Original research

Kinematic changes during running-induced fatigue and relations with core endurance in novice runners

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\textbf{A R T I C L E I N F O}

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\textbf{A B S T R A C T}

\textbf{Objectives:} This study aimed to investigate kinematic changes experienced during running-induced fatigue. Further, the study examined relations between kinematic changes and core endurance.

\textbf{Design:} Repeated measures and correlation.

\textbf{Methods:} Seventeen novice runners participated in a running-induced fatigue protocol and underwent core endurance assessment. Participants ran at a steady state corresponding to an intensity of 13 on the Borg scale and continued until 2 min after a Borg score of 17 or 90% of maximum heart rate was reached. Kinematic data were analyzed for the lower extremities and trunk throughout a running protocol and, on separate days, core endurance measures were recorded. Changes in pre- and post-fatigue running kinematics and their relations with core endurance measures were analyzed.

\textbf{Results:} Analysis of peak joint angles revealed significant increases in trunk flexion (4°), decreases in trunk extension (3°), and increases in non-dominant ankle eversion (1.6°) as a result of running-induced fatigue. Post-fatigue increased trunk flexion changes displayed a strong to moderate positive relation with trunk extensor core endurance measures, in contrast to expected negative relations.

\textbf{Conclusions:} Novice runners displayed an overall increase in trunk inclination and increased ankle eversion peak angles when fatigued utilizing a running-induced fatigue protocol. As most pronounced changes were found for the trunk, trunk kinematics appear to be significantly affected during fatigued running and should not be overlooked. Core endurance measures displayed unexpected relations with running kinematics and require further investigation to determine the significance of these relations.

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1. Introduction

Increased levels of physical activity are currently being promoted in an attempt to curtail rising rates of disease associated with sedentary behavior. A popular form of physical exercise is recreational running. Literature has shown that runners experience a high number of running-related injuries (RRI),\textsuperscript{1} this number being particularly high in novice runners.\textsuperscript{2} While there is little consistency in literature regarding causes of RRI,\textsuperscript{3} measures such as high BMI, previous injury, and previous sports activity without axial loading have been shown to be risk factors in novice male runners.\textsuperscript{4}

It is generally assumed that suboptimal lower limb movement patterns may increase injury risk in runners. Specifically, excessive pronation and its main component, rearfoot eversion, have been linked to RRI.\textsuperscript{5} It has also been reported, for experienced runners, that rearfoot eversion during running may increase with fatigue.\textsuperscript{6–8} The latter suggests that fatigue may increase injury risk due to adverse effects on lower limb kinematics and may be even more so in novice runners. However, effects of running-induced fatigue on lower limb kinematics have, to our knowledge, not been studied in novice runners.

Lower extremity loading while running would be increased by a lack of control of the trunk center of mass position over the stance leg hence sufficient strength of muscles that stabilize the pelvis and trunk has been emphasized in relation to injury risk.\textsuperscript{9–11} In accordance with this, the effect of trunk kinematics on injury risk during running has gained increasing interest in recent years. Indeed, relations between hip muscle strength and dynamic endurance and running kinematics\textsuperscript{12,13} as well as injury risk in experienced athletes\textsuperscript{14} have been demonstrated. Moreover, it has been shown that trunk muscle fatigue, caused by isolated trunk extension exercise, causes an increase in trunk flexion and inclination during running.\textsuperscript{15} It is, therefore, conceivable that fatigue of these muscles developing during sustained running may cause progressive changes of trunk kinematics. In line with this, training and testing of...
endurance of muscles stabilizing the pelvis and trunk, often coined core endurance, is deemed important in practice. However, to our knowledge, neither the effect of running-induced fatigue on trunk kinematics, nor the relation between changes in trunk kinematics in running and commonly used static core endurance measures have been established in novice runners.

Given the lack of literature concerning effects of fatigue in novice runners as well as the lack of evidence regarding the role of core endurance in this context, the aim of this study was to investigate trunk and lower extremity kinematics in novice runners using a running-induced fatigue protocol simulating a typical running session. The study additionally aimed to gain insight into relations between running kinematics and measures of core endurance. It was hypothesized that fatigue would result in increased rearfoot eversion and trunk flexion and that potential changes in running kinematics would be more pronounced in runners with low core endurance. In addition, since changes in trunk kinematics with fatigue during running do not necessarily result from fatigue of proximal musculature as changes in lower extremity kinematics can also affect pelvis and trunk movements, we performed a comprehensive analysis of lower extremity kinematics.

