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Research article

The effect of an acute bout of rubber tube running constraint on kinematics and muscle activity

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Abstract
We examined the effect of an acute bout of treadmill running with rubber tube (RT) and without rubber tube (NT) elastic constraints on electromyographic (EMG), 3D kinematics variability, and blood lactate concentration (LA). In the RT test, the constraints were attached to the hips and ankles. The selected variables were compared between 30 min of NT running and 30 minutes of RT running in 13 healthy recreationally trained male runners who had no prior exposure to RT. Statistical analysis revealed significantly higher EMG variability ($p < 0.01$) and muscle activity ($p < 0.05$) during RT compared to NT that decreased over time approaching NT, indicating movement pattern adaptation. 3D-kinematics and their variability remained generally unaltered. Changes occurred predominantly in the sagittal plane, specifically to the knee and the swing. A significant increase in LA was measured at the end of RT ($p < 0.05$). These findings suggest that RT running influences muscle recruitment and variability, but has only a minor influence on kinematics. Changes in LA were significant, although relatively small. The observed adaptations in EMG and kinematics suggest that the RTs provide a possibility to create within movement variability in various sports, and thus, variable training conditions may foster strategies to increase the ability to flexibly adapt to different and new situations.

Key words: Treadmill running variance ratio, 3-D analysis, EMG.

Introduction

It is well documented that movement variability is inherent in almost all movements (Van Emmerik and Van Wegen, 2000). In addition to faster recovery from possible perturbations, the beneficial or functional variability provides for flexibility, coordination, and reduction in energy expenditure (Davids et al., 2004; Stergiou and Decker, 2011). New approaches (e.g. differential learning (Schöllhorn et al., 2009)) integrate these views not only to improve learning, but also to adjust performance in terms of technique (Preatoni et al., 2010; Schöllhorn et al., 2009). Since it has been demonstrated that variability provides useful information for behaviour regulation and optimization, athletes should gain valuable knowledge through additionally created variability to help adapt their movements in changing environments (Davids et al., 2004; Schöllhorn et al., 2009).

However, it must be annotated that not all variability improves performance (Hamill et al., 2006). The applied variability must be adjusted to a functional bandwidth (Haudum et al., 2011; 2012a). That is because variability too broadly applied is not relevant to the improvement of performance, and too tightly set boundaries (no variability) constrain the athletes' movements and hamper the possibility of performance progress (Birklbauer et al., 2006; Stergiou and Decker, 2011). Hence, the induced variability should remain within or near the movement skill to maintain the desired pattern. To achieve within-movement variability, goal-oriented constraints may induce an increase in functional variability, and subsequently, improve performance.

In running, several physiological or biomechanical factors contribute to performance (Fletcher et al., 2009), which coaches try to optimize. However, to prepare the runner for changing environments (e.g. uneven ground, small obstacles), the use of variable constraints could be constructive in a way, that allows exploring different functional movement patterns as a consequence of the induced perturbations (Stergiou et al., 2001). For instance, the application of tubes (RT) may create additional elastic forces (i.e., additional to the elastic energy from gravitational, potential and kinetic energy stored in compliant connective tissue and tendinous structures (Sasaki and Neptune, 2006)): therefore, it may influence existing *natural* reactive forces. Due to their properties, RT may increase or decrease elastic forces and may also influence the variability in reactive forces (i.e. non-muscular forces acting on the body) (Bernstein, 1967). Consequently, runners must become acquainted with the RT to adapt to the increased variability within consecutive strides (e.g. by adapting the muscle impulses) and adjust accordingly to a different running pattern that allows for the utilization of the forces produced by the RT. In addition, if effectively used, the constraints may result in reduced energy expenditure, as this form of energy is a major contributor in running (Ferrauti et al., 2010; Neptune et al., 2008; Saunders et al., 2004).

A first impression of how these constraints influence muscle activity during running was demonstrated previously by Birklbauer et al. (2008) and Haudum et al. (2008; 2012a). In this treadmill running study, the authors reported an increased integrated EMG variability and increased muscle activity during an acute bout compared to normal running, which decreased in some muscles over time during this acute bout of RT running suggesting adaptation to the constraints (Haudum et al., 2012a). Nevertheless, the study was limited to stride integrated EMG analyses and no conclusions on running kinematics or the like were made.

However, since the intention of the RTs is to in-

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duce exploratory behaviour and to use the applied variability to optimize the running pattern, we hypothesize that there are also alterations in kinematics, which may further affect metabolic energy expenditure. Therefore, this study was conducted to assess the influences of such constraints on running kinematics and metabolism. In contrast to the research so far (Birklbauer et al., 2008; Haudum et al., 2008; 2012a), we separately investigated the influences in stance phase and swing. That is the RT influences may be different between those two stride phases because swing provides more freedom for the lower extremity since, in contrast to the stance phase, there is no ground contact during swing, and therefore, swing may show more effect of the RT application. Since this constraint is both dynamic and variable, we further analysed and compared the variability of kinematics at the ankle, knee and hip angles, as well as EMG waveforms.

