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Research article

The influence of external perturbations on running kinematics and muscle activity before and after accommodation

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Abstract
In the current study, the running pattern of the lower extremity was examined while being perturbed through tubes attached between the ankles and the lower back to analyze influences on the running pattern variability before and after a varied running intervention. 3D-kinematics, joint coupling and electromyography (EMG), as well as their variability, were analyzed in ten healthy male participants during treadmill running (10.5 km·h^{-1}). Pre- and post-tests each consisted of 2 x 30 min treadmill running (one with and one without tubes). The results showed major acute effects on EMG and kinematics, as well as joint coordination variability, due to the constraints ($p < 0.05$). After the intervention, a process of normalization of most kinematic and EMG parameters occurred; however, EMG variability, kinematic variability and joint coordination variability were reduced during tube running below normal running level ($p < 0.05$). The findings further indicate rapid kinematic adaptations while muscle activity appears to require longer practice to adapt. The constraint serves to acutely increase variability, but may lead to reduced variability when applied for a longer period of time.
Key words: Adaptation, variability, joint coordination, tube constraints.

Introduction

Despite the large body of running literature, researchers still explore running with respect to biomechanical aspects or joint coupling coordination (e.g. Hamill et al., 2000; Hamill et al., 1999; Stergiou et al., 2001b). In recent years, following the paradigm shift in the domains of motor control and biomechanics in terms of variability, variability became a main field of interest for research in running. Due to the complex interaction of many degrees of freedom, the coordination of lower extremity joints and segments provides important information for the role of variability in movement coordination since it has been interpreted as being both harmful and essential (Heiderscheit et al., 2002). However, the growing body of literature has demonstrated, that variability is necessary for flexibility and adaptability in movements, which allows handling the frequently and unexpectedly varying situations (Bartlett et al., 2007; Van Emmerik and Van Wegen, 2000).

Despite the increasing amount of literature on running and variability, most studies investigated running under standardized, principally constant conditions. Little research is available on the coordination and variability between lower extremity segments or muscles under varied conditions (Stergiou et al., 2001b). Varying situations would, however, better reflect the real world situation (i.e., different situations like when walking or running on a forest path or trail) and can easily be achieved by simply using different kinds of constraints (e.g., obstacles or tubes (Haudum et al., 2012; Jaffe et al., 2004; Stergiou et al., 2001b)). With respect to the tubes, they are somehow a kind of unforeseen obstacles. They may simulate running through the forest, where the runner sees the ground; however, he may have to react to possible perturbations when, for example, a branch or something lying on the ground, which he steps on, unexpectedly moves or breaks. That is, the runner knows that he is stepping on a branch or little stone but he cannot exactly predict its moving or breaking. Alike, during running with tubes, the runner knows that he is running with tubes; however, he cannot exactly anticipate how the tubes perturb his running pattern. When running with tubes of a certain length the runner knows that at a certain time point in the running cycle the tubes are overstretched and for example, when there is no ground contact after toe-off, the tubes will perturb the running pattern in a way. The actual perturbations, however, depend on many facts (e.g. step length or amount of bending and stretching of the knee or hip) and the runner must, thus, accordingly react and adapt his running pattern.

Constraints have recently been used to manipulate motor behavior to develop stability of functional coordination patterns (Davids and Glazier, 2009). By applying different constraints, single movement aspects (e.g., forefoot position at heel strike) can be highlighted or weakened. Moreover, dynamic constraints (e.g., by externally applying perturbations) may help optimize adaptation to single or multitudinous movement aspects (e.g., hip, knee and ankle movements during swing) (Davids and Glazier, 2009).

From a practical or therapeutic viewpoint, perturbing movement executions by altering constraints may be a way to observe different coordinative movements or adaptation strategies in highly automated skills (Button et al., 2000). For example in running, the application of tubes to the lower extremities requires that runners learn to handle sudden unfamiliar perturbations.

Acute effects of such perturbations (i.e., tubes attached between hip and ankle) have been evaluated in runners who were exposed to such perturbations for the first time (Haudum et al., 2010; Haudum et al., 2012). Comparisons to running without tubes (NT running) showed that running with tubes (RT running) affected

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electromyography (EMG), whereas kinematics remained almost unaltered. The EMG data of rectus femoris, tibialis anterior and lateral gastrocnemius reflected significantly higher integrated EMG variability and increased muscle activity, which partly returned to normal throughout the test. 3D-kinematics, however, were only influenced in the sagittal plane motion by the tube application. That is, the knee was more flexed during RT running while hip and ankle joints, as well as the calculated variability within all joints did not show significant differences to NT running and also stride duration remained unchanged (Haudum et al., 2010; Haudum et al., 2012). These results support the assumption that variability on sublevels enables a stable movement outcome (Bernstein, 1967) and that some kind of a preferred movement path exists (Nigg, 2001).

Since only acute effects were investigated and joint coordination and its variability were not addressed, the question is how repeated RT running alters the running pattern (i.e., kinematics and muscle activity) and joint coordination variability assuming that adaptation must occur.

Hence, the purpose of this intervention study was to determine (1) how runners adapted to such constraints after a 7-week training intervention with this constraint in their muscle activity and kinematics, (2) whether RT running affects variability in kinematics, EMG and joint coordination, and (3) whether there are differences in adaptation between the kinematics, EMG and joint coordination.

