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# Adaptations of Lumbar Biomechanics after Four Weeks of Running Training with Minimalist Footwear and Technique guidance: Implications for Running-Related Lower Back Pain

Szu-Ping Lee

*University of Nevada, Las Vegas*

Joshua P. Bailey

*University of Nevada, Las Vegas*

Jo Armour Smith

*Chapman University, [josmith@chapman.edu](mailto:josmith@chapman.edu)*

Stephanie Barton

*University of Nevada, Las Vegas*

David Brown

*University of Nevada, Las Vegas*

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# Adaptations of Lumbar Biomechanics after Four Weeks of Running Training with Minimalist Footwear and Technique guidance: Implications for Running-Related Lower Back Pain

## Comments

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## Authors

Szu-Ping Lee, Joshua P. Bailey, Jo Armour Smith, Stephanie Barton, David Brown, and Talia Joyce

ADAPTATIONS OF LUMBAR BIOMECHANICS AFTER A FOUR-WEEK RUNNING  
TRAINING WITH MINIMALIST FOOTWEAR AND TECHNIQUES:  
IMPLICATIONS FOR RUNNING-RELATED LOWER BACK PAIN

Szu-Ping Lee, PT, PhD<sup>1</sup>

Joshua P. Bailey, MS<sup>2</sup>

Jo Armour Smith, PT, PhD<sup>3</sup>

Stephanie Barton, DPT<sup>1</sup>

David Brown, DPT<sup>1</sup>

Talia Joyce, DPT<sup>1</sup>

<sup>1</sup>Department of Physical Therapy, University of Nevada, Las Vegas, Nevada, USA

<sup>2</sup>Department of Kinesiology & Nutritional Science, University of Nevada, Las Vegas, Nevada, USA

<sup>3</sup>Department of Physical Therapy, Chapman University, Orange, California, USA

Corresponding author:

Szu-Ping Lee, PT, PhD

Department of Physical Therapy, University of Nevada, Las Vegas

4505 S. Maryland Parkway, Box 453029, Las Vegas, NV 89154-3029, USA

Phone: (702)895-3086

Email: [szu-ping.lee@unlv.edu](mailto:szu-ping.lee@unlv.edu)

## Highlights (for review)

- A 4-week minimalist style running training was conducted in recreational runners.
- After training, runners exhibited reduced lumbar extension angle during stance.
- After training, runners exhibited reduced lumbar paraspinal muscle activation.
- Changes in lumbar kinematics and muscle activation transferred to normal running.
- No runner reported any adverse effect during the 4-week training.

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ADAPTATIONS OF LUMBAR BIOMECHANICS AFTER A FOUR-WEEK  
**RUNNING TRAINING WITH MINIMALIST FOOTWEAR AND TECHNIQUES:**  
IMPLICATIONS FOR RUNNING-RELATED LOWER BACK PAIN

## ABSTRACT

**Objectives:** To investigate the changes in lumbar kinematic and paraspinal muscle activation before, during, and after a 4-week minimalist running training.

**Design:** Prospective cohort study.

**Setting:** University research laboratory.

**Participants:** 17 habitually shod recreational runners who run 10-50 km per week.

**Main outcome measures:** During stance phases of running, sagittal lumbar kinematics was recorded using an electro-goniometer and activities of the lumbar paraspinal muscles were assessed with electromyography. Runners were asked to run at a prescribed speed (3.1m/s) and a self-selected speed.

**Results:** For the 3.1 m/s running speed, significant differences were found in the calculated mean lumbar posture ( $p=0.001$ ) during stance phase, specifically the runners ran with a more extended lumbar posture after minimalist running training. A significant reduction of the contralateral lumbar paraspinal muscle activation was also observed ( $p=0.039$ ). For the preferred running speed, similar findings of a more extended lumbar posture ( $p=0.002$ ) and a reduction in contralateral lumbar paraspinal muscle activation ( $p=0.047$ ) were observed.

**Conclusion:** A 4-week minimalist running training produced significant changes in lumbar biomechanics during running. Specifically, runners adopted a more extended lumbar posture and reduced lumbar paraspinal muscle activation. These findings may have clinical implications for treating individuals with running-related lower back pain.

