KINEMATIC STRATEGIES TO KEEP AN UNCHANGED MARGIN OF STABILITY DURING TREADMILL RUNNING ON AN EVEN AND UNEVEN SURFACE

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Understanding how to control stability when running, particularly when being exposed to uneven terrain, is vital to prevent falls and to get an insight into compensatory strategies while running on uneven terrain. The purpose of this study was to assess surface related differences of the margin of stability, kinematics of hip and knee and upper body acceleration which may affect the control of running stability. Eighteen healthy younger adults ran on an even and an uneven surfaced treadmill for two minutes at fixed speeds of 2.0 m/s (female) and 2.2 m/s (male), respectively. Results showed an unchanged margin of stability in both conditions. Further, lower limb kinematics, step width variability and upper body acceleration increased on the uneven surface meaningfully to keep the extrapolated centre of mass within the base of support.

KEY WORDS: locomotion, irregular surface, instability, motor control.

INTRODUCTION: Walking and running in laboratory settings on an even surface is generally not representative of real-world locomotion. Uneven terrain and different surface configuration may lead to altered walking and running patterns in comparison to controlled locomotion across an even surface (Gates, Wilken, Scott, Sinitski, & Dingwell, 2012; Voloshina & Ferris, 2015). These natural perturbations force the central nervous system to adjust locomotor patterns appropriately to ensure stability. Thus, understanding how to control stability when running, particularly when being exposed to uneven terrain, is vital to prevent falls and to get an insight into compensatory strategies while running on uneven terrain.

Previous studies investigating gait adaptions in response to challenging locomotion focused mainly on walking across compliant surfaces (MacLellan & Patla, 2006), in destabilising environment (Gates et al., 2012; Marigold & Patla, 2005; McAndrew Young, Wilken, & Dingwell, 2012) or walking across a surface with hidden objects underneath (Menz, Lord, & Fitzpatrick, 2003). Studies assessing changes during running on different surfaces are rare (Sterzing, Apps, Ding, & Cheung, 2014; Voloshina & Ferris, 2015). Although step-width and step-width variability have been associated with frontal plane stability during walking, they may not describe stability extensively since neither considers the trajectory of the centre of mass (CoM) relative to the edge of an individual's base of support (BoS) (Rosenblatt & Grabiner, 2010). This issue has been addressed by Hof (2008) and led to the introduction of the margin of stability (MoS), which accounts for position and velocity of the CoM (Xcom) relative to the BoS. While previous studies on walking on uneven surfaces used the MoS to describe the relation of the Xcom to the BoS (McAndrew Young et al., 2012), running on uneven surfaces has not been investigated using the MoS concept and thus lacking possible insightful information into control strategies of locomotion during running.

Therefore, the purpose of the study was to assess surface related differences in the margin of stability, hip and knee joint kinematics and upper body acceleration during the stance phase. We hypothesised first, that the mean (MoS_{ml}) and minimal (MoS_{ml_min}) mediolateral MoS would change due to increasing demands of surface condition and running. Second, we hypothesised kinematics, i.e., upper body acceleration, step width, hip and knee kinematics would differ between conditions.

METHODS: All participants gave written informed consent and the study was approved by the local ethics committee of the University of Kassel (E05201602). Eighteen healthy younger adults (11 male, 7 female; height 177±6 cm, weight 71±13 kg; 24 ± 3 years old) ran

on an even surfaced treadmill (Laufergotest, Erich Jäger, Würzburg, Germany) and an uneven surfaced treadmill (Woodway®, Weil am Rhein, Germany) laminated with terrasensa® classic [Sensa® by Huebner, Kassel, Germany]) for two minutes at fixed speeds of 2.0 m/s (female) and 2.2 m/s (male), respectively. We used a six-camera motion capture system (Oqus 3+, Qualisys AB, Gothenburg, Sweden) operating at 300 Hz to track the motion of 50 super-spherical markers placed bilaterally at prominent landmarks according to a modified IOR-model (Istituto Ortopedico Rizzoli) (Leardini et al., 2007). Data were processed using Visual3D (C-Motion, Germantown, MD, USA). Raw kinematic marker trajectories were interpolated and smoothed with a fourth-order zero-lag Butterworth low-pass filter with a cut-off frequency of 6 Hz. Spatiotemporal gait variables, joint angles of the knee and hip and the margin of stability in mediolateral direction were calculated using the formula provided by Hof (2008) and time-normalised from footstrike to toe-off; i.e., stance phase, since it is the phase of the gait cycle. Gait events were identified by a velocity based algorithm (O'Connor, Thorpe, O'Malley, & Vaughan, 2007), which was recently validated for the identification of gait events on uneven surfaces (Eckardt & Kibele, 2017). Further, the root-mean-square (RMS) of the mediolateral acceleration of the upper body and at toe-off was computed. RMS provides a measure of dispersion similar to standard deviation, only relative to zero rather than the mean.
To test our hypotheses, we conducted paired *t*-tests to investigate differences between conditions. Exploratory Software for Confidence Intervals was used for the calculation of Cohen's effect size d_{unb} (an unbiased estimate of the population effect size δ) and associated 95% confidence intervals (see Cumming, 2012 for details). Following Cohen (1988), *d*-values ≤ 0.49 indicate small effects, $0.50 \leq d \leq 0.79$ indicate medium effects, and $d \geq 0.80$ indicate large effects. Alpha level was set at 5%. All tests, except *t*-tests, were performed using SPSS version 23.0 (SPSS Inc., Chicago, IL, USA).