2. Methods

A total of 17 participants (10 females, 7 males) participated in the study. Participants had a mean age of 26.4 (SD 3.1) years, weight of 66.9 (SD 11.0) kg, height of 172 (SD 10.2) cm, and BMI of 22.5 (SD 2.7). Novice runners free of injury were recruited from the general population. To be eligible to take part in the study, participants were required to be between 20 and 45 years of age and having ran less than 2–3 times per week for <10 km and/or <45 min per session, but having the physical capacity to run at a self-selected pace for approximately 30 min and/or 5 km at a time. Individuals reporting a history of lower extremity injury requiring surgery or formal rehabilitation, severe back pain in the previous year, cardiovascular risks for physical exercise, formal core stability training, previous running experience at a competitive level, or clinical obesity (BMI ≥ 30) were excluded. All participants provided written informed consent and the study was granted ethical approval by the Ethical Committee of the Faculty of Human Movement Science of the VU University Amsterdam, The Netherlands; 2011-16R.

Participants were asked to come to the lab on two separate days. On the first day, core endurance measures were performed. The core endurance measures were performed on a standard plinth and consisted of the lateral musculature test (side-bridge), the flexor endurance test, and the back extensor test. The lateral musculature test involves the participants lifting their hips off the plinth while supporting themselves with their elbow and feet. The flexor endurance test involves the participants holding a sustained trunk flexion angle of 35° with knees bent and feet supported while sitting on the plinth. The back extensor test involves the participants lying prone with their trunk over the edge of the plinth (holding neutral position) while legs are supported. Additionally, a modified Trendelenburg test, in which the participants are asked to hold their hips at neutral in one-legged stance, was performed bilaterally to measure hip abductor endurance. For all measures, participants were asked to sustain static positions at neutral and were timed in seconds using a stopwatch. Failure was determined when the participants lost their neutral postures at which point the timer was stopped. Participants were given a 2-min rest period between all measures to allow for recovery. All measures were performed in randomized sequence. Participants were blinded regarding measures of performance throughout the testing procedure. Anthropometric characteristics were taken on days corresponding with core endurance measures.

On the second day, participants took part in a steady state running-induced fatigue protocol on a treadmill (Biotar Giant™, Biometrics, Almere, The Netherlands). Minor alterations were made to the protocol utilized by Diersk et al.7 to best suit our population. Participants started walking on the treadmill at a speed of 6 km/h. They were asked to rate their perceived exertion by means of the 15-point Borg scale18 and were monitored for heart rate (Polar RS100, Polar Electro Oy, Woodbury, NY) by an examiner every minute throughout the trial. Speed was increased in increments of 1 km/h every 2 min until an intensity of 13 (somewhat hard) on the Borg scale was reached. Participants continued to run at the given steady state speed until a Borg score of 17 (very hard) or 90% of maximum heart rate (HRmax estimated as 220 – age)19 was reached, at which point they continued to run for 2 additional minutes. Participants then performed a cool-down at a self-selected speed.

All participants were provided with new neutral running shoes (Nike Air Pegasus) for the running protocol. The dominant leg was defined as the leg the participant would use to kick a ball. No visual or verbal stimuli were provided throughout the protocol and participants were blinded with regards to speed and duration of the trial.

Trunk and lower extremity kinematics were recorded at a sample rate of 100 samples/s throughout the running protocol using an Optotrak motion capture system (Optotrak Certus®, Northern Digital Inc., Waterloo, Ontario). Two 3-camera arrays were positioned behind the participant, 40° from the midline. Optical cluster markers consisting of three diodes fixed to rigid plates were fastened with Velcro to neoprene sleeves for the lower extremities, a neoprene belt for the pelvis, and a neoprene harness for the trunk to obtain kinematic data. Plates were fastened to the heel of the shoes using adhesive tape.

Before the experiment, the positions of the cluster markers were related to anatomical landmarks20 using a 6-marker point to indicate the location of anatomical landmarks defining anatomical segment axis systems. Prior to data analysis, marker coordinates were filtered using a 4th order low-pass Butterworth filter with a cut-off frequency of 15 Hz. Data were extracted for analysis 1 min after steady state was reached and 1 min after fatigue (Borg 17/90% HRmax) was reached. Subsequently, based on the anatomical calibration and cluster marker data instantaneous orientations of the anatomical axis systems for all segments of interest were determined and orientation of distal segments were expressed relative to proximal segments. Euler decomposition of the resulting local orientation matrices, in the order, flexion/extension, lateral flexion or abduction/adduction or eversion/inversion, and finally torsion was used to obtain joint angles. Heel strikes were defined as lowest point of the right foot during stance, and a stride cycle as the time between two consecutive heel strikes. Data corresponding to timeframes of twenty consecutive stride cycles of the right foot were averaged. In the event of obstructed markers during strides, affected strides were removed and averaged over a minimum of nineteen stride cycles. Maximal and minimal joint angles during the averaged stride cycle were extracted to determine peak angles. To determine changes in peak angle, mean differences between pre- and post-fatigue data were calculated.