Hence, the aims of this study were to analyse the following: 1) are there differences between RT and NT in the stride kinematics and do this influences differ between separate stride, stance phase and swing analyses, 2) the adaptation to RT in kinematics over a 30 min run and 3) whether RT running would affect blood lactate concentration (LA).

Methods

Subjects

Thirteen male recreational runners (mean ± SD: age = 26.3 ± 8.4 yrs; height = 1.78 ± 0.09 m; body mass = 74.4 ± 2.5 kg) volunteered to participate in this study. The study was approved by the local ethics committee and signed written informed consent was obtained from all subjects prior to testing.

Experimental procedure

The test runs consisted of 2 x 30 min running trials on a motorized treadmill (HP Cosmos Quasar 170/65, Traunstein, Germany) at 3.0 m·s^{-1} and 0% grade. One 30 min run consisted of RT and one without rubber tubes (NT) running. The order of running was counterbalanced across runners. Tests were separated by a 60 min recovery period. Subjects warmed-up for 5 min at 2.3 m·s^{-1} without rubber tube harness before the start of the test. Subjects wore their own running shoes during all test runs and warm ups. Warm-up time was not included in the 30 min test. Kinematic and EMG data were recorded in six 2 min blocks (0-2, 3-5, 13-15, 16-18, 25-27 and 28-30).

Training device

A specially designed harness type belt (Tendybelt, Salzburg, Austria; Figure 1) (Haudum et al., 2012a) was used to attach the RT constraint harness between the lower back and both ankles (Thera-Band GmbH, Dornburg-Frickhofen, Germany). The RTs were attached at the iliosacral joint and at the ankle (heel tab) of the running shoes. RT length was standardized at 40% of the individual leg length corresponding to approximately 48 N at 100% leg length (Haudum et al., 2012a). Additionally, the resistance was checked with a spring balance device (Macroline 100N; PESOLA AG, Baar, Switzerland) and adjusted as necessary. The length and resistance was chosen as tests prior to this experiment unveiled that while this combination does perturb the running pattern, running is still possible (i.e., the running pattern may still be used in a slightly modified way).

Figure 1. One runner while running with the RT constraint.

Data collection

Whole-body 3D kinematic data were collected using a Vicon motion capture system (Peak, Oxford, UK) sampling at 250 Hz. Retro-reflective markers were attached according to the Vicon Plug-In-Gait marker set. The synchronization between EMG data logger and the Vicon system was achieved via flashlight signal.

EMG recordings (2000 Hz sampling frequency) were measured from the tibialis anterior (TA), gastrocnemius lateralis (GL), and rectus femoris (RF) using bipolar Ag/AgCl surface electrodes (Skintact, Leonhard Lang GmbH, Innsbruck, Austria). Skin preparation and electrode placement was conducted accordingly (Hermens et al., 1999; Merletti and Parker, 2004). A single ground electrode was placed on the middle shaft of the tibia. EMG cables were taped to the skin (Fixomull stretch; BSN Medical, Hamburg, Germany) to minimize movement artifacts. The raw signal was converted from analog to digital (DAQ 6024 A/D card, National Instruments, Austin, Texas, USA) and stored using IKE-master software (IKE-Software Solutions, Salzburg, Austria). The signal was preamplified at the source (bandwidth 10-500Hz, 3dB) with a differential amplifier (Biovision, Werheim, Germany). Prior to running tests, amplification was individually adjusted for each runner and each muscle to maximize resolution and prevent the clipping of signals.

Data processing and analysis

The first 90 strides of each 2 min block during the 30 min test were used for the analysis. Only the right leg was used for the analysis. In the first 2 min block (min 0-2), the first 10 strides were removed and the subsequent strides (11-100) were used for analysis. This ensured that runners who had just finished the warm-up started at zero speed and finished accelerating to the prescribed speed of 3.0 $m \cdot s^{-1}$; the difference in data collection due to adjustment to speed differences was excluded from the analyses.

After manual labelling, Vicon motion raw data were filtered using a Woltring filter routine with an Mean square error value of 10 (Woltring, 1986). A whole body anatomical coordinate system was defined via markers and anthropometric data of each subject. The stride cycle was defined as the distance between the first and the subsequent heel strikes of the right leg. Heel strikes and toe-offs were derived from the vertical velocities and the position profiles of the heel and toe markers (Fellin et al., 2010). Flexion/extension, abduction/adduction and the internal/external rotation angles of hip, knee, and ankle, as well as the centre of mass (COM) trajectories, were exported to IKE-master software for further analysis. Strides were normalized to 101 points (0%-100% intervals). Stance phases and swing were normalized to 101 points separately. Subsequently, kinematic parameters during stride, stance phase and swing were extracted for statistical analysis: minimal, maximal, range of motion (ROM) for all three angles, and the COM trajectory.

