Characterizing Swing-Leg Retraction in Human Locomotion

K. L. Poggensee*, M. A. Sharbafi**, and A. Seyfarth**

* *School of Kinesiology, University of Michigan, Ann Arbor, Michigan, USA*
E-mail: ktpognc@umich.edu
** *Lauflabor Locomotion Lab, TU Darmstadt, Darmstadt, Germany*
E-mail: {sharbafi/seyfarth}@sport.tu-darmstadt.de

Swing-leg retraction, the backward rotation of the swing leg just prior to ground contact, is observed in human locomotion. While several advantages of swing-leg retraction, like gait stability and perturbation rejection, are shown by conceptual models, there is currently very little experimental data on swing-leg retraction in human motion. In this paper, kinematic data for twenty-eight subjects walking and running at different speeds are analyzed. Swing-leg retraction was shown to exist in walking and running at every non-zero speed. Additionally, swing-leg retraction speed and acceleration linearly increase with gait speed. At comparable gait speeds, swing-leg retraction speed is higher for running than for walking.

Keywords: Swing-leg retraction; walking; running.

1. Introduction

One of the most frequently addressed characteristics in gait modeling is the issue of stability. Humans tend to stay upright during locomotion through a number of different mechanisms. These mechanisms are not uniformly distributed among humans or even within their individual gait pattern, so it is sometimes challenging to choose an appropriate control method that mimics human motion while also providing stability to the system. One simple leg adjustment approach is using a fixed angle of attack (θ_{TD}) of the swing leg prior to landing[1] (See Fig. 1). A constant θ_{TD} would allow for a larger range of acceptable leg stiffnesses at higher gait speeds. Although this scheme has some advantages like simplicity and less need for sensory feedback, a minimum running speed of more than 3.5 m/s, much higher than preferred transition speed (PTS),[a] is required for stable running.[1] Any large changes to θ_{TD} would either slow the model (for decreased θ_{TD}) or cause a sudden fall (for higher θ_{TD} values). The model therefore requires leg stiffness and θ_{TD} measurements to fall within a limited range dependent on the running speed.

In 2003, Seyfarth et al.[3] proposed an alternative method to increase the stability of the model: a constant swing-leg retraction (SLR) speed. Swing-leg retraction, i.e., lowering the leg to the ground before touchdown, is a method to match the angular velocity of the leg to the ground speed. Using a spring-mass model, they demonstrated that a SLR control scheme would not only allow for stability across a wider range of gait speeds, but the model would also reach its steady state in fewer steps. This resulted in a model that was less sensitive to forward speed, pre-selected leg angle, and leg stiffness than the previous model which used fixed θ_{TD}.

Since 2003, there have been several studies to verify SLR as a control scheme in gait models and to find an optimal SLR speed for those models,[4–8] though literature on SLR in human motion is sparse. Swing-leg retraction was observed in Muybridge's images on human locomotion[9] and in some experimental studies accompanying papers focused on its presence in modeling.[3,7,10,11] Many of the experiments included a perturbing obstacle and featured only one running speed. Using a large pool of subjects, across several speeds, walking and running, we aimed to determine if SLR is present in normal human gait, and, if so, to quantify the relevant parameters. Assuming SLR is used to stabilize the system, walkers and runners should have higher SLR speeds for higher gait speeds. Likewise, SLR acceleration should increase in both walking and running. At the same gait speed, SLR speed and acceleration should increase for running compared to walking due to the different landing styles of the two motions.