Methods

Participants

Thirteen recreational runners volunteered for the study. However, due to injury or illness only ten runners (mean age: 26.1 ± 7.1 yrs, mean height: 1.77 ± 0.7 m, mean weight: 72.0 ± 6.6 kg) could be included in the analyses. All participants were treadmill-experienced, but were novices in the use of the constraints (Figure 1). The study was approved by the local ethics committee. Written informed consent was obtained from all participants.

Training device

A harness (Figure 1; Tendybelt, Salzburg, Austria) was used to fix elastic constraints in the form of tubes (Thera-Band GmbH, Dornburg-Frickhofen, Germany) at the back of the hip and the ankle (i.e., at the heel tab of the running shoes). Tube length was standardized at 40% of the individual leg length, although the actual length was individually adjusted after resistance was checked with a spring balance device (Macroline 100N; PESOLA AG, Baar, Switzerland) to ensure the predefined 48 N at 100% leg length (Haudum et al., 2012). Various RT lengths and resistances were previously tested and this one in combination with the used tubes was found to meet the criteria of a variability constraint best (i.e., perturbing the running pattern to increase variability but not to make running almost impossible by destroying the running pattern).

Procedure

Pre- and post-tests were completed before and after a 7-week intervention. The tests were run on a treadmill (HP Cosmos Quasar 170/65, Traunstein, Germany). The treadmill speed was set at 10.5 km·h^{-1} and 0% grade for all tests. Prior to each test a 5-min warm-up (8.5 km·h^{-1}; 0% grade) was conducted without tubes. The warm-up time was not included in the test time. There was a recovery time of 60 min between the two tests. The order of presentation was counterbalanced across participants. Kinematics and EMG were recorded in all runs.

Figure 1. Training device.

Training intervention

Runners completed a total of 18 training sessions of RT running on a treadmill (10.5 km·h^{-1} and 0% grade). Alternately, 3 and 2 sessions were run each week. The duration was increased from 45 min for the first two sessions to 50 min (sessions 3-6) and then to 55 min (sessions 7-18). This gradual increase was intended to help participants adapt to RT running as it was assumed that the energy cost of RT running would decrease with practice.

Training contents

The training intervention was compiled according to the differential learning approach (Schöllhorn et al., 2009) and guidelines proposed by Birklbauer et al. (2006) to support the runner's exploratory behavior with the tubes and to structure the amount of induced variability. The differential learning approach (Schöllhorn et al., 2009) claims that the differences between executions provide essential information to establish the individually most effective and optimal movement pattern. The guidelines (Birklbauer et al., 2006) highlight keypoints, which should be considered when applying variability and they were used to structure the training exercises with respect to the amount and how variability was induced. The guidelines involve, for example, (1) the knowledge of the movement to-be-learned (i.e. which are the key points of the movement), (2) the goal oriented induced variability (i.e. variability should be applied in a way that it supports the development of the movement, which means that there is a specific purpose why variability is applied exactly in that way), (3) the range of difference that decreases with the process of learning (the rather large variations at the beginning of learning become finer and finer throughout learning, which, nevertheless, results in the same experienced variability since perception is more precise with enhanced skill levels), (4) that the athlete is disturbed by the usage of motor constraints, and (5) by alterations within the reactive phenomena (the latter two being already realized by the tube application). The exercises should help the runners utilize the tubes to support their movement. Besides different tube applications, variations were created through instructions. Examples were: (1) work actively against the tubes during late swing; (2) let the tubes drag the heel passively upwards; (3) move the knee extremely up and forward. The exercises were applied continuously while running and changed every two minutes. Only in case of changing the tube position, runners stopped to change the position and immediately continued to run; otherwise, they ran throughout the session performing the different instructions and exercises.

Data collection

Kinematic and EMG data were sampled in 2-min blocks starting at minute 0, 3, 13, 16, 25 and 28. The first 90 strides of each 2-min block were selected for analysis. In the first 2-min block of each test run (i.e., min 0-2) the first 10 strides were removed and the subsequent strides (i.e., 11-100) were selected for analysis to ensure the runners had finished accelerating and influences due to speed differences could be excluded. EMG and kinematics were synchronized by a flashlight signal.

Kinematic data were collected with an 8-camera Vicon 3D-motion analysis system (Vicon Peak, Oxford, UK). Forty-one markers were attached according to the Plug-In-Gait model and sampling rate was 250 Hz.

Due to economic reasons, EMG recordings were only obtained from the right leg (Haudum et al., 2012; Haudum et al., 2011b). Muscle activity from rectus femoris (RF), tibialis anterior (TA), and lateral gastrocnemius (LG) were recorded using Ag/AgCl surface electrodes (circle shaped, bipolar; Skintact, Leonhard Lang GmbH, Innsbruck, Austria). Skin preparation and electrode placement was done. To minimize cable movement artifacts, cables were taped to the skin using Fixomull stretch (BSN Medical, Hamburg, Germany). Electrodes were not removed in-between the two runs. EMG data were bandpass-filtered from 10 Hz to 500 Hz in hardware (Biovision, Werheim, Germany) and sampled at 2000 Hz. Prior to the first test run, participants had a short test run to adjust amplifier gains and prevent clipping off. The same setup was used for the post-test measurements.

Data processing and analysis

Kinematic data

After manual labeling, marker trajectories were smoothed via a Woltring routine (mean square error value of 10) (Woltring, 1986) and kinematics were calculated using the Plug-in-Gait ® model. Individual strides were defined with respect to the right leg movement and were further separated into stance phase and swing. These events were identified using the vertical velocities and the position profiles of the heel and toe markers (Fellin et al., 2010; Lamoth et al., 2009). Stance time was determined from right heel strike and right toe off. Calculated sagittal hip, knee and ankle angles, as well as center of mass (COM) trajectory data were exported to IKE-master (IKE-Software Solutions, Salzburg, Austria). All data then were normalized to 100% of stride, stance phase or swing (101 data points).