To detect variability in angles, the variance ratio (VR) was used to quantify the variability of the trajectories and to assess intra-individual stride-to-stride, stance-to-stance, and swing-to-swing variability within each data block according to Hershler and Milner (1978). The following formula was used to calculate the VR:

$$VR = \frac{\sum i \sum j\ (Eij - Ej)^2 / \ m(n-1)}{\sum i \sum j\ (Eij - E)^2 / \ (mn-1)}$$

where i = 1…m is the numbers of strides; j = 1…n is the number of data point; Eij the angle value of stride number i at time j; Ej is the mean joint angle value at time epoch j over all strides; and E is the mean of the entire joint angle trajectory. The VR values range from 0 to 1: 0 indicates no variability and 1 indicates high variability. In addition, to detect a possible shift in stance phase and swing, the stance-swing-ratio was calculated.

The EMG was processed using IKE-master software. The signal was bandpass-filtered (10-300 Hz) using a second-order Butterworth filter and then full-wave rectified (Haudum et al., 2012a). To create a linear envelope, data were low-pass filtered at 10 Hz using a 4^{th} order zero-lag digital Butterworth filter (Neptune et al., 2008). Stride, stance phase, and swing for EMG analysis were triggered by the heel and toe markers. Root-mean-square EMG (RMS) over the entire cycle, stance phase and swing were computed to monitor changes in muscle activity. Stride, stance phase, and swing were normalized to 101 data points and VR was calculated within each 2 min block.

Blood lactate concentration

Blood lactate concentration (LA) was determined from a 20 µl sample collected from the earlobe before and immediately at the end of each test to determine the running effort during NT and RT. For statistical analysis only the post-run samples were used. Blood samples were stored in 1 ml glucose/lactate hemolyzing solution (EKF Diagonstic GmbH, Barleben, Germany), and subsequently analysed. Blood LA was analysed using a BiosenTM 5040 analyzer (EKF Diagonstic GmbH, Barleben, Germany).

Statistical analysis

Statistical calculations were performed using SPSS ver. 18.1 (SPSS Inc., Chicago, IL, USA) software. Data were verified for normality (Kolmogorov-Smirnov test) and sphericity (Mauchly test). If sphericity was not present, the Greenhouse-Geisser correction test was used. To determine significant differences in kinematic and EMG data for stride, stance phase, and swing between NT and RT running, a 6 (data block) x 2 (running condition) repeated measures ANOVA was applied. Dependent variables were VR, minimum angle, maximum angle, ROM, COM trajectory, stride, stance phase and swing duration, and RMS. A paired *t*-test was used to determine differences in LA. Significance for all analyses was set at $p < 0.05$. In addition, the effect calculations based on partial eta squared (η^2_p) were performed.

Results

Comparing NT and RT, joint angle analyses (see Table 1) displayed significantly greater peak knee flexion $F(1,10) = 7.16$ $p < 0.05$; $\eta^2_p = 0.42$), but less peak knee extension ($F(1,10) = 142.04$; $p < 0.001$; $\eta^2_p = 0.93$) resulting in a similar ROM for stride during RT (Figure 2 and 3). The RT running exhibited similar ankle flexion and extension with greater ROM ($F(1,10) = 6.12$; $p < 0.05$; $\eta^2_p = 0.38$). We found greater hip extension ($F(1,10) = 68.21$; $p < 0.001$; $\eta^2_p = 0.87$) and less flexion for RT running ($F(1,10) = 19.20$; $p < 0.01$; $\eta^2_p = 0.64$). For internal/external rotation angles, larger knee ROM was found for NT running ($F(1,10)>27.63$; $p < 0.05$; $\eta^2_p > 0.37$). The COM trajectories demonstrated larger displacements for RT running due to a greater COM elevation during the swing phase ($F(1,10)>11.10$; $p < 0.01$; $\eta^2_p > 0.55$).

Despite similar stride durations, the stance-swing-ratio changed from 39.5% and 60.5% for NT running, to 36.3% and 63.7% with RT running ($F(1,10) = 19.20$; $p < 0.01$; $\eta^2_p > 0.62$).

Mean ankle VRs ranged from 0.02 to 0.10 for NT vs. 0.02 to 0.09 for RT, mean knee VRs from 0.01 to 0.06 for NT vs. 0.01 to 0.08 for RT, and mean hip VRs from 0.09 to 0.28 for NT vs. 0.09 to 0.20 for RT. No significant differences in variability were found for angles in any of the 3 planes (Figure 2). However, a trend for greater ankle variability during the RT running for flexion/extension during swing was observed ($F(1,10) =3.47$; $p < 0.09$; $\eta^2_p = 0.26$). The same occurred for VR at the hip for abduction/adduction during swing and the knee VR for flexion/extension during stance phase ($F(1,10)>4.01$; $p < 0.09$; $\eta^2_p > 0.25$).