**Key words:** running; lower back pain; kinematics; EMG

1       43    **Introduction**  
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4       44           Running is one of the fastest expanding participation segments of sports and  
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7       45    exercise. In the United States, It was estimated that 19 million people ran more than  
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9       46    100 times in 2011, a 9.3% increase from 2010.(NSGA, 2011) The number of marathon  
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11       47    finishers increased by more than 75.5% in the last decade.(Lamppa, 2014) However,  
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13       48    the drastic increases in the popularity of running are accompanied by an increase in the  
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15       49    number of injured runners. Nielsen et al. reported that over the course of one year,  
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17       50    23.1% of novice runners sustained running-related injuries to the lower extremity or  
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19       51    back.(Nielsen, et al., 2014) According to a 2013 survey of running event participants,  
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21       52    10.1% of the runners reported experiencing a running-related lower back injury within  
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23       53    the last 12 months.(Yoder, 2013) Walter et al. have shown injuries pertaining to the  
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25       54    back and pelvis account for approximately 25-35% of all running-related  
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27       55    injuries.(Walter, Hart, McIntosh, & Sutton, 1989) In addition, preliminary data showed  
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29       56    that running more than 20 miles per week can increase the odds of persistent LBP five-  
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31       57    fold.(Gonzalez, Akuthota, Min, & Sullivan, 2006)  
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39       58           The repetitive impact loading during running is a possible mechanism for  
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41       59    developing lower back structural changes and pain in runners.(Cavanagh & Lafortune,  
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43       60    1980; Dimitriadis, et al., 2011; Hamill, Gruber, & Derrick, 2014; Hamill, Moses, &  
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45       61    Seay, 2009) Dimitriadis et al. reported transient disc height reduction following 1 hour  
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47       62    of running measured using MRI in a static posture. Furthermore, the disc height  
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49       63    reduction was greatest in the lumbosacral region identifying a location of higher load  
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51       64    absorption.(Dimitriadis, et al., 2011) Garbutt et al. also observed that running speed is  
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53       65    positively related to the extent of stature shrinkage measured immediately after  
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55       66    running.(Garbutt, Boocock, Reilly, & Troup, 1990) While acute structural changes of  
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1 67 the spine are not directly indicative of pain, over time the mechanical stress associated  
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3 68 with running's repetitive loading can potentially lead to changes in spinal structure and  
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5 69 possibly overuse musculoskeletal symptoms including running-related lower back pain.  
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9 70 The recent interest in the body's natural ability to attenuate impact loads during  
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11 71 running has led to a resurgence of barefoot and minimalist style running as a means to  
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13 72 reduce the risk of running-related injuries.(Perkins, Hanney, & Rothschild, 2014; Rixe,  
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15 73 Gallo, & Silvis, 2012; Tam, Astephen Wilson, Noakes, & Tucker, 2014) This running  
16  
17 74 style typically focuses on running barefoot or wearing shoes with minimal heel  
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19 75 cushion. Due to the reduced impact attenuation of the footwear, the runners typically  
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21 76 adapt a change of foot strike pattern from rear to mid or forefoot and a reduction of  
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23 77 peak impact force. In essence, the proposed benefits from running with the minimalist  
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25 78 footwear were based on the theory that it promotes a movement pattern that is  
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27 79 conducive to lower shock loading during running.(De Wit, De Clercq, & Aerts, 2000;  
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29 80 Derrick & Mercer, 2004; Divert, Mornieux, Baur, Mayer, & Belli, 2005; Mercer,  
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31 81 Vance, Hreljac, & Hamill, 2002; Robbins & Hanna, 1987)  
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39 82 It has been postulated that the biomechanical adaptations (i.e. foot strike  
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41 83 pattern) associated with running barefoot or in minimalist footwear can lead to  
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43 84 kinematic changes in the lumbo-pelvic region. For example, Delgado et al. reported  
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45 85 decreased overall lumbar range of motion and peak leg impact measured via leg  
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47 86 acceleration following an acute foot strike pattern shift from the rearfoot to  
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49 87 forefoot.(Delgado, et al., 2013) However, this study had a number of important  
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51 88 limitations: first, the effects of foot strike pattern on lumbar range of motions were  
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53 89 examined in a single data collection session. The participants were acutely instructed to  
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55 90 run using specific foot strike patterns, which may or may not translate to a more  
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1 91 permanent movement pattern change. Second, the effect of minimalist running on  
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3 92 paraspinal muscle activation was not examined. Excessive paraspinal muscle activation  
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6 93 is hypothesized to contribute to increased lumbar spinal loading. Third, in practice, it  
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8 94 may be unrealistic and ill-advised to suggest drastic changes in foot strike and running  
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10 95 mechanics to injured or at-risk runners. It is clinically more meaningful to understand  
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12 96 the progression of responses in lumbar biomechanics to minimalist style running over a  
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15 97 longer duration of training.