2. Methods

2.1. *Experiment Description*

The data was collected in two experiments.[12] Subjects walked or ran on a treadmill (type ADAL-WR, Hef Tecmachine, Andrezieux Boutheon, France) at different speeds, dependent on the experiment. Motion capture data (Qualisys, Gothenburg, Sweden) from 11 markers and ground reaction force data (12 piezo-electric force transducers within the treadmill)

[a]PTS is the speed at which transition between running and walking is easiest. In humans, this transition is typically preferred at a speed of about $1.9 - 2.1$ m/s.[2]

were collected. Experiment I had 21 subjects (11 female, 10 male) walking and running at different percentages of their preferred transition speed (PTS). Preferred transition speed was determined as the average of the velocities at which the subject switches from walking to running and from running to walking. In Experiment II, seven subjects (1 female, 6 male) ran at 3 and 4 m/s. The characteristics of the subjects are included in Table 1.

Table 1. Subject characteristics (mean ± standard deviation) and individually preferred transition speed (PTS) for each experiment.

	N	Age (years)	Height (m)	Mass (kg)	PTS (m/s)
Experiment I	21	25.4 ± 2.7	1.73 ± 0.09	70.9 ± 11.7	2.1 ± 0.1
Experiment II	7	23.4 ± 1.1	1.80 ± 0.11	77.5 ± 8.8	N/A

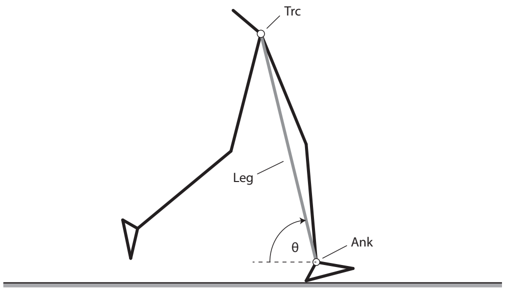

Fig. 1. Leg axis (defined as the line segment between the greater trochanter, Trc, and the ankle joint, Ank) and leg angle (θ). Adapted from Lipfert (2010).[12]

2.2. *Swing-Leg Retraction Computations*

Fig. 1 shows the simplified leg model used in this study. The virtual leg was defined by the straight line from the marker on the greater trochanter to the ipsilateral ankle marker. Leg angle (θ) with respect to the horizontal was calculated for each frame (Fig. 1). All calculations were done in Matlab (R2013a The Mathworks, Inc., Natick, MA, USA). To remove noise, we applied a low-pass filter (zero-lag, second-order Butterworth with a cut-off frequency of 40 Hz) to the marker data. Angular velocities and accelerations were calculated and then filtered with a cut-off frequency of 10 Hz.

Swing phase ends with touchdown (TD), the moment the distal end of the leg hits the ground, as determined by the vertical ground reaction forces. The vertical ground reaction force data were also filtered with a cut-off frequency of 40 Hz, and TD was determined as the frame at which vertical ground reaction force exceeded 5 N. Swing-leg retraction speed was calculated as the average angular velocity 20 ms before TD, and SLR acceleration as the average angular acceleration within the same time period.

2.3. *Data Analysis*

Swing-leg retraction was considered to exist if 0°/s was not included within one standard deviation of the mean SLR speed across all subjects, i.e., if the global mean SLR speed was positive and the mean was more than one standard deviation above zero. Linear regressions were calculated for SLR speeds and accelerations with respect to gait speed for each experiment. Means were compared between walking and running with a one-way ANOVA. Results were considered statistically significant for $p < 0.05$.

3. Results

Swing-leg retraction exists for running at all speeds and walking at all non-zero speeds. The relation between SLR speed and gait speed is approximately linear for walking and running speeds under 125% PTS (Fig. 2).