RMS data were significantly greater for RF during RT compared to NT running ($F(1,10)=13.31$; $p < 0.01$; $\eta^2_p = 0.60$), but were marginally not significant for TA ($F(1,10)= 3.84$; $p = 0.07$; $\eta^2_p = 0.26$). During swing, all muscles were more active during RT running

Table 1. Mean minima (min) and maxima (max) and range of motion (ROM) for all three joints and for all three measured planes. Data are means (±SD).

	hip		knee		ankle	
Sagittal plane						
stride	**NT**	**RT**	**NT**	**RT**	**NT**	**RT**
min	-5.6 (6.2)*	-18.3 (4.5)*	6.31 (4.5)*	11.7 (3.6)*	-21.3 (6.5)	-22.7 (6.2)
max	42.5 (5.6)*	34.7 (4.9)*	91.8 (9.2)*	96.8 (9.2)*	29.6 (4.6)	29.5 (5.1)
ROM	48.1 (3.9)	53.0 (3.7)	85.5 (9.3)	85.0 (9.2)	50.9 (6.4)*	52.1 (6.2)*
stance	**NT**	**RT**	**NT**	**RT**	**NT**	**RT**
min	-3.1 (7.5)*	-15.4 (5.8)*	7.7 (4.6)*	12.7 (4.0)*	-13.9 (10.1)	-15.7 (8.6)
max	39.4 (6.0)*	28.6 (5.2)*	42.9 (5.9)*	44.2 (4.5)*	29.6 (4.6)	29.5 (5.1)
ROM	42.5 (5.1)	44.9 (5.0)	35.2 (4.0)	31.5 (3.5)	43.5 (9.0)	45.2 (7.4)
swing	**NT**	**RT**	**NT**	**RT**	**NT**	**RT**
min	-5.6 (6.2)*	-18.3 (4.5)*	6.6 (4.6)*	12.1 (3.4)*	-21.3 (6.5)	-22.7 (6.2)
max	42.2 (5.6)*	34.6 (5.0)*	91.9 (9.1)*	96.8 (9.2)*	16.2 (4.3)	13.4 (3.8)
ROM	47.8 (3.7)	52.9 (3.8)	85.4 (9.3)	84.7 (9.3)	37.6 (7.4)	36.6 (5.2)
Frontal plane						
	hip		**knee**		**ankle**	
stride	**NT**	**RT**	**NT**	**RT**	**NT**	**RT**
min	-6.2 (2.5)	-6.8 (3.3)	-1.3 (6.4)	-1.0 (3.8)	-6.1 (6.7)	-4.7 (5.2)
max	8.1 (2.9)	8.6 (2.7)	33.8 (15.2)	29.6 (14.5)	6.6 (3.7)	6.7 (4.2)
ROM	14.3 (2.5)	15.0 (3.6)	35.1 (12.9)	30.7 (12.6)	13.4 (5.9)	12.1 (6.0)
stance	**NT**	**RT**	**NT**	**RT**	**NT**	**RT**
min	-2.10 (3.3)	-2.3 (4.2)	-0.9 (6.5)	-0.5 (4.0)	-5.5 (6.3)	-3.9 (5.1)
max	8.1 (2.9)	8.4 (2.8)	12.0 (8.8)	11.3 (7.0)	6.3 (3.5)	6.5 (4.1)
ROM	10.2 (3.3)	10.7 (4.1)	12.8 (6.3)	11.8 (4.4)	12.4 (5.5)	11.0 (4.8)
swing	**NT**	**RT**	**NT**	**RT**	**NT**	**RT**
min	-6.2 (2.6)	-6.8 (3.3)	0.0 (4.6)	-0.0 (3.2)	-5.5 (6.3)	-4.6 (4.8)
max	4.8 (2.6)	5.0 (2.7)	33.8 (15.2)	29.7 (14.5)	4.5 (3.6)	4.1 (3.8)
ROM	11.0 (2.3)	11.8 (2.3)	33.8 (13.4)	29.7 (12.9)	10.5 (5.6)	9.3 (3.4)
Transverse plane						
	hip		**knee**		**ankle**	
stride	**NT**	**RT**	**NT**	**RT**	**NT**	**RT**
min	-6.8 (15.6)	-6.8 (10.7)	-31.3 (13.5)	-24.8 (12.2)	-21.78 (10.3)	-21.0 (11.0)
max	31.9 (16.2)	28.0 (14.9)	10.5 (9.8)	11.0 (9.6)	20.87 (12.3)	17.9 (9.7)
ROM	38.7 (10.2)	34.9 (7.1)	43.0 (7.4)*	36.5 (5.0)*	42.65 (11.2)	38.9 (9.5)
stance	**NT**	**RT**	**NT**	**RT**	**NT**	**RT**
min	-4.1 (16.6)	-4.3 (11.0)	-24.9 (12.4)	-20.0 (10.5)	-20.9 (9.9)	-20.4 (11.1)
max	12.7 (18.4)	12.0 (12.6)	9.3 (10.3)	9.5 (10.4)	18.9 (12.6)	15.4 (10.5)
ROM	16.8 (5.6)	16.3 (4.78)	35.0 (8.3)	30.0 (6.4)	39.8 (10.8)	35.8 (9.3)
swing	**NT**	**RT**	**NT**	**RT**	**NT**	**RT**
min	-4.9 (16.6)	-6.1 (11.0)	-31.3 (13.2)	-25.0 (12.2)	-15.3 (11.3)	-13.8 (10.0)
max	32.5 (16.4)	28.2 (14.9)	2.2 (10.0)	5.6 (9.7)	18.9 (12.9)	17.4 (9.4)
ROM	37.4 (10.0)	34.33 (7.0)	34.6 (10.4)	31.3 (7.3)	34.2 (13.1)	31.1 (6.7)

The asterisk (*) indicates significant differences between NT and RT.

