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Vertical adaptation of the center of mass in human running on uneven ground

M. Ernst [a,b,*], M. Götze [a], R. Müller [a], R. Blickhan [a]

[a] Motion Science, Institute of Sport Science, Friedrich Schiller University Jena, Seidelstrasse 20, 07749 Jena, Germany
[b] Institute of Solid Mechanics, Faculty of Mechanical Engineering, Technische Universität Braunschweig, Schleinitzstrasse 20, 38106 Braunschweig, Germany

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ABSTRACT

In running we are frequently confronted with different kinds of disturbances. Some require quick reactions and adaptations while others, like moderate changes in ground level, can be compensated passively. Monitoring the kinematics of the runner's center of mass (CoM) in such situations can reveal what global locomotion control strategies humans use and can help to distinguish between active and passive compensation methods.

In this study single and permanent upward steps of 10 cm as well as drops of the same height were used as mechanical disturbances and the adaptations in the vertical oscillation of the runners CoM were analyzed. We found that runners visually perceiving uneven ground ahead substantially adapted their CoM in preparation by lifting it about 50% of step height or lowering it by about 40% of drop height, respectively. After contact on the changed ground level different adaptations depending on the situation occur. For persisting changes the adaptation to the elevated ground is completed after the first step on the new level. For single steps part of the adaptation takes place while returning to the ground. The consistent adaptations for the different situations support the idea that controlling the CoM by adapting leg parameters is a general control principle in running.

* Corresponding author at: Motion Science, Institute of Sport Science, Friedrich Schiller University Jena, Seidelstrasse 20, 07749 Jena, Germany. Tel.: +49 3641 945714; fax: +49 3641 945702.

E-mail address: michael.ernst@uni-jena.de (M. Ernst).

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1. Introduction

While jogging or running in an urban environment or on nature trails we face major and minor disturbances requiring quick reactions and adaptations. For example we actively initiate turning, sidestepping pedestrians, or jumping over obstacles. On the other hand, minor disturbances such as sudden moderate changes in ground level or stiffness can be compensated passively (e.g., Ferris, Louie, & Farley, 1998; Grimmer, Ernst, Günther, & Blickhan, 2008). Investigating the kinematics of the runner's center of mass (CoM) in such situations can reveal what global locomotion control strategies we use and can help to distinguish between willingly initiated (actively controlled) or mechanical (passively controlled) reactions.

In running, the trajectory of the CoM is determined by the action of the stance leg and the external forces (e.g., gravitation). A common way to describe the dynamics and kinematics of running is to use the spring-mass model and its parameters (leg stiffness, orientation and length; Blickhan, 1989). For example, in running on surfaces with altered ground stiffness it could be shown that humans adapt their leg stiffness to compensate for changes in the ground stiffness (Ferris et al., 1998; Ferris, Liang, & Farley, 1999; Kerdok, Biewener, McMahon, Weyand, & Herr, 2002). These adaptations in leg stiffness were correlated with a nearly unaffected CoM deflection for both known and unknown changes in ground stiffness. From this the authors inferred that the control of the CoM trajectory might be a general principle in running and that adaptation of leg stiffness does represent a measure to achieve this (Ferris et al., 1999; Kerdok et al., 2002). Runners encountering ground level changes adapt leg stiffness, too (Grimmer et al., 2008; Müller & Blickhan, 2010; Müller, Ernst, & Blickhan, 2012). But they also alter leg orientation and length. Using numerical modeling (SLIP), it could be demonstrated that the adaptation process is able to stabilize running (Seyfarth, Geyer, & Herr, 2003; Grimmer et al., 2008). However, until now the CoM strategies humans use while running on uneven ground are not precisely identified yet. For example, whether they prefer controls that keep the CoM trajectory unchanged (Ernst, Geyer, & Blickhan, 2009; Koepl et al., 2011) similar to the findings for running on surfaces with ground stiffness changes or controls which map the terrain to the CoM height (e.g., in a deadbeat behavior, Seyfarth & Geyer, 2002; Ernst, Geyer, & Blickhan, 2012).

There are three commonly used methods for determining the CoM motion - the sacral marker method, the segment analysis method, and the dynamic method by double integrating ground reaction forces (GRF). The sacral marker method uses a single marker placed on the sacrum to approximate the CoM trajectory (Thirunarayan, Kerrigan, Rabuffetti, Croce, & Saini, 1996; Saini, Kerrigan, Thirunarayan, & Duff-Raffaele, 1998). It has been shown that by using this simple and easy to apply method the vertical motion of the CoM during running can be estimated with high precision (Gullstrand, Halvorsen, Tinmark, Eriksson, & Nilsson, 2009; Halvorsen, Eriksson, Gullstrand, Tinmark, & Nilsson, 2009). But it has also been reported that running at low speed (Gullstrand et al., 2009) or switching to walking (Gard, Miff, & Kuo, 2004) increase the systematical error associated with this method. A more precise method for low velocities or 3D trajectories using only kinematic data is the segment analysis method. It requires a full-body marker set and sufficient knowledge of the mass distribution within the body (e.g., Eames, Cosgrove, & Baker, 1999; Gard et al., 2004; Halvorsen et al., 2009).

Based upon Newton's Second Law, double integrating the GRF is another way to determine the trajectory of the CoM. Thereby, the accuracy depends not only on the precision of the GRF measurement but also on the integration constants (initial position and velocity of CoM). For steady-state running, that is running with constant velocity and constant vertical excursion of the CoM over a couple of steps, the average CoM velocity is constant (zero for average vertical velocity). This simplifies determination of the integration constants (Donelan, Kram, & Kuo, 2002; Gard et al., 2004). Speed is not sufficiently constant while running on short tracks or uneven ground. In particular, the average vertical speed is not zero. A promising way of determining the CoM was currently suggested by using a mixture of both kinematic and dynamic data avoiding the disadvantages of each method (Maus, Seyfarth, & Grimmer, 2011).

The main goal of this study is to show what CoM strategies human runners use while running on uneven ground. Therefore, we analyze the vertical adaptations of the runners CoM height to different