THE USE OF LEG RETRACTION IN OBSTACLE AVOIDANCE

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INTRODUCTION

For stable human running, the spring mass model predicts that a proper adjustment of the leg angle of attack $\alpha_0$ to the leg stiffness $k_{\text{LEG}}$ is required (Seyfarth et al., 2002a). However, model stability cannot be achieved at low running speeds ($\leq 3 \text{ m/s}$). Furthermore, at moderate speeds ($\sim 5 \text{ m/s}$), a high accuracy of the angle of attack ($\pm 1^\circ$) is required, necessitating precise control of leg orientation. In humans and animals, leg retraction is observed where the swing-leg is moved rearward towards the ground during late swing-phase. In a simulation study, such a rotational leg control at the end of the swing phase is shown to be a simple strategy to improve running stability (Seyfarth and Geyer, 2002b).

In this study we ask whether leg retraction is actually used to stabilise running. Therefore, we studied undisturbed and disturbed human treadmill running.

MODEL PREDICTIONS

The spring mass model reveals that, for proper adjustments of leg stiffness $k_{\text{LEG}}$ and angle of attack $\alpha_0$, an asymptotically stable running pattern can be found. By introducing leg retraction, the angle of attack becomes a result of the onset angle $\alpha_R$, the retraction speed $\omega_R$, and the duration of retraction until touch-down (Figure 1).

Figure 1: A rotational control of the leg prior to landing (leg retraction) is a simple strategy to stabilise running.

The simulation shows that a small retraction speed $\omega_R$ (e.g. $50^\circ/\text{s}$) can significantly improve running stability. For instance, an increased given initial apex height (e.g. 1.25 m in Figure 2) can be compensated for within 2 steps. As a consequence, leg retraction is capable to stabilise running also at low speeds ($\leq 3 \text{ m/s}$), which is not predicted without retraction.

Figure 2: Centre of mass trajectories for spring-mass running ($k = 20 \text{ kN/m}, m = 80 \text{ kg}$) with and without retraction ($\alpha_R = 50^\circ/\text{s}$ and $\omega_R = 0^\circ/\text{s}$). For each condition, the same initial apex height is used ($y_0 = 1.25 \text{ m}$), and for the simulation with retraction, a retraction angle of $\alpha_R = 60^\circ$ is assumed. Without retraction, the model reaches a steady state condition after 8 steps in contrast to about two steps with retraction.

To test the significance of leg retraction on running stability at low speeds (3 m/s), we hypothesise that ($H_1$) leg retraction is present in treadmill running, ($H_2$) the leg length $\lambda_{\text{LEG}}$ remains rather unchanged during retraction, ($H_3$) the angular range of leg retraction $\alpha_0 - \alpha_R$ is enlarged in disturbed running compared to the undisturbed situation, ($H_4$) the retraction speed $\omega_R$ is not affected by obstacle avoidance, and ($H_5$) the leg stiffness $k_{\text{LEG}}$ is not affected by obstacle avoidance.

EXPERIMENTAL SETUP

An instrumented treadmill (Woodway, Germany) with Kistler force sensors was equipped with an obstacle-machine (Figure 3). Triggered by the vertical ground reaction force, every 9-16 seconds a cylindrical-shaped bar (2.5 cm diameter, 12 cm above the belt) moves towards the human runner at a speed equivalent to the treadmill surface, forcing the subject to change his swing phase kinematics to avoid the obstacle. The leg kinematics were recorded using an infrared 3D camera system (Vicon).

Using this apparatus, we conducted experiments on five male subjects (mass 79.6 ± 5.9 kg, age 30.6 ± 3.2 yrs) performing treadmill running at 3 m/s. At the onset of swing-leg retraction and at touch-down, leg angle $\alpha$ and length $\lambda_{\text{LEG}}$ (based on the measured hip and ankle marker positions) were used to characterise the kinematic leg control prior to landing. The leg stiffness $k_{\text{LEG}}$ during stance phase is approximated using the maximum vertical ground reaction force $F_{\text{MAX}}$ and the maximum leg compression $\Delta\lambda_{\text{MAX}} = \max(\lambda_0 - \lambda)$ with $k_{\text{LEG}} = F_{\text{MAX}} / \Delta\lambda_{\text{MAX}}$. 
RESULTS

During treadmill running (Figure 4, Table 1), leg retraction is observed (Table 1: \( \alpha_{\text{SHIFT}} = 4.5 \pm 0.9^\circ \)) within a small angular range (H1). In this period, leg length remains rather constant (H2).