($F(1,10)>5.96$; $p < 0.05$; $\eta^2_p > 0.46$), while during stance phase, significant differences were found for RF only ($F(1,10)=6.05$; $p < 0.05$; $\eta^2_p = 0.40$). Almost all RMS results yielded decreases in RMS over time ($F(1,10)>4.31$; $p < 0.05$; $\eta^2_p > 0.28$), except TA for stride and RF for swing.

EMG data showed higher variability than kinematic data (Figure 2) substantiated by up to twice as high VRs for EMG compared to kinematics (see Figure 4 for EMG VRs). The stride and stance phase data for all 3 muscles demonstrated greater variability during RT running ($F(1,10)>11.80$; $p < 0.01$; $\eta^2_p < 0.58$). Swing data for TA marginally failed significance with ($F(1,10)=4.49$; $p = 0.06$; $\eta^2_p = 0.31$) while no significant differences were found between the two conditions for RF and GL ($F(1,10)=3.47$; $p > 0.06$; $\eta^2_p = 0.31$). The 2 x 6 interactions revealed significant differences for RF and GL ($F(1,10)>5.48$; $p < 0.01$; $\eta^2_p > 0.35$; Figure 4), as variability was greater for RT running in the beginning, but decreased towards the end of the run and was similar to NT.

The post run LA was significantly higher for RT (2.5 ± 1.4 $mmol \cdot l^{-1}$) compared to NT running (2.2 ± 1.4 $mmol \cdot l^{-1}$) ($p < 0.05$; $\eta^2_p = 0.20$).

Discussion

In the present study, the effect of RT running on variability in kinematics and EMG was investigated, as well as joint angles, EMG activity and blood LA.

The main findings in the kinematics revealed that particularly extension/flexion angles were influenced by the RT. When examining the COM trajectory, a higher vertical displacement was observed in swing during RT running. Contrasting kinematics and EMG yielded stronger effects of RT on EMG than kinematics. An additional difference observed was the shift towards a longer

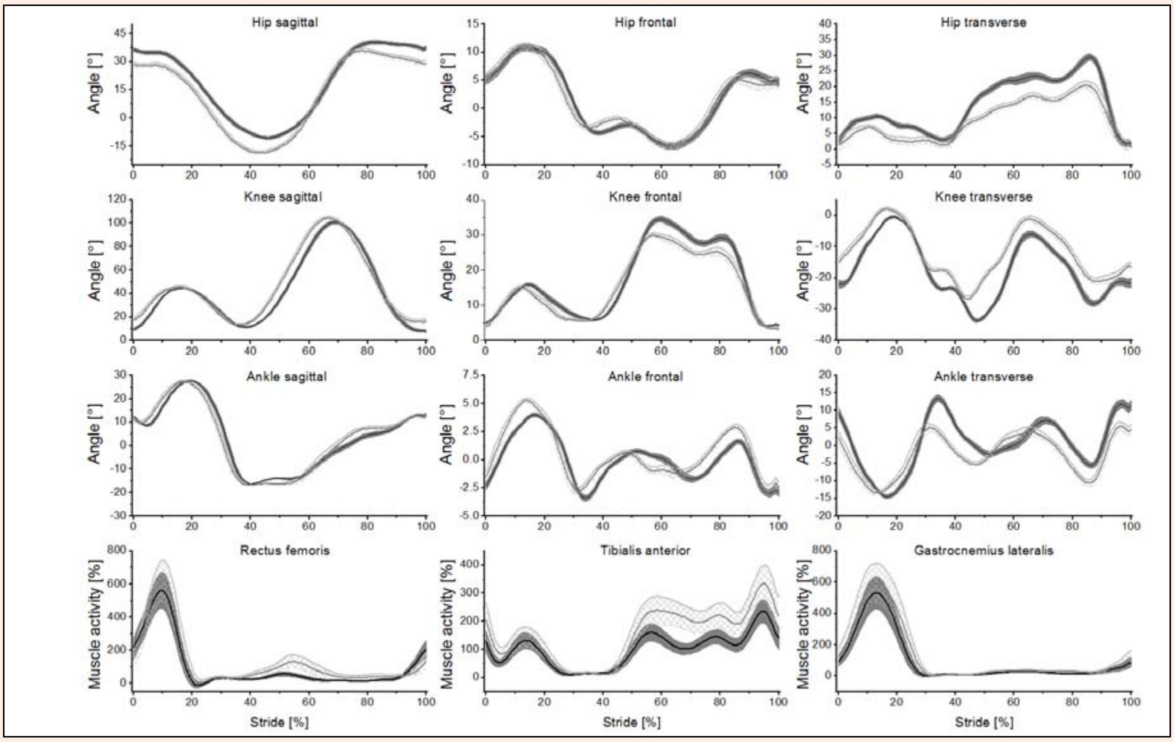

Figure 2. Representative results of hip, knee and ankle joint trajectories and EMG of one runner, which reflect the overall trend of all runners. Depicted are the mean curves and the point-to-point standard deviation of all three planes and all three muscles. Solid black lines represent mean curves of NT running and the grey area represents the standard deviation. The grey solid lines represent the RT running condition and the dense grey area represents the standard deviation. The presented EMG values were normalized to the average EMG value during NT running. This average value was taken as 100 %-baseline and the normalized data are expressed as a percentage of this baseline value.

swing phase as RT running was accompanied by increased knee flexion without altering the stride duration.