Coordination variability was assessed between the hip and knee joint and the knee and ankle joint with respect to the sagittal plane motion using the vector coding (VC) technique suggested by Tepavac and Field-Fote (2001). Angle-angle plots were used for vector coding the data to determine the angle (shape) and magnitude (length) of the vector between consecutive data points. The amount of variability of shape (i.e., angular deviation) and magnitude (i.e., length deviation) was quantified over all strides within each 2 min block between each two adjacent points on the angle-angle plot. The stride-to-stride variability was calculated for each percent of the stride, stance phase, or swing, providing a measure of between-trial and within-participant coordination variability. The mean variability was determined by averaging variability across the entire stride, stance phase or swing. Since the shape data are circular data, its calculation is based on circular statistics. The linear standard deviation of the vector length was placed in the range of 0-1 by scaling the normalized vector length to the maximal possible standard deviation of that point-to-point interval. In addition, the product of shape and magnitude (i.e., the coefficient of correspondence (CoC)) was determined, which describes the overall variability throughout the movement. The advantage of this VC technique over Hamill et al.'s (2000) approach is that it incorporates the measurement of both shape and magnitude (Wheat & Glazier, 2005) as it takes also the joint angle velocity into account. A coefficient of 0 indicates high variability with near random nature and 1 indicates no variability in joint coordination with all values being identical (Tepavac and Field-Fote, 2001).

Unlike the VC technique, the variance ratio (VR)of the joint angle trajectories was calculated as a further measure to provide essential information on variability in each single joint. Moreover, as it was also applied to EMG, it allowed the comparison of kinematics and EMG data. It describes the ratio of the mean variance between corresponding data points in individual strides to the total variance of the entire data and ranges from 0 to 1. However, in contrast to VC, 0 indicates similar waveforms (i.e., no variability), and 1 indicates dissimilar waveforms (i.e., high variability) (Granata et al., 2005; Kadaba et al., 1985).

The kinematics of interest were selected from stride, stance phase and swing and included minima, maxima, range of motion and the variability parameters VR and VC (i.e., angular deviation, vector length deviation and coefficient of correspondence), as well as the vertical displacement of the COM. In addition, the stance-swing-ratio was calculated.

EMG data

Post-processing was performed in IKE-master. Recorded data were bandpass-filtered from 10 to 300 Hz

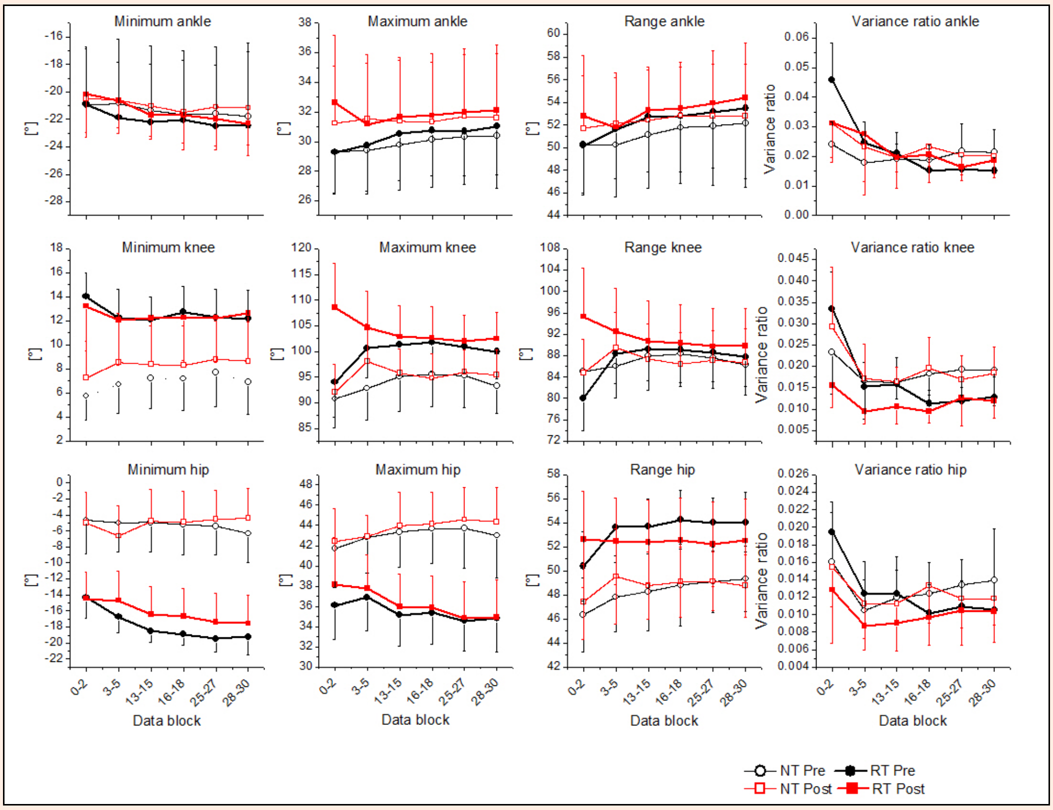

Figure 2. Mean minima, maxima, ranges of motion and VRs for stride of each 2-min block for pre- and post-tests (means ± 95%-confidence interval).