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19 98 The purpose of this study was to investigate the effects of a 4-week running  
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21 99 training **transitioning runners to minimalist footwear and techniques** on the lumbar  
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23 100 kinematics and paraspinal muscle activation in habitually shod runners. We  
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25 101 hypothesized that the runners will exhibit a reduction of lumbar range of motion and  
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27 102 paraspinal muscle activation during the stance phase of running after training.  
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### 31 32 103 ***Methods***

#### 33 34 35 104 *Subjects*

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38 105 Seventeen volunteers from the local running population was recruited. This  
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40 106 sample size was determined *a priori* based on a previous investigation on how change  
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42 107 of foot strike pattern affects lumbar posture.(Delgado, et al., 2013) To achieve an 80%  
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44 108 power, with  $\alpha$  level of 0.05, we calculated a sample size of 13 is needed to detect a  
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46 109 difference in a repeated measures study design. Additional 4 subjects were recruited to  
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48 110 account for potential attrition. The participants were included if they were: 1) age 18-45  
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50 111 years (Kienbacher, et al., 2015), 2) current recreational runners who run between 10-50  
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52 112 km during a typical week, and 3) habitual shod runners. Participants were excluded  
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54 113 from the study if they exhibited any of the following: previous experience with  
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1 114 minimalist or barefoot running, any orthopedic surgeries that permanently change the  
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3 115 musculoskeletal structure of the lower extremity and spine (i.e. joint replacement,  
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6 116 spinal surgery, etc.), any injuries or conditions within the last 8 weeks that prevented  
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8 117 their normal running training. Two participants dropped out of the study due to an  
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10 118 unrelated injury and a personal reason, resulting in 8 male and 7 female participants  
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12 119 who completed the 4-week training program (Table 1).  
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16 **TABLE 1.** Demographic, anthropometric and running characteristics of the participants  
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	<b>Mean ± SD</b>
Age	24.7 ± 2.6 years
Body mass	70.4 ± 12.7 kg
Height	1.72 ± 0.09 m
Body Mass Index	23.9 ± 2.7 kg/m <sup>2</sup>
Sex	7 female, 8 male
Running Training Distance	
Typical week	17.3 ± 5.5 km
Week Prior to Intervention	13.4 ± 7.3 km
Typical Run	5.4 ± 1.8 km

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51 122 Prior to participation, the objectives, procedures, risks of the study, and rights of  
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53 123 the participant were explained to each participant, and an informed consent approved  
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56 124 by the **Institution Review Board of XXX University** was signed by each participant.  
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1 125 Instrumentation