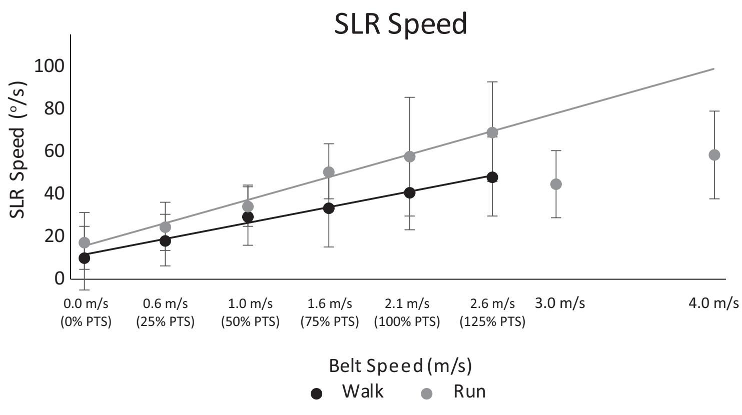

Fig. 2. SLR speeds for walking and running for both experiments. Data points are the global means at each speed with errors bars of one standard deviation and associated trendlines. The trendline for running is extended to include data from Experiment II.

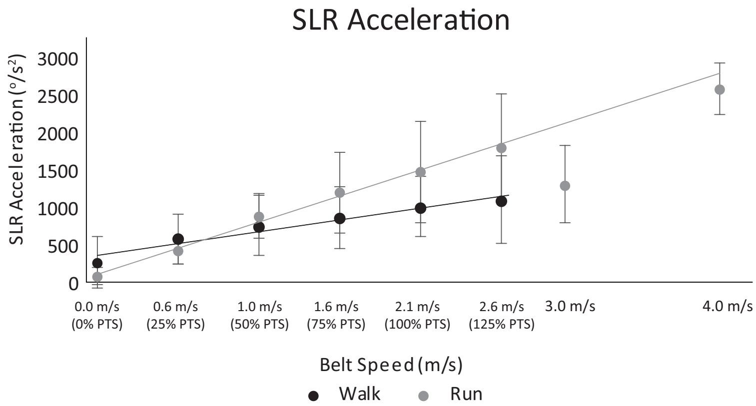

Fig. 3. SLR accelerations for walking and running for both experiments. Data points are the global means at each speed with errors bars of one standard deviation and associated trendlines. The best-fit line for running is extended to include data from Experiment II.

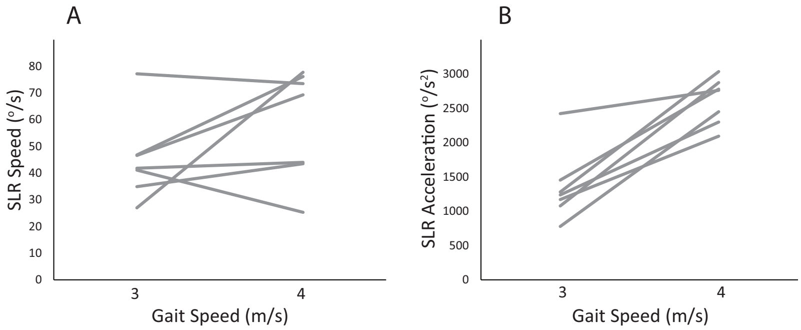

Fig. 4. SLR speeds (A) and accelerations (B) for subjects (II) running at 3 and 4 m/s. Each line represents data for one subject.

SLR acceleration and gait speed also show a linear trend for all walking and running speeds shown (Fig. 3). It should be noted that while there are significant trends for the different experiments, the trends are not necessarily continuous between experiments.

As speed increases to 125% PTS, variance increases. The positive correlation between SLR speed and gait speed was statistically significant for both walking and running for Experiment I. Removing two outliers in Experiment II would yield a similar result (Fig. 4), but not with all subjects included. In addition, SLR acceleration increased with gait speed for all types of gait in the study. At comparable speeds, running results in a higher SLR speed ($p < 0.01$) and acceleration ($p < 0.01$) than does walking (Table 2).

Table 2. Regression analysis for SLR speed and acceleration in walking and running.

	SLR Speed (°/s)			SLR Acceleration (°/s^2)		
	Walk (I)	Run (I)	Run (II)	Walk (I)	Run (I)	Run (II)
Slope	0.30	0.43	13.44	6.29	13.81	1267.07
R^2	0.40	0.52	0.14	0.30	0.61	0.71
p	< 0.01	< 0.01	0.20	< 0.01	< 0.01	< 0.01

Note: Slope is the slope of the best-fit line for the data across all subjects. Values are shown for the two styles of gait with their corresponding experiment in parentheses.