(Butterworth 2nd order), full-wave rectified and low-pass filtered (10 Hz fourth order zero-lag digital Butterworth filter) to create linear envelopes (Haudum et al., 2012). The calculated kinematic triggers were used to differentiate stride, stance phase and swing EMGs. Akin to kinematic data, EMG waveforms of stride, stance phase and swing were normalized to 101 data points to calculate the VRs within each 2 min block. The root mean square values of the entire stride, stance phase or swing were calculated from the bandpass-filtered signal to demonstrate muscle activity. Since the maximal voluntary isometric contraction data for the calf muscles were far below the dynamic running situation, no normalization of the EMGs was performed and therefore no comparisons between pre- and post-test muscle activity were possible.

Statistical analysis

Data were checked for normality (Kolmogorov-Smirnov test) and sphericity (Mauchly test; in the case of necessity, the Greenhouse-Geisser correction was used) using the software package PAWS SPSS 18.1 (SPSS Inc., Chicago, IL., USA). To estimate differences for kinematic and EMG data, test time point (pre and post) x condition (RT and NT) x data block (2-min blocks) repeated measures analyses of variance (RMANOVA) were performed. Additionally, test time point x data block RMANOVAs were calculated to estimate the change over time within each running condition. The variables of interest were statistically compared at a confidence level of $p < 0.05$. Effect size partial eta squared ($_p\eta^2$) also was calculated.

Results

Kinematics

A summary of the minima, maxima, ranges of motion, as well as VRs for stride, stance phase and swing is given in Figures 2-4.

Hip flexion was significantly higher and extension smaller during both RT runs resulting in a larger range of motion ($p < 0.01$; $_p\eta^2 > 0.70$) compared to NT. The knee angle showed higher flexion ($p < 0.05$; $_p\eta^2 > 0.48$) and less extension ($p < 0.01$; $_p\eta^2 > 0.83$) during both RT test runs. At the post-test, knee range of motion was significantly greater for stride ($p = 0.02$; $_p\eta^2 = 0.51$), but marginally failed significance for swing ($p = 0.06$; $_p\eta^2 = 0.38$) during RT running compared to NT running. Tendencies for higher ankle range of motion were observed during pre-test RT running for stride and stance phase ($p < 0.06$; $_p\eta^2 > 0.42$), but not during the post test. The RT running also resulted in significantly higher vertical displacement of the COM ($p < 0.05$; $_p\eta^2 > 0.68$).

Stride duration was significantly shorter during NT running ($p = 0.03$; $_p\eta^2 = 0.47$). The stance-swing-ratios unveiled a shorter stance phase and longer swing ($p < 0.05$; $_p\eta^2 > 0.48$) during RT running for pre- and post-tests. However, an approximation of RT running towards NT running was observed after intervention (Table 1).

Variability of kinematics

The amount of variability in running kinematics is presented in Figure 5 and 6 by means of example data of one participant.

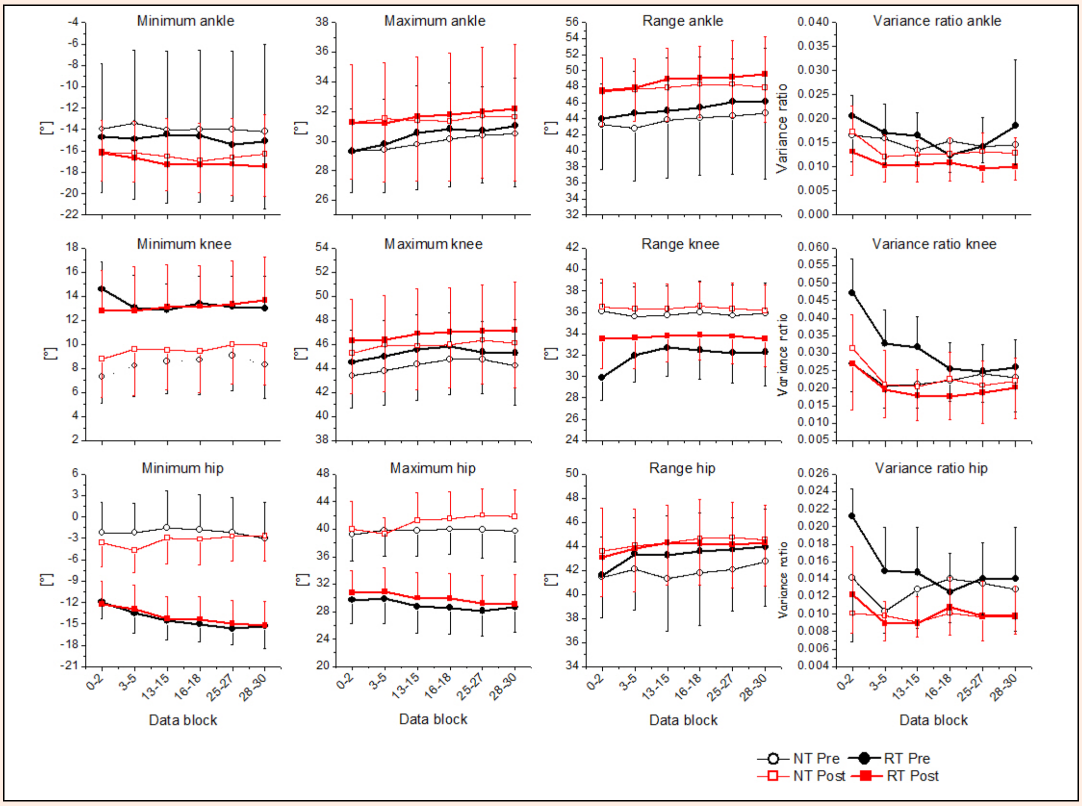

Figure 3. Mean minima, maxima, ranges of motion and VRs for stance phase of each 2-min block for pre- and post-tests (means ± 95%-confidence interval).