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4 126 All testing was done with the participants running on a treadmill (PrecorC956;  
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7 127 Woodinville, WA, USA). Lumbar sagittal range of motion was captured using an  
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9 128 electrogoniometer (SG150/B Series; Biometrics Ltd., Newport, UK) connected to a  
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11 129 wireless transceiver (Delsys Trigno Biaxial Goniometer Adapter; Delsys Inc., Natick,  
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13 130 MA, USA). The center of the electrogoniometer was positioned over the spinous  
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15 131 processes of the 3<sup>rd</sup> lumbar vertebrae. Sagittal plane lumbar range of motion was  
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17 132 captured at 2000 Hz. Electromyography (EMG) signals of the paraspinal muscles were  
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19 133 captured using a wireless surface EMG system (Trigno Wireless System; Delsys Inc.,  
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21 134 Natick, MA, USA). Sampling frequency of the EMG signal was 2000 Hz.  
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27 135 EMG preparation consisted of shaving the location to remove any hair,  
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29 136 cleansing the site with an alcohol swab, and abrading the site with a rough, dry paper  
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31 137 towel until the skin becomes flush in color. The EMG sensors were attached using  
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33 138 double-side tape. Pairs of surface EMG sensors were placed bilaterally over the  
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35 139 palpated lumbar paraspinal muscle bellies approximately 2-5 cm from the spinous  
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37 140 process of the 3<sup>rd</sup> lumbar vertebrae. The electrodes were placed in parallel with the  
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39 141 fiber direction of the lumbar paraspinal muscle in accordance to the established surface  
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41 142 EMG protocol (Merletti, Rau, Disselhorst-Klug, Stegeman, & Hagg, 2016; Zipp, 1982)  
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47 143 Foot strike incidents were monitored using 2 thin film pressure sensors (Model  
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49 144 402; Interlink Electronics Inc. Camarillo, CA, USA) placed inside of the shoes  
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51 145 connected through a Delsys wireless transceiver (Delsys Trigno 4-Channel FSR  
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53 146 Sensor). The sensors were attached to the bottom of the foot. The pressure sensor was  
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55 147 round and 12.7 mm in diameter with a thickness of 0.45 mm. Foot pressure data was  
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1 148 sampled at 2000 Hz for the rearfoot and 148 Hz for the forefoot. The difference in  
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4 149 sampling frequency was due to a hardware limitation. Since the duration of a stance  
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6 150 phase when running at the speeds used in this study (2.8-3.5 m/s) was observed to be  
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8 151 350-500 ms, we determined that the 148 Hz sampling frequency for the forefoot  
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10 152 pressure sensor would still provide sufficient temporal resolution (6.76 ms) to identify  
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12 153 the instant of toe-off with high degree of accuracy. EMG, lumbar kinematics, and foot  
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14 154 strike pressure data were time-synchronized through a trigger module (Delsys Trigger  
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16 155 Module; Delsys Inc., Natick, MA) to a motion capturing computer (Nexus 1.8, Vicon  
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18 156 Motion Systems Ltd., Oxford, UK).

#### 23 24 157 Procedure

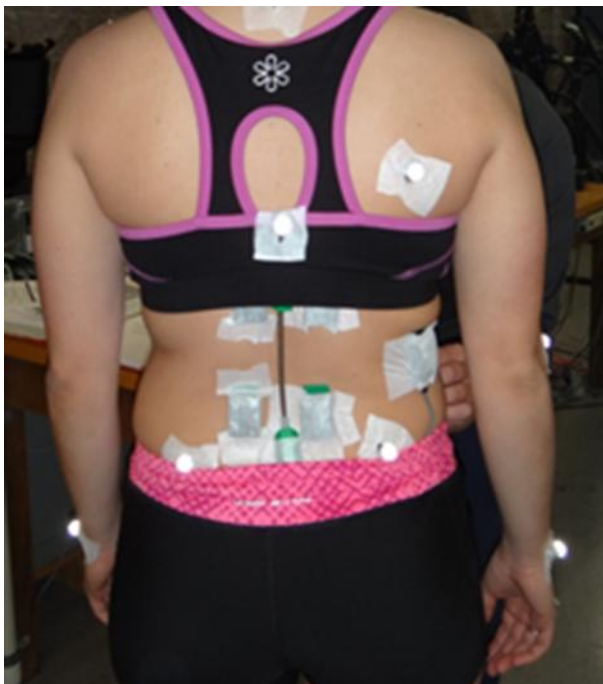
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27 158 Each participant was tested in 3 sessions (PRE, MID, POST); the PRE session  
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29 159 was conducted on the day prior to the beginning of the 4-week training program; the  
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31 160 MID was at the 2-week point; the POST assessment was completed at the end of the  
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33 161 training (4-week). During each session, the testing began by measuring the runner's  
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35 162 height and weight, followed by instrumentation.

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38 163 Maximal voluntary isometric contraction (MVIC) of back extension was  
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40 164 conducted with the subject in a prone position. The MVIC amplitude of the lumbar  
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42 165 paraspinal muscles was used to normalize the muscle activation level. The subject was  
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44 166 secured to a treatment table using straps. The tightness of the straps was adjusted to  
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46 167 elicit a neutral (lack of hyperextension) alignment during the back extension against the  
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48 168 strap. Two investigators provided additional stabilization of the legs as the participant  
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50 169 performed two 5-second MVIC trials.