All kinematic variables were analyzed in Matlab version R2011a (The MathWorks Inc., Natick, MA) using the 3-dimensional (3D) linked segment model developed by Kingma et al.21 All joint angles were referenced from anatomical posture. Trunk and hip, knee, and ankle kinematics were analyzed. Both dominant and non-dominant sides were analyzed to ensure no major discrepancies were evident. Given inherent measurement error associated with hip, knee, and ankle rotation, as well as hip and knee movement in the frontal plane, data were not analyzed for these variables.
All statistical analysis was performed using PASW statistics 18.0 (IBM corp., Armonk, NY). Changes between pre- and post-fatigued kinematic values for trunk flexion, extension, lateral flexion, and rotation, hip and knee flexion and extension, and ankle inversion, eversion, dorsiflexion, and plantar flexion were analyzed using paired Student T-tests for both the dominant and non-dominant side. Relations between core endurance measures and changes in trunk peak angles were determined using a Pearson correlation coefficient. All variables were analyzed individually and multiple comparisons were accounted for using a Bonferroni correction. Statistical significance was set at p < 0.05.

3. Results

In the event of equipment malfunction, participant’s data were excluded for corresponding measures (N: Table 1). Participants reached a mean speed of 2.6 (SD 1.6) m/s and required an average of 19.7 (SD 7.8) minutes to reach fatigue.

All kinematic findings are presented as mean values in Table 1. Using trunk flexion as an example, average peak trunk flexion angle was 9.0° (SD 6.6) when running at a pre-fatigued level at the beginning of the trial. Trunk flexion angle increased by 4.0° (95% CI 2.5–5.6) to reach a peak angle of 13.0° (SD 6.6) at the end of the trial.

Fig. 1. Example kinematic time series. Plots of typical kinematic time series over an averaged stride cycle displaying peak joint angle data during pre- and post-fatigued running. Per variable analyzed data from one subject best representative of the group mean data were selected.
Table 1
Peak joint angles.

<table>
<thead>
<tr>
<th>Peak joint angle</th>
<th>Dominant</th>
<th></th>
<th>Non-dominant</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>Pre-fatigue (SD)</td>
<td>Fatigued (SD)</td>
<td>Change (95% CI)</td>
</tr>
<tr>
<td>Trunk</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexion</td>
<td>17</td>
<td>9.0 (6.6)</td>
<td>13.0 (6.6)</td>
<td>4.0 (2.5–5.6)</td>
</tr>
<tr>
<td>Extension</td>
<td>17</td>
<td>–0.8 (7.0)</td>
<td>–3.8 (7.4)</td>
<td>3.0 (2.0–4.2)</td>
</tr>
<tr>
<td>Lateral flexion</td>
<td>17</td>
<td>7.4 (3.6)</td>
<td>7.4 (3.7)</td>
<td>0.0 (–1.2 to 1.3)</td>
</tr>
<tr>
<td>Rotation</td>
<td>17</td>
<td>8.8 (3.9)</td>
<td>9.2 (4.8)</td>
<td>0.4 (–1.2 to 2.1)</td>
</tr>
<tr>
<td>Hip</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexion</td>
<td>16</td>
<td>43.8 (8.2)</td>
<td>44.3 (9.1)</td>
<td>0.5 (–0.9 to 2.0)</td>
</tr>
<tr>
<td>Extension</td>
<td>16</td>
<td>12.1 (6.7)</td>
<td>14.8 (7.8)</td>
<td>2.7 (0.4–5.0)</td>
</tr>
<tr>
<td>Knee</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexion</td>
<td>15</td>
<td>89.0 (10.2)</td>
<td>92.2 (12.7)</td>
<td>3.2 (–0.2 to 6.5)</td>
</tr>
<tr>
<td>Extension</td>
<td>15</td>
<td>–10.0 (5.4)</td>
<td>–90.5 (5.7)</td>
<td>1.0 (–0.4 to 2.5)</td>
</tr>
<tr>
<td>Ankle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plantar flexion</td>
<td>16</td>
<td>22.1 (5.6)</td>
<td>22.6 (6.1)</td>
<td>0.5 (–0.9 to 2.0)</td>
</tr>
<tr>
<td>Dorsiflexion</td>
<td>16</td>
<td>18.4 (4.4)</td>
<td>18.1 (4.1)</td>
<td>0.3 (–0.5 to 1.2)</td>
</tr>
<tr>
<td>Pronation</td>
<td>16</td>
<td>11.9 (4.6)</td>
<td>12.9 (4.3)</td>
<td>1.0 (0.4–1.7)</td>
</tr>
<tr>
<td>Supination</td>
<td>16</td>
<td>9.3 (3.8)</td>
<td>9.6 (3.3)</td>
<td>0.3 (–0.6 to 1.3)</td>
</tr>
</tbody>
</table>