During obstacle avoidance, the kinematics of the swing phase were significantly changed (Figure 4). However, the leg retraction strategy (H1 and H2) is equally applied. Here, a significantly increased range of leg retraction (\( \alpha_{\text{SHIFT}} = 9.1 \pm 3.6^\circ \)) is observed (H3).

Table 1: Comparison of leg stiffness \( k_{\text{LEG}} \) and gait parameters between undisturbed and disturbed conditions (mean \( \pm \) S.D. for 5 subjects; for each subject at least 39 undisturbed steps and 3-4 disturbed steps are taken into account). The differences between disturbed and undisturbed data are compared using a paired t-test (significance with \( p < 0.05 \) is denoted by an asterisk ‘*’).

<table>
<thead>
<tr>
<th></th>
<th>undisturbed</th>
<th>disturbed</th>
<th>difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k_{\text{LEG}} ) (kN/m)</td>
<td>25.2 ( \pm ) 6.8</td>
<td>22.9 ( \pm ) 3.9</td>
<td>(-2.3 \pm 4.4)</td>
</tr>
<tr>
<td>( \alpha_{R} ) (deg)</td>
<td>64.3 ( \pm ) 2.0</td>
<td>61.3 ( \pm ) 1.5</td>
<td>(-3.0 \pm 2.5)</td>
</tr>
<tr>
<td>( \alpha_{0} ) (deg)</td>
<td>68.8 ( \pm ) 2.1</td>
<td>70.4 ( \pm ) 2.7</td>
<td>(1.7 \pm 2.1)</td>
</tr>
<tr>
<td>( \alpha_{\text{SHIFT}} ) (deg)</td>
<td>4.5 ( \pm ) 0.9</td>
<td>9.1 ( \pm ) 3.6</td>
<td>(4.7 \pm 3.0 \ast)</td>
</tr>
<tr>
<td>( \omega_{R} ) (deg/s)</td>
<td>137 ( \pm ) 9</td>
<td>159 ( \pm ) 21</td>
<td>(22 \pm 13 \ast)</td>
</tr>
<tr>
<td>( \lambda_{R} ) (cm)</td>
<td>94.2 ( \pm ) 1.8</td>
<td>95.9 ( \pm ) 1.7</td>
<td>(1.7 \pm 2.3)</td>
</tr>
<tr>
<td>( \lambda_{0} ) (cm)</td>
<td>93.2 ( \pm ) 2.0</td>
<td>94.9 ( \pm ) 1.8</td>
<td>(1.7 \pm 2.1)</td>
</tr>
<tr>
<td>( \lambda_{\text{SHIFT}} ) (cm)</td>
<td>-1.0 ( \pm ) 0.5</td>
<td>-1.0 ( \pm ) 1.1</td>
<td>(0.0 \pm 1.0)</td>
</tr>
</tbody>
</table>

DISCUSSION

Leg retraction is an experimentally observable strategy, traditionally associated with ground speed matching. Our experimental results suggest that retraction might also be important for the stabilisation of human running. This is supported by the fact that, after obstacle avoidance, the observed landing condition (\( \alpha_{0}, \lambda_{0} \)) was almost identical to the undisturbed condition. Moreover, during the subsequent stance phase, the leg function was characterised by a similar leg stiffness and an almost unchanged leg kinematics.

Leg retraction is a feedforward control scheme, and therefore, can neither avoid obstacles nor place the foot at desired foot-targets. Rather, the scheme provides a mechanical 'background stability' that may relax the control effort to regain steady-state locomotion. This holds in particular for low running speeds, where stable running was not predicted without leg retraction. It remains for future research to understand to what extent environmental sensory information might allow varied kinematic trajectories and an increase in the stabilising effects of swing-leg retraction. For instance, in this study the increased retraction velocity in obstacle running could indicate such a compensating kinematic adjustment to further improve running stability.

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REFERENCES