 m/s on the ground. It appears the transition speed on the ground was a little faster than that on a treadmill. In the case of the forward walk–run transition speed, Van Caekenberghe et al. (2010) reported that the transition speed on a treadmill (2.61 m/s) was lower than that on the ground (2.85 m/s), which is similar to my experiments. In addition, the forward walk–run transition is also known to cause the decrease in the fatigue of the dorsiflexor muscle (Hreljac, 1995; Hreljac et al., 2008). These previous studies suggest that during sideways locomotion, the walk–gallop transition speed in the experiment on a treadmill, which required longer task execution (more than 2 min at the transition speed), was lower than that on the ground because of fatigue of some local muscle stress might be released.

### **3. Practical application**

In this thesis, I have shown the distinct roles of each lower limb in sideways walk and gallop. This is an important finding not just to know how to move sideways but also to understand complex human locomotion. For example, to change the direction in walking, anticipatory postural adjustments on the prior step were observed (Xu et al., 2004). Increasing the approaching speed makes lateral cutting movements more difficult (Vanrenterghem et al., 2012). These studies indicated that the change of direction movements are not accomplished during single-leg stance (Rand and Ohtsuki, 2000); nevertheless, further studies will be required to measure kinetics and kinematics in some consecutive cutting movements. In strength training, skill coaching, and the prevention of disability and rehabilitation, the role sharing between the limbs from a prior step to the subsequent step during moving in all directions must be considered.

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