1 170 Following the MVIC trials, the goniometer was attached to the participant in a  
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4 171 relaxed standing posture (Figure 1). The lumbar flexion/extension angle in this resting  
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6 172 standing position was defined as neutral (0°). The electrogoniometry procedure was  
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8 173 established in a prior study.(Delgado, et al., 2013) The two pressure switch sensors  
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11 174 were attached to the plantar surface of the foot of the dominant leg (defined as the  
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13 175 preferred leg to kick a ball with).  
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20 177 **FIGURE 1.** Placement of the EMG electrodes and the electrogoniometer  
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51 180 *Biomechanical Testing*  
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54 181 The testing began with a warm-up in which the participants walked on the  
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57 182 treadmill at 1.33 m/s for 1 minute, the speed increased 0.22 m/s at the end of every  
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1 183 minute until the runner reached the prescribed running speeds. If the runner reported  
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3 184 discomfort during this period, the investigators stopped to make necessary adjustments  
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6 185 before the runner resumed the warm-up.  
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9 186 During all running trials, the participant wore his or her own running shoes. The  
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11 187 participant ran at two speeds: a control speed of 3.1 m/s and a self-selected running  
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14 188 speed. For the preferred speed, the participant was blinded to the treadmill display and  
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16 189 an investigator changed the speed according to the runner's indication. Runners were  
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19 190 instructed to select a speed that felt close to their typical running training speed. Three  
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21 191 20-second trials were collected at each speed.  
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25 192 After the first running data collection session (PRE), participant was fitted with  
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27 193 a pair of standardized minimalist running shoes (Brooks® PureDrift; Brooks Sports,  
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29 194 Inc., Seattle, WA, USA). The sock liner of the shoes was removed as specified by the  
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31 195 manufacturer to nullify the heel-to-toe offset. After the shoe fitting, an investigator  
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34 196 explained the training program, which the runner was to adhere to for the next 4 weeks.  
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38 197 Minimalist Running Training Protocol  
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41 198 The participants were instructed to begin by running 10% of their normal  
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43 199 running mileage in the minimalist shoes. Every 2 weeks the participants would increase  
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46 200 the running distance wearing the minimalist shoes by no more than 10-20% of their  
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48 201 total running distance. This was intended to allow the runners to safely do 30-50% of  
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51 202 their running in the minimalist shoes by the end of week 4. This program was designed  
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53 203 based on the recommendation that minimalist shoe running should be gradually  
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55 204 incorporated into a person's normal running regimen to allow the body structures to  
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58 205 adapt to the different mechanical stressors.(Robillard, 2010, 2012)  
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1 206 Each participant was given general instructions on minimalist running  
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4 207 techniques including maintaining relaxed shoulders, trunk, and a slight bend at the knee  
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6 208 throughout the running stride.(Robillard, 2010, 2012) The runners were also  
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8 209 recommended to try to land upon the forefoot as gently as possible. However, no  
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11 210 explicit feedback regarding each runner's running form was given during any of the  
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13 211 data collection sessions. This was done to simulate a common self-initiated transition to  
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15 212 the minimalist running shoes which is typically done with little external feedback or  
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18 213 guidance.

21 214 The runners were asked to keep a running log, including the time of each run,  
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23 215 the distance, and which shoes (normal or minimalist) they wore for the run. Each  
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25 216 participant was asked to record all of this information in their training log every day for  
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27  
28 217 4 weeks. The runners were asked not to change their normal training mileage.  
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31 218 Participants were advised to wear only their normal running shoes or the minimalist  
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33 219 shoes provided and not changing to different shoes during the 4-week  
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36 220 period. Participants were also instructed to perform a schedule of exercise drills  
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38 221 including: the Marble Drill, Jump Drill, and Walk in Place as typically suggested to  
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41 222 increase the strength of the feet (Table 2).

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228 **TABLE 2.** Weekly progression of the minimalist style running training  
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	Percentage mileage recommended to run in minimalist footwear	Recommended exercise drills to perform
Week 1	10%	Walk in Place 2x/day Marble drill 1x/day
Week 2	20%	Jump drill 2x/day Walk in Place 2x/day Marble drill 1x/day
Week 3	20%-30%	Jump drill 3x/day Walk in Place 2