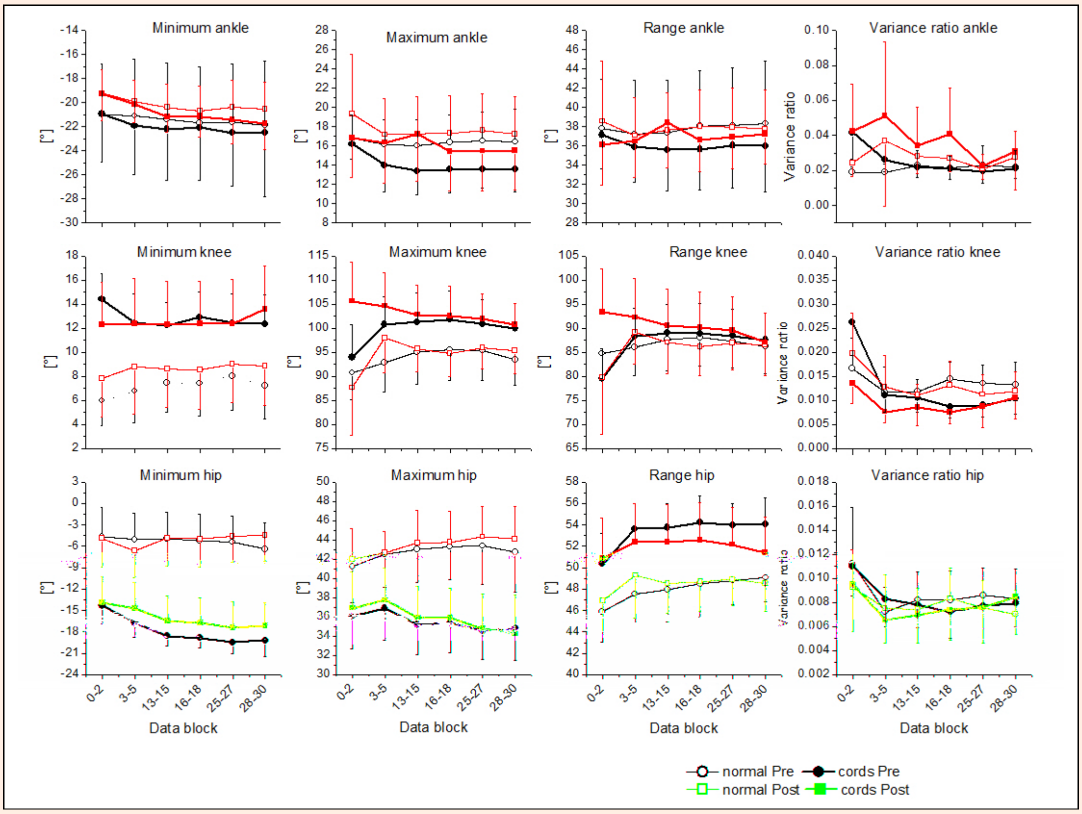

Figure 4. Mean minima, maxima, ranges of motion and VRs for swing of each 2-min block for pre- and post-tests (means ± 95%-confidence interval).

Table 1. **Mean stride duration and stance-swing ratios. Data are means (± SD).**

	Test condition	Stride duration [sec]	stance time [%]	swing time [%]
Pre-test	**NT running**	.75 (.03)	38.31 (3.6)	61.69 (3.5)
	RT running	.76 (.03)	35.61 (2.9)	64.39 (3.1)
Post-test	**NT running**	.75 (.03)	39.68 (4.0)	60.32 (3.2)
	RT running	.76 (.03)	37.56 (3.2)	62.44 (2.7)

Vector coding: At the pre-test, RT running showed increased hip-knee and knee-ankle joint coordination variability in the first 2 min for stride, followed by a decrease over the test towards or below NT level in all three VC parameters ($p < 0.05$; ${}_p\eta^2 > 0.30$). The same was observed for magnitude and CoC for swing data ($p < 0.01$; ${}_p\eta^2 > 0.38$). The RT training indicated a significant effect on hip-knee and knee-ankle joint coordination variability demonstrated by the decreased coordination variability during RT for all stride and swing parameters at the post-test ($p < 0.05$; ${}_p\eta^2 > 0.46$) compared to NT. For stance, RT post-test joint coordination data unveiled significantly lower angular deviations ($p < 0.05$; ${}_p\eta^2 > 0.53$) and significantly lower CoC for knee-ankle coordination ($p < 0.05$; ${}_p\eta^2 > 0.48$), while the difference between RT and NT hip-knee coordination was marginally not significant ($p < 0.07$; ${}_p\eta^2 > 0.41$).

Variance ratio: At the pre-test, all three joints showed significantly higher variability at the beginning of RT running that decreased below the level of NT running ($p < 0.05$; ${}_p\eta^2 > 0.30$). In the post-test runs, knee and hip stride VR were significantly higher during NT running ($p < 0.05$; ${}_p\eta^2 > 0.40$). Swing analyses demonstrated a decrease in variability for both running conditions in the hip joint ($p < 0.05$; ${}_p\eta^2 > 0.53$). Ankle post-test data for NT running showed higher VR compared to RT running ($p = 0.02$; ${}_p\eta^2 = 0.53$), and the ankle swing VRs were higher in both pre-test runs compared to the post-test runs ($p < 0.05$; ${}_p\eta^2 > 0.54$).