Joint angle measures in degrees presented as mean (SD).

* Significant at p < 0.05.

Greatest changes were seen in increased peak trunk flexion of 4.0° and decreased peak trunk extension of 3.0°. Significant increases in peak joint angle were also found for non-dominant ankle eversion (1.6°). Although not statistically significant, there was a trend toward significance for dominant ankle eversion (1.0°), dominant hip extension (2.7°), and non-dominant hip extension (1.8°). No significant increases were found for remaining trunk, hip, knee, or ankle kinematics. Examples of kinematic time series illustrating typical peak joint angle data during averaged stride cycle are presented in Fig. 1.

Core endurance measures are presented in Table 2. One participant experienced shoulder pain during the lateral musculature test and was subsequently excluded from corresponding correlational analysis (N: Table 2). No negative relations were found between post-fatigue changes in maximal trunk flexion, extension, lateral flexion, or rotation and core endurance tests. However, a significant positive relation was found between increased peak trunk flexion angle and extensor endurance ($r = 0.735, p = 0.001$), displaying a relation between larger kinematic changes and better core endurance. No significant positive relations were found between remaining post-fatigue kinematic changes and core endurance tests.

4. Discussion

In the current study, the primary hypothesis that running in a fatigued state would result in increased eversion and trunk flexion angles was confirmed. Greatest changes were seen for the trunk, displaying increased peak flexion and decreased peak extension, indicating an overall increase in trunk inclination during running. Increases in peak joint angle were found for ankle eversion in the non-dominant leg. A relatively large increase for bilateral hip extension was also found, although this was not statistically significant. The secondary hypothesis that kinematic changes would be more pronounced in runners with poor core endurance was not confirmed. On the contrary, a positive relation between kinematic changes and core endurance was found, raising questions with respect to the underlying mechanism.

The present study confirms the finding in previous studies utilizing similar running protocols, of an increase in eversion by running-induced fatigue and expands this finding to novice runners. As variables pertaining to our findings of increased trunk flexion were not analyzed in these other studies, comparison to existing literature is limited. The existing studies found increased tibial internal rotation, increased knee internal rotation, and decreased knee adduction with fatigue, however these results should be interpreted with caution due to potential measurement error involving soft-tissue artifact and landmark associated error related with analysis of these variables. In view of this inherent measurement error, these variables were not analyzed in the current study.

A number of explanations exist for the observed kinematic changes in the ankle and trunk. Increased ankle eversion, proposed as a contributing factor to running-related injury, has been linked to local fatigue of the ankle musculature during running. Although our finding of an average 1.3° increase in eversion is subtle, cumulative effects of these kinematic changes during repeated running may well be a contributing factor to injury. This increase in eversion over the course of the running trial indicates that runners may require additional pronation support when fatigued. The effects of fatigue may, therefore, be relevant when selecting appropriate running footwear.

Trunk kinematics have not yet been investigated using protocols simulating recreational running, however local fatigue of the.

Table 2
Core endurance measures.

<table>
<thead>
<tr>
<th>Core endurance test</th>
<th>Dominant</th>
<th></th>
<th>Non-dominant</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>Time to failure (SD)</td>
<td>N</td>
<td>Time to failure (SD)</td>
</tr>
<tr>
<td>Flexor endurose</td>
<td>17</td>
<td>118.4 (82.6)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Back extensor</td>
<td>17</td>
<td>114.3 (47.3)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Lateral musculature</td>
<td>17</td>
<td>59.8 (21.7)</td>
<td>16</td>
<td>57.9 (23.1)</td>
</tr>
<tr>
<td>Modified Trendelenburg</td>
<td>17</td>
<td>158.1 (61.1)</td>
<td>17</td>
<td>185.2 (71.8)</td>
</tr>
</tbody>
</table>

Endurance measures in seconds presented as mean (SD).