Variability

The EMG variability (Figure 4) during NT running and VRs were similar for the within-condition values reported in the literature on matured skills (Granata et al., 2005). However, the early VRs in the newly RT running pattern are more in line with VRs of unskilled behaviours such as was measured in children (Granata et al., 2005), which is not surprising as the task was a novelty for the runners. Nevertheless, in contrast to those values found in the literature, the VR rather fast improved throughout the RT test run, demonstrating high variability when RT running is first performed but rather quickly approaching NT level and becoming more repeatable.

Comparing our findings on EMG variability and RT with other RT studies in the literature, our results on variability during RT running are in agreement with Haudum et al. (2012a), Birklbauer et al. (2008) and Haudum et al. (2008), who all found increased variability during RT running compared to NT.

Contrasting stance phase and swing VRs, greater variability for the swing was observed as the legs are free to move (no ground contact) and the RT may induce greater influence on the leg movement. The upper body may also act as a kind of stabilizer against the RT perturbations, which would further support the minor influences during stance and the more obvious swing perturbations. The increased EMG variability may be due to complexity of the muscle coordination pattern to create appropriate interplay (Bernstein, 1967) and *resist* the RT perturbations. The variability reflected exploratory behaviour and the nervous system's ability to create muscle synergies to satisfy the demand of RT running (Müller & Sternad, 2008). These differences between consecutive strides were deviations from the optimal movement pattern, which provided relevant information for future adaptations (Schöllhorn et al., 2009). The runners' feedback supported the exploratory running behaviour because after the RT trial runners complained that, especially at the beginning, RT running was perceived as extremely difficult but over time and by exploring different ways how to use the RT and kind of somehow playing with the RT, they more and more adapted to RT. This perceived adaptation is in line with our results, since a detailed analysis of EMG variability throughout the running test revealed that especially in the beginning the RT running resulted in greater variability, which decreased during the test ($\eta^2_p > 0.35$).

These changes in variability reflect the traditional motor learning curves or paradigms, in which variability decreases throughout learning (Stergiou and Decker, 2011) and are further supported by Bertenthal (1999), who reported that the amount of variability resulted in a U-shaped function when learning a new movement. During RT running, subjects gained better control of the movement and the variability subsequently decreased due

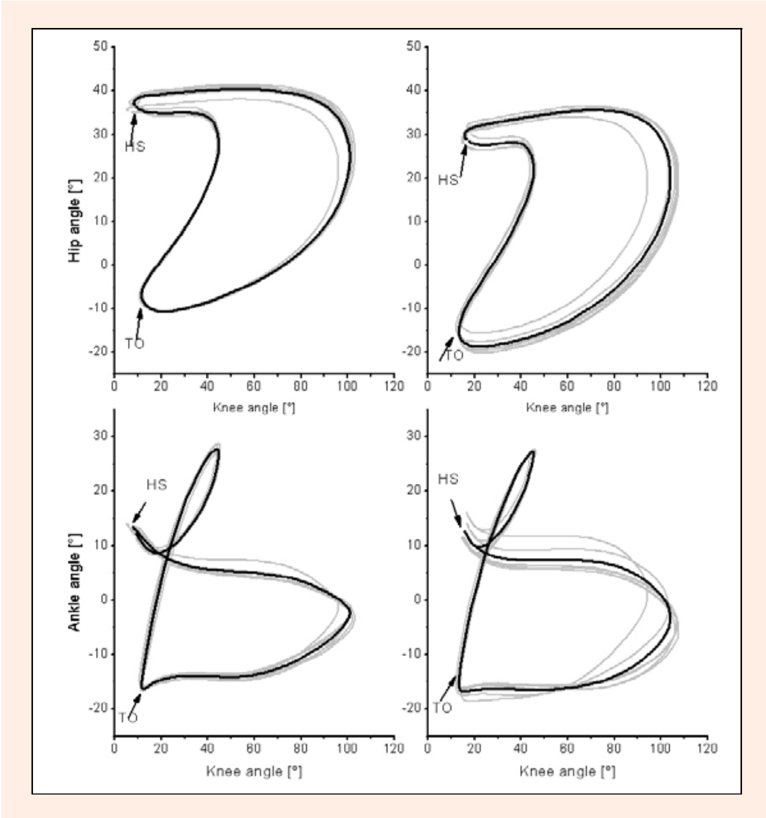

Figure 3. Examples of sagittal hip-knee (upper two) and knee-ankle (lower two) angle-angle-plots for a single representative subject. Shown are the average curves of the six data blocks (grey lines) and the total average (black line). The left two plots display the NT running and the right side depicts RT running. The difference between the two running conditions is noticeable during swing in the knee-ankle plot. Representative data reflect the overall trend for all runners. (HS = heel strike; TO = toe-off)

to the adaptation to the RT. The anew increase in variability, which also reflects some kind of behavioural repertoire and flexibility and is described by the U-shape could not be supported since no increase occurred in this study. However, it may occur during longer tests (>30 min) or when additional practice times may result in an increased and more structured and functional variability (Wilson et al., 2008).