Muscle activity

Significantly higher RF activity was observed in both RT test runs ($p < 0.05$; ${}_p\eta^2 > 0.50$). The TA was also significantly more active at the pre-test during RT running for stride ($p = 0.04$; ${}_p\eta^2 = 0.49$) and swing ($p = 0.02$; ${}_p\eta^2 = 0.55$), whereas post-test swing data marginally failed significance level ($p = 0.06$; ${}_p\eta^2 = 0.42$). A significant interaction for LG pre-test data was found as muscle activity was increased at the beginning of RT running and decreased towards NT running level over time ($p = 0.02$; ${}_p\eta^2 = 0.42$).

EMG variability

The pre-test data showed higher variability for RT running in all three muscles ($p < 0.\ 05$; ${}_p\eta^2 > 0.41$). After practice, no significant differences were found. The LG data hint at a reversal effect as a trend for higher VR during NT running was found following practice ($p = 0.09$; ${}_p\eta^2 = 0.32$).

The stance phase analysis unveiled higher variability for LG ($p = 0.00$; ${}_p\eta^2 = 0.72$) for RT running and a decrease over time towards NT running level ($p = 0.01$; ${}_p\eta^2 = 0.33$) before training. Higher VR for TA for RT running ($p = 0.01$; ${}_p\eta^2 = 0.60$) was found after the intervention. No significant differences were found for RF.

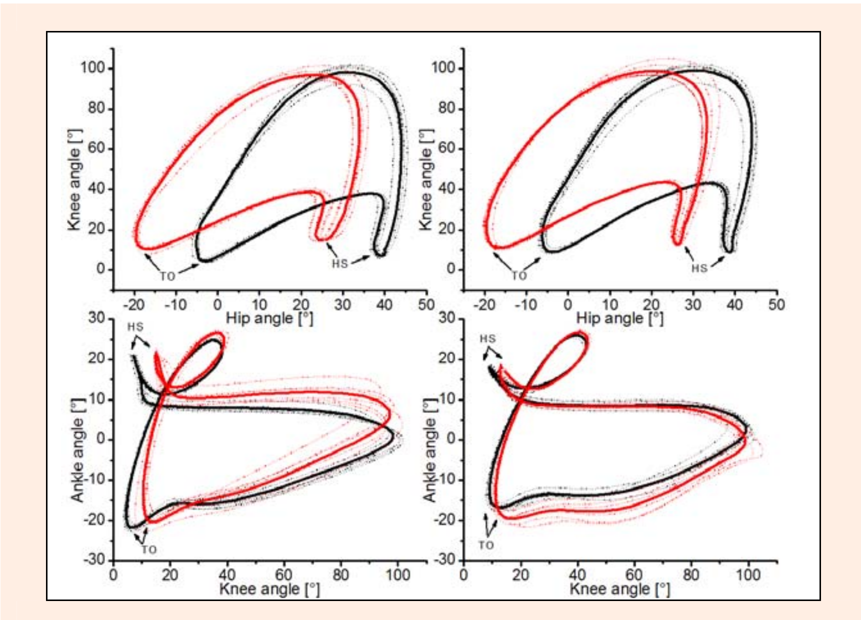

Figure 5. **Hip-knee and knee-ankle angle-angle plots of one representative runner. The left two graphs display the pre-test data, the right two the post-test data. The upper level shows the hip-knee plots and the lower two the knee-ankle plots. Black dotted lines show NT running means of each 2-min block, red dotted lines RT running means of each block. The thick black and red lines represent the grand mean of the entire 30 min test. Especially in the knee-ankle plots, the higher variability due to the RT and the occurred adaptation to them are well reflected. Heel strike is indicated by HS and toe-off by TO.**