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paraspinal musculature has been shown to increase peak trunk flexion angle during running.\textsuperscript{15} Fatigued local trunk musculature may directly result in decreased ability to maintain upright posture during running. This explanation, however, is at odds with our finding that participants who displayed better core endurance exhibited larger trunk kinematic changes when fatigued. Our findings suggest that more complex relations between core endurance and running kinematics exist. Increased trunk flexion has been suggested to be a compensatory strategy related to shock attenuation during gait and drop jumping.\textsuperscript{24,25} Negative work at landing has been shown to be redistributed to more proximal and larger muscles during shock attenuation in jumping-induced fatigue.\textsuperscript{26} Additionally, positive work during push-off may be redistributed from calf muscles to hip extensor muscles with fatigue, as has been shown during increasing running speed\textsuperscript{27} and uphill running.\textsuperscript{28} Increased hip extension velocity with calf muscle fatigue, which would correspond with this explanation, has previously been reported.\textsuperscript{29} The tendency toward increased hip extension angles in the present study would thus correspond with this redistribution of joint power during propulsion. Better core endurance may allow for larger changes in trunk angle allowing trunk extensor and hip extensor muscles to contribute more to negative work in shock attenuation at landing as well as placing hip extensor muscles in a more favorable position to contribute to propulsion. Further research incorporating kinetic data and other fatigue measures is needed to determine if these more complex relations do, in fact, exist.

Another explanation for unexpected relations between core endurance and running kinematics may lie in the static nature of the measures performed. Static endurance measures were chosen since they are commonly used in practice. In a study involving dynamic endurance measures,\textsuperscript{12} it was shown that participants with better local hip endurance exhibited smaller changes in kinematic variables during running, namely stride length and hip extension, in contrast to our findings. Discrepancy of findings may, therefore, be due to differences in core measures taken between studies. It has also been suggested that strength, rather than endurance measures, may be more applicable to functional performance during high-speed events.\textsuperscript{14} Findings of improved running kinematics following a strength training program aimed at the hip musculature\textsuperscript{13} further support this. Dynamic endurance and/or strength measures of core muscles may, therefore, have exhibited expected relations in contrast with the static core endurance measures used. Further investigation is required to determine differences between these varying measures of core stability.

Although the running protocol was designed to simulate a novice runner’s typical running session, a number of limitations remained. Measures were taken while participants ran on a treadmill rather than solid ground, the latter being common for recreational running. While kinematic analysis between the two is comparable, issues such as external environment and adjustment of running patterns to treadmill running can continue to be an influential factor.\textsuperscript{30} Although potential measurement error was reduced as much as possible, it is important to consider that inherent measurement error exists in human movement analysis due to soft-tissue artifact and landmark associated error.\textsuperscript{22,23} In the current study, movement of surface markers observed visually and through analysis of data resulted in exclusion of data in a number of trials. However, possible smaller changes not identifiable during data analysis may have influenced results.

The current study analyzed the effects of running-induced fatigue on kinematic changes in the lower extremity as well as the trunk, the latter often overlooked in kinematic analysis. Recruiting inexperienced runners and utilizing a running protocol simulating recreational running makes the study’s findings applicable to novice runners, a population at increased risk for running-related injury.\textsuperscript{2,3} The kinematic changes found as a result of fatigue display potential predisposing factors for injury. Direct relations between running kinematics and predispositions to running-related injury require further investigation. Additionally, relations between running kinematics and core stability should be further investigated to determine if more complex relations exist and to what extent these relations impact performance and injury risk.

5. Conclusion

Novice runners displayed an overall increase in trunk inclination and increased ankle eversion peak angles when fatigued utilizing a running-induced fatigue protocol. As most pronounced changes were found for the trunk, trunk kinematics appear to be significantly affected during fatigued running and should not be overlooked. Core endurance measures displayed unexpected relations with changes in running kinematics and require further investigation to determine the significance of these relations.

Practical implications

- Increases in maximum peak eversion develop during running-induced fatigue and should be taken into consideration when choosing footwear.
- Increases in trunk inclination develop during running-induced fatigue and may affect loading and performance.
- Core endurance measures are related to changes in running kinematics with fatigue. This may support core endurance training in runners.

Conflict of interest

The authors declare that they have no conflict of interest.

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