Despite the increase in EMG variability, kinematic VRs remained stable in response to dynamic external perturbations contributed to by the RT ($\eta^2_p < 0.27$). This difference between EMG and kinematics VRs supported our attempt to increase within-movement variability. The marginal difference between NT and RT VRs underlined the complex connection between movements and nervous system, and the outstanding property that despite the increased EMG variability or even better *because* of the increased EMG variability kinematic VRs remained almost unchanged. The increased variability on muscular level offered the possibility to maintain a rather similar pattern on kinematic level (i.e. the redundant degrees of freedom in the leg offer locomotor control to be achieved via a wide range of recruitment strategies (Granata et al., 2005)). Nevertheless, it is interesting to note that the multijoint segment may also compensate RT perturbations in some way. As can be observed in the graphical illustration of the angle-angle plots (Figure 3), the knee-ankle plots did not only show more variability than the hip-knee plots (which could be explained by the degrees of freedom of the two involved joints; i.e., due to their distance to the trunk, the knee-ankle combination can act with more freedom than the proximal hip-knee combination, where the hip is constrained by the trunk, and is in turn more affected by the RTs). Comparing the two knee-ankle combinations (Figure 3), however, demonstrates that there is an influence by the RTs since the variability within the RT condition is higher than in the NT condition.

With respect to stride duration, we found higher variability during NT than during the early minutes of RT ($\eta^2_p = 0.29$). According to Bernstein (1967), this reduction in stride variability would reflect a freezing in the case that the runners were overpowered by the RT and could not use the RT. Since variability approached normal running within the RT interval, a release and utilization, respectively, occurred pointing again to an adaptation. Contrasting kinematic and EMG variability supports Bernstein's (1967) findings that variability on a sublevel reflects inter-segmental coordination to achieve a desired movement outcome. Our EMG data reflected higher variability as the nervous system attempted to stabilize running pattern of kinematics utilizing diverse recruitment strategies (Granata et al., 2005).

Joint angles and muscle activity

Joint angles were most often influenced in sagittal plane movement and less in transverse or coronal plane. That sagittal plane motion is greater than motion in transverse and coronal plane is in line with the literature

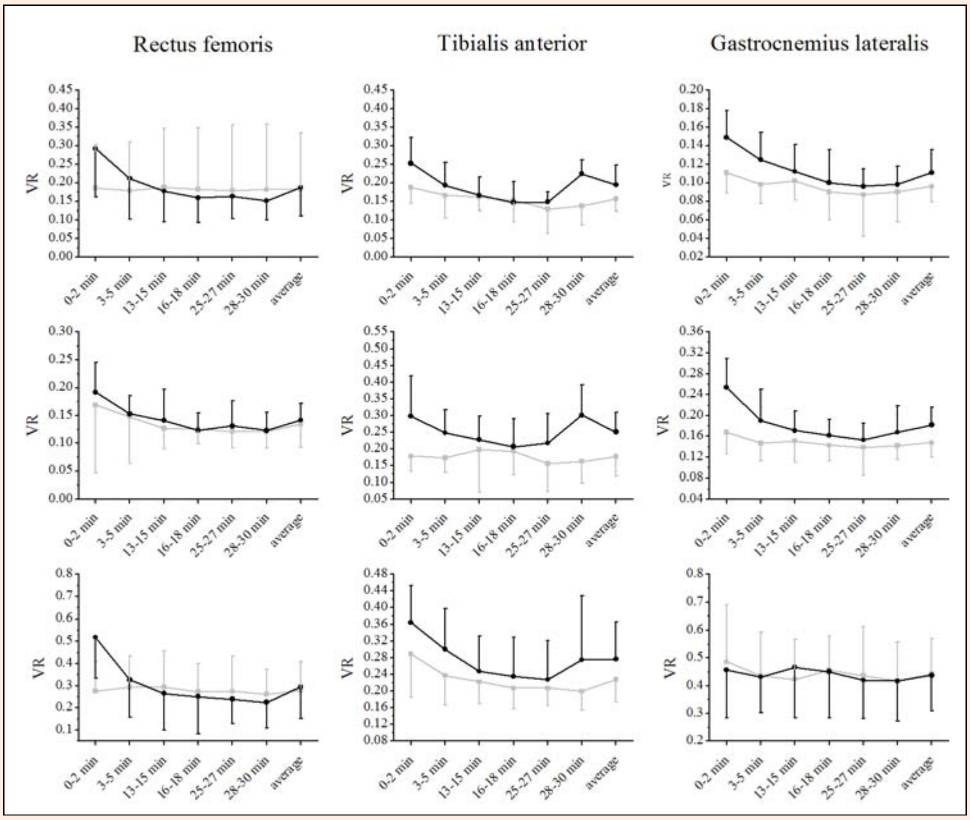

Figure 4. Mean (±SD) variance ratios for EMG data for stride (top), stance (middle) and swing (bottom). Grey lines represent NT, black lines show RT means.