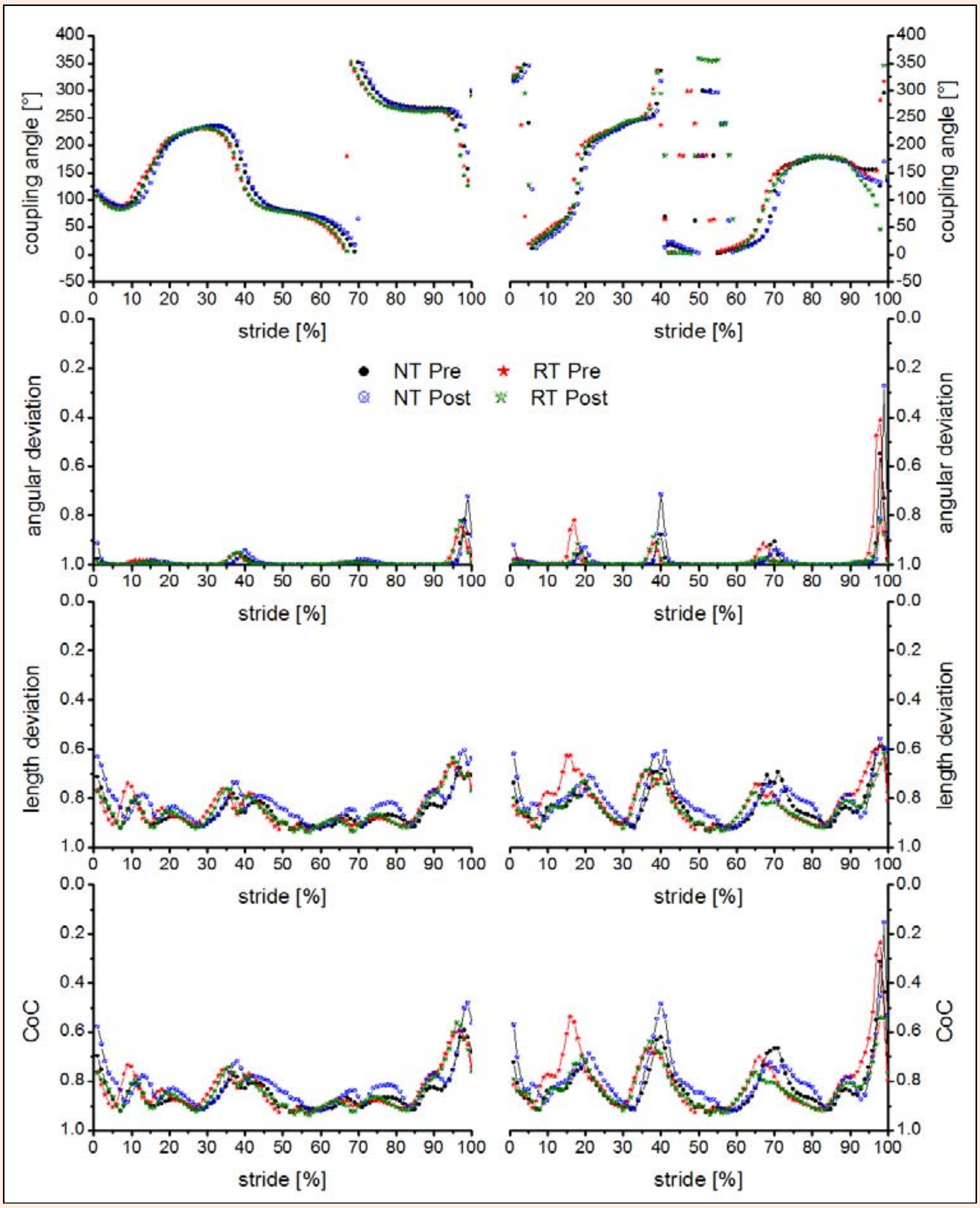

Figure 6. Mean vector coding plots of one representative runner. The left column represents the hip-knee data, the right column the knee-ankle data. Mean coupling angle (a), mean angular deviation (b), mean length deviation (c), and mean coefficient of correspondence (d) for the respective couplings. The coupling angle in particular demonstrates the differences observed in joint angle values; however, within each situation, the variability is rather low, as supported by the VC results.

For swing, a significant interaction effect was found for RF (p = 0.00; ${}_p\eta^2$ = 0.58), as the initially high VR for RT running decreased below NT running level.

Post-test results point at a higher VR for NT running compared to RT running (${}_p\eta^2$ = 0.24). No significant differences were found for TA or LG.

Discussion

The aim of the study was to investigate the effects of an RT running intervention on 3D-lower extremity kinematics, muscle activity and their variability, as well as joint coordination variability. The results demonstrated that the first exposure to RT running led to significantly increased muscle activity and higher VR of EMGs and kinematics and joint coordination variability compared to NT running, which confirms results of previous studies (Haudum et al., 2010; Haudum et al., 2011b). Surprisingly, most of the VC and VR results were reversed after the intervention. A significantly elongated swing time was observed during RT running due to a higher vertical displacement of the COM and influences on knee and hip parameters. Interestingly, kinematic stride, stance phase and swing parameters did reveal significant, yet not large, influences through the RT application (Figures 2-4).

Kinematics and joint coordination

Similar to the results of Haudum et al. (2010; 2011b), kinematics were less perturbed than muscle activity. The main kinematic influences in response to the tubes were observed in the knee joint (Figure 5) and may compensate the tube perturbations in some way, while the more active

RF is assisting this compensation. Since the tubes support knee flexion, the RF may resist this motion.

Even though significant changes in joint angle kinematics were found, their magnitude was quite modest. Combining the influences on kinematics and the resultant altered stride duration or stance-swing ratio, the movement pattern of NT running was reproduced in a marginally modified form after the 7-wk intervention. These findings indicate that the RT running pattern has not to be learned, but rather requires some kind of relearning of the ordinary running pattern. It appears that runners tried to maintain a preferred movement path (Nigg, 2001) achieved through a possible reorganization of the muscular coordination (Button et al., 2002) or the tube constraint. As can be seen in the coupling angle in Figure 4, the different running conditions differ only marginally and display a rather constant running pattern. This confirms our intention to increase movement-inherent variability without destroying the running pattern.

Despite the different approaches (i.e., single joint analysis or joint coordination), VC and VR revealed quite similar results. Following an initial increase in variability at the first RT exposure, the occurring accommodation led to a more stable, more repetitive pattern, which was even more obvious in the post-RT runs. The increased early joint coupling variability in the pre-test may serve an adaptive role and guarantee controllability, (Heiderscheit et al., 2002; Mullineaux & Uhl, 2010). Since the tube perturbations vary from stride to stride due to the marginally different initial conditions (Haudum et al., 2012), the observed early increases in variability stem from a blend of exploration and flexibility. This characteristic may function in facilitating faster adjustments and may further have perceptual function. The higher variability is also in line with research on, for example, different types of shoes, which also denotes an unfamiliar situation (Hamill et al., 1999; Stergiou et al., 2001b).