4. Discussion

Although several studies have shown the importance of SLR in locomotion modeling, few have looked at its presence in normal human gait.[13] Based on our data, we can say that SLR exists in human walking for non-zero speeds and running for all speeds. Therefore, SLR is not only an effective control strategy for locomotion modeling, but it is also a realistic one.

Karssen et al.[5] showed that the optimal SLR speed depends only on gait speed. Although our data disagree with the optimal SLR speed derived from their model, the trend in the data agrees with their claim. This is achieved primarily through motion of the foot with respect to the ground. Adding SLR increases the vertical velocity of the foot, simultaneously decreasing the horizontal velocity with respect to the ground. Assuming a constant total foot speed with and without SLR, it is clear that SLR depends only on gait speed; the faster the gait speed, the faster the SLR in order to achieve it. This would be difficult to directly test in humans, given that SLR is achieved through neuromuscular activity[14] and cannot be voluntarily added or removed without altering some of its effects. However, the linear trend in SLR speed for low running and most biological walking speeds is promising. At higher running speeds, while the observed SLR speeds are within the range predicted by previous studies,[3] two outliers greatly affected the linear regression in SLR speed. We thus cannot conclude that there is a trend at higher speeds. In order to make any claims, we would like to repeat the experiment with a larger number of subjects running across a larger range of belt speeds.

For each gait speed in Experiment I, SLR speed was higher in running than in walking. The differences were not statistically significant, due to the large degree of variability, although the difference between walking SLR speed and running SLR speed increases with gait speed, indicating a greater need for SLR in running at higher speeds than in walking.

The linear relation between SLR acceleration and gait speed can be explained by the higher forces needed for acceleration of the legs with increasing speed. At higher gait speeds, there is a greater demand for the ground-speed matching effect of SLR, increasing the SLR acceleration in order to quickly achieve SLR. As the first derivative of velocity, a linear trend in acceleration would imply a quadratic relationship between gait and SLR speed. Thus, the linear relation observed must then be explained by some other variable, e.g., knee torque or the effect of gravity. Nonetheless, we can conclude that a constant SLR acceleration dependent on gait speed is present at all observed gait speeds in walking and running.

Intersubject variability increased as gait speed increased, in conjunction with an increase in intrasubject variability. Variability is necessary to reduce sensitivity to slight disturbances in order to recover oneself from a misstep and can be magnified at higher gait speeds. This did not greatly affect the results and may be reduced by adding more steps to the analysis, though the large amount of variability at higher speeds may have been a contributing factor in the break in linearity between experiments. Experiment II was done with seven different subjects from the 21 in I. There may be a continuous linear trend in SLR acceleration for running given the data from both experiments, but that cannot be determined from the two measurements, i.e., two absolute gait speeds, taken from II.

The next step in characterizing SLR in normal walking and running would be to perform one comprehensive experiment with subjects running and walking at each of the presented speeds. Each subject showed the linear trend, so it would be interesting to examine what determines the slope of the data if it becomes clear that the slope is not uniform across subjects. In addition to an increase in data collected at each speed, future research should include more speeds and different types of gait. Our study focused on SLR parameters, but combining SLR data with force and electromyography data could help to answer questions about the control policy for SLR.

5. Conclusion

Swing-leg retraction does exist in humans. Both SLR speed and acceleration increase at a linear rate in walking and in running up to 125% PTS, after which only SLR acceleration significantly increases; the linear increase was not consistent across the two experiments. SLR speed was higher in running than in walking at comparable gait speeds, and the difference between walking and running SLR speeds was more pronounced at higher gait speeds. Variability across all measures increased with gait speed.

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