(Novacheck, 1998) and is logical because the sagittal plane is the progression plane. Therefore, it was rather surprising that frontal and transverse plane angles did reveal almost no significant differences and were rather resistant against the RT perturbations.

The higher hip extension and the reduced flexion (η^2_p > 0.63) during RT may be the reason for the increased RF activity, as it had to work against the tube. The knee in the NT situation flexed 91° vs. 96° in the RT situation, which hints towards a utilization of the tubes as 96° approaches flexion angles typical for sprinting (Novacheck, 1998). Further, the increased knee flexion (η^2_p = 0.42) may be the reason for the change in stance-swing-ratio, which is the consequence of additional reactive forces. The knee joint together with the muscular adaptations compensated for the RT changes, and thus, at large enabled the use of a preferred movement path (Nigg, 2001). The similar joint kinematics in NT and RT demonstrated that RT can be used to increase within-movement variability during practice and force athletes to explore marginally different movement patterns.

Since stride time remained unchanged during RT running, the longer swing time (η^2_p = 0.63), a result of the greater vertical motion of the COM and knee flexion, indicated that despite the unfamiliar constraint, runners could utilize the RTs. However, the other constraints (i.e. treadmill running and stride time) may have been too difficult to allow a severe change in the running pattern.

The increased muscle activity (η^2_p > 0.26) in the three measured muscles was in line with previous research (Birklbauer et al., 2008; Haudum et al., 2012a) and supported the slightly increased energy demand found in the LA results. However, this was in contrast to another study, in which Haudum et al. (2012b) investigated acute effects of RT use in ski touring. They found no significant difference in LA levels for RT at the end of a 90 min ski touring trial. In the present study, the test duration of 30 min may have been too short to reduce muscle activation and also to energetically adapt the running pattern. The higher muscle activity may also be a consequence, as RT running may also shift attention to the involved joints and increase muscle engagement as reported in the literature in other sports (Vance et al., 2004).

According to the graphical illustrations, the most obvious difference between NT and RT was present in the RF prior and during mid-swing phase that may indicate better response to the demands of RT running (Novacheck, 1998). This increased burst may reflect the hip flexor function (Cavanagh, 1990), which might, due to the RT application, require higher activity. Since RF is active in hip flexion and knee flexion-extension, it may be perturbed by the RT during the entire stride and, in case of no utilization of the tubes, has work against the tubes in both phases.

In TA and GL, our data suggested that during the second half of the swing and late swing phase, the co-activation of TA and GL may indicate a stabilization attempt in preparation for ground contact (Novacheck, 1998). This observation was found in all except one of our runners. Both muscles were mostly affected during their eccentric work prior to heel strike. And this eccentric phase may also be a key to use the tubes as this utilization may further contribute to the propulsion via release during subsequent contractions (Saunders et al., 2004). This is supported by the importance of the ground contact preparation, as this preparation has higher significance than the toe-off preparation (Novacheck, 1998).

The RT affected the reactive forces both positively and negatively, since they may be hindering or supporting the movement. Therefore, they may require either more or less muscle activity. This uncertainty of how the RT influenced the running pattern was also evident in the higher muscle activity, which may reflect higher alertness in order to accordingly respond, and metabolically in the LA values.

Another explanation for the higher muscle activity may be that the rebound of elastic energy, in particular, during the late stance phase, which resulted in a shorter stance phase and longer swing time. However, due to this utilization of elastic energy, especially prior to foot contact, more eccentric muscle work and therefore energy was required for braking in order to adjust the individual RT running behaviour. After some more RT practice time, this eccentric work due to adaptation may no longer be necessary. The observation of the decrease in muscle activity ($\eta^2_p > 0.28$) supported this theory.

There are some limitations of this study. Besides the low number of runners, additional muscles may have provided more information on the actual effect of the tubes. In order to estimate the effect of the RT in the long term, future studies are warranted to examine the effect of an intervention with such a constraint or to analyse less automated skills and the effect of RT on relearning or unlearning a technique.

Conclusion

The results of this study suggest that an acute bout of RT running produced greater changes in EMG variability compared to kinematics, which remained rather stable throughout the RT test and led to a modest increase in blood LA at the end of the RT test. The RT appears to be a useful device to increase within-movement variability and break up the constant movement pattern, yet still leaves some freedom to explore new, different running patterns. For training, the RT provides the opportunity to practice under variable conditions that are difficult to anticipate, and therefore, may help athletes to create better adaptation mechanisms.

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Key points

- Adaptation to training device occurred quite rapidly.
- Changes in muscle activity were more pronounced than kinematic changes due to the training device.
- Training device may be used to increase within-movement variability.
- Participants may learn to flexibly adapt to variable constraints.

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