Since the NT results were not influenced by the RT intervention, no transfer of the RT intervention on the NT running pattern occurred. With respect to the RT running pattern, the tubes may act as limiting constraints. Despite the primary assumption that the kinematics' variability as well as joint coordination variability would increase through the tubes and the intervention, a kind of freezing occurred. The RT running pattern unveiled a greater degree of repeatability, reflected in the reduced post-test VC and VR variability. Perhaps the constant tube application implied too much resistance, which in the longer term constrained the RT running pattern in the same way as do injuries (Hamill et al., 2000; Heiderscheit et al., 2002), which, in turn, led to reduced joint coordination variability.

Concluding for the kinematic results, it appears that runners adapted to the RT application used in the test runs as the variability parameters after the intervention did no more unveil changes throughout the test runs.

Muscle activity

During the early acquisition to the unfamiliar constraint, the increase in muscle activity may reflect a process to regain control and to adjust to the tubes (i.e., reorganize the running pattern (Button et al., 2002)). The high level of RF activity may be due to increased co-contraction following the unfamiliar tube constraint running (Basmajian & De Luca, 1985). Despite the not sampled antagonists in the thigh, it may be hypothesized that the RT training led to RT adaptation and reduced co-contraction. The still increased muscle activity following practice ($_{p}\eta^2 > 0.41$) could be interpreted as the necessary effort to work against the tube resistance, or as a newly developed coordinative structure (Lay et al., 2002).

Another explanation for the higher muscle activity during RT running may be reasoned to maintain the overall leg stiffness (Morin et al., 2011). That is, because RT running perturbs the running pattern of the legs, the change in the stance-swing ratio may be the result of altered leg stiffness. The higher muscle activity may be utilized to compensate the perturbations and to better control leg stiffness (Miller et al., 2008; Morin et al., 2011; Stergiou et al., 2001a).

Although on-off times were not calculated, visual inspections of muscle on-off times indicated that some runners activated their muscles earlier during early RT running. The most likely explanation is that the earlier muscle activation may be one of the strategies utilized to functionally resist the tube perturbations to continually find the appropriate motor response and also to control ankle stiffness before heel strike (Button et al., 2002; Stergiou et al., 2001a). This would also be in line with the runners' feedback after the first RT running test as they perceived an adaptation to the tubes and, in line with Bernstein's freezing and freeing (1967), could release their movements after some time. Apparently, the perceived releasing was adaptation to the tubes, but not an actual release in the degrees of freedom as the movement was more stable on both muscular and kinematic observational level.

The significantly greater variability during early RT running is another indicator for more responsive stabilizing control and the unfamiliarity of RT running. Comparing the VR data with other values in the literature, pretest VRs of RT running are similar to less matured movement patterns (Granata et al., 2005; Kadaba et al., 1985). Through a practice-related decrease, the VRs of RT running approached the level of NT running, which indicates adaptation to the tubes and a normalization of the running pattern on muscular level (Granata et al., 2005).

Interesting results unveiled the comparison of the changes in muscle activity and EMG VR before and after training. Despite the almost unchanged muscle activity during RT running, a reversal effect occurred for VR as EMGs were more variable during RT running compared to NT running before practice, but were less variable after practice.

Combining kinematic and EMG data, our results showed quite similar effect to as have been observed in walking with unstable shoes (i.e., MBT), where also differences due to the level of observation were found and, further, repeated walking with MBT shoes also resulted in reduced variability during MBT walking (Stöggl et al., 2010). Such studies along with the current one, on the one hand, confirm findings of neurobiological or artificial neural network illustrations. That is, the human nervous system is perfectly made for adaptation and the extraction of rules (i.e., generalization ability) (Haudum et al., 2011a). Throughout the intervention, runners acquired an appropriate rule for RT running that allows the best movement adjustments for the actual situation in order to cope with the constraint. On the other hand, these results demonstrate that different stimuli and experiences are necessary to be apt to adapt to new situations (i.e., the variable experiences gained throughout practice may have supported the adjustment to the tubes and allowed for faster adaptation). For the RT test situation this means that the rule for RT running has accordingly been developed.

Nevertheless, there are some limitations of the current study. One is that only three muscles were measured. It is likely that more muscles would allow better demonstration of the actual influences. A further limitation may be that no kinetic data were measured, which should be added in future investigations. There is also a small chance of type I error inflation beyond the $p < 0.05$ standard given that more statistical tests were performed on the same data.

Conclusion

In summary, the study indicated that kinematic adjustments to the applied dynamic constraints occurred rather quickly, but it required longer practice to manage the perturbations on muscular level. Furthermore, the joint couplings demonstrated that engaging in such running intervention results in reduced lower extremity coupling variability. Hence, such constraints provide a possibility to induce acute movement-inherent variability and may help to better adapt to unfamiliar situations if variability in the perturbations is guaranteed, which may not be the case in the test situation due to the constant tube position. Future studies may analyze RT running in RT-experienced runners when being forced to permanently run with different RT applications. They may also include further coordination analysis techniques, such as continuous relative phase since it incorporates both angular displacement and velocity, which might provide additional useful information.

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Key points

- Normalization of the EMG variability after the training intervention during running with the dynamic constraint
- Joint coupling variability was reduced after practice intervention during constrained running
- Kinematic adaptations happen fast while muscle activity requires longer practice
- Sublevels (i.e., EMGs) were more influenced by the constraint than the macroscopic kinematics.

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