RESULTS: All means and statistical values are displayed in table 1. Neither MOS_{ml} (-4%), nor MOS_{ml_min} (1%) did not show any meaningful differences between running on the even and uneven surfaced treadmill. We found step width decreased meaningfully from even to uneven running by 19%, whereas step width variability meaningfully increased by 32%. When running on the uneven surfaced treadmill, participants tend to increase mediolateral acceleration of the mean upper body (28%) and at toe-off (35%). Sagittal plane kinematics demonstrated meaningful increases in hip flexion (7%) and knee flexion (5%) during running on the uneven surfaced treadmill compared to the even one. Looking at the frontal plane, further statistically meaningful differences were found at hip- and knee adduction/abduction (-13% / 12%) as well as in in the transversal plane; i.e., knee rotation (6%).

Table 1: Means (M), variability (SD) and statistical results during the stance phase

	Even surface	Uneven surface	*t*-value (*df* = 17)	*p*-value	d_{unb}	95%-CI (d_{unb})
	M ± SD	M + SD				
Step width (m)	0.09 ± 0.01	0.08 ± 0.03	-6.21	< .001	-0.77	(-1.18 – -0.42)
Step width variability (m)	0.01 ± 0.00	0.02 ± 0.04	3.16	.006	0.99	(0.29 – 1.78)
MoS_{ml} (m)	0.11 ± 0.02	0.10 ± 0.02	- 1.52	.150	-0.25	(-0.62 – 0.10)
$MoS_{ml\ min}$ (m)	0.07 ± 0.01	0.07 ± 0.02	0.19	.855	0.04	(-0.43 – 0.52)
Upper body acc (g)	1.35 ± 0.17	1.86 ± 0.26	7.36	< .001	2.07	(1.46 – 3.26)
Upper body acc TO (g)	1.03 ± 0.54	1.58 ± 0.71	5.93	< .001	0.87	(0.15 – 1.60)
Hip flex/ext (°)	14.60 ± 4.42	15.68 ± 4.95	2.44	.028	0.22	(0.03 – 0.43)
Hip add/abd (°)	3.46 ± 1.94	3.07 ± 1.17	-2.32	.035	-0.21	(-0.91 – 0.48)
Hip rot (°)	6.78 ± 4.57	6.25 ± 4.56	-0.79	.489	-0.11	(-0.61 – 0.58)
Knee flex/ext (°)	31.79 ± 3.12	33.44 ± 3.22	3.59	.003	0.49	(0.18 – 0.85)
Knee abb/abd (°)	3.32 ± 2.17	3.79 ± 2.61	4.49	< .001	0.19	(-0.50 – 0.89)
Knee rot (°)	-14.13 ± 9.76	-15.01 ± 9.39	2.15	.048	0.09	(-0.79 – 0.60)

Note: d_{unb} *is an unbiased estimate of the population effect size δ; CI = confidence intervals;* MoS_{ml} is the mean mediolateral margin of stability and MoS_{ml_min} is the minimum of the mediolateral margin of stability; TO = toe-off.

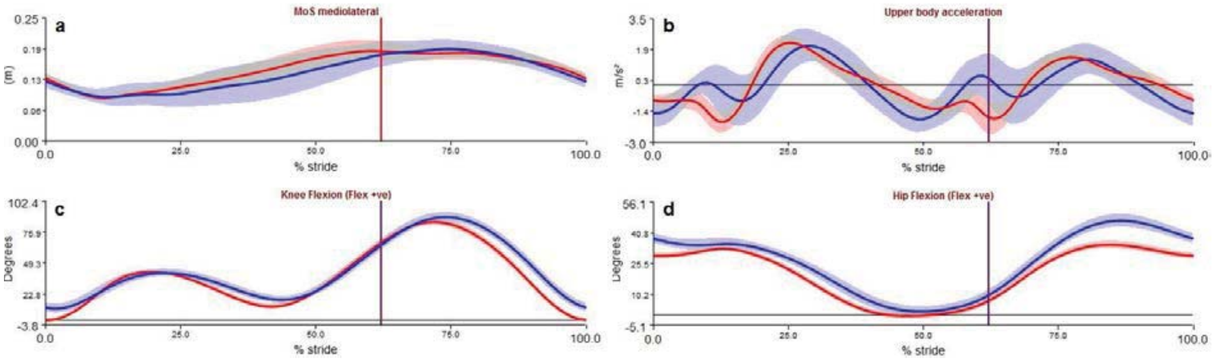

Figure 1: Graphs show the mean and standard deviation of a) MoS_{ml}; b) Upper body acceleration; c) Knee flexion/extension; d) Hip flexion/extension of one participant. Values are time-normalised to a full stride from footstrike to footstrike. Even surfaces treadmill (red lines) and uneven surfaced treadmill (blue lines). Vertical lines mark the toe-off.

DISCUSSION: In the present study we analysed the margin of stability during running on even and uneven surfaced treadmills. MOS_{ml} and MOS_{ml_min} demonstrated unchanged values across conditions, which did not confirm our first hypothesis. Kinematics meaningful differ between conditions confirming our second hypotheses. By increasing hip and knee joint flexion and thus adjusting their running patterns, they adapt a more crouched running on the uneven surfaced treadmill. This is in line with other studies investigating running on uneven surfaces finding increased lower limb kinematics and variability (Sterzing et al., 2014; Voloshina & Ferris, 2015).

Notably, participants did not increase step width when running on the uneven surfaced treadmill, which is a general adaptive mechanism during walking across a uneven surface (MacLellan & Patla 2006). They rather decreased step width by 19%. This is in contrast to Voloshina and Ferris (2015), who found no changes in mean spatio-temporal step parameters. This may due to different surface configurations as Voloshina and Ferris (2015) equipped their treadmill surface with foam blocks, whereas our treadmill has a more undulating profile. However, in line with our investigation they did find increases in step width variability. Since neither MOS_{ml} nor MOS_{ml_min} did change, it seems that participants are in better active control of the Xcom in the frontal plane during running on the uneven surfaced treadmill and that foot placement is actively chosen to attain a minimum MoS_{ml}. But increases in step width variability and lower limb kinematics might not be the only adaptive strategies young healthy adults have to adjust to uneven surface locomotion. Moe-Nilssen and colleagues (1998) found that walking across an uneven surface implies an increase in upper body acceleration. This might be due to mechanical perturbations, but it also might be a compensatory strategy to maintain the Xcom within the BoS. During the late stance and propulsion phase, a greater hip extension at toe-off is associated with increased upper body acceleration (Lindsay, Yaggie, & McGregor, 2014). The hip flexion/extension angles seem to be almost similar at the toe-off (figure 1d), but acceleration profiles (figure 1b) differ meaningfully, especially at late stance. This might suggest that upper body acceleration is not entirely controlled by lower extremity propulsion, but to some extend independent and acting to the ipsilateral side of the toe-off to keep the whole body Xcom within its BoS. This is further supported by a study from Curtze and colleagues (2011) investigating amputees gait over a rough and smooth surface. Amputees did not increase their step width when walking across an irregular surface, however they did increase the lateral component of arm-swing velocity to push the upper body CoM back within a stable MoS_{ml}.

CONCLUSION: This study showed that healthy humans can compensate easily for challenging uneven surfaces during running to keep the Xcom within their BoS; especially by counteracting perturbations with increased step width variability and upper body acceleration, highlighting the importance of frontal plane stability. Increased kinematic variability helped to expand the system's robustness to deal with unexpected perturbations (M. Latash, 2012). Exploiting kinematic variability (i.e., available degrees of freedom) during training might expand the flexibility of the central nervous system to respond to altering conditions to run stable and economical. Running performance is multifactorial, including whole-body joint coordination and especially strengthening the core might facilitate transfering toques from the lower to the upper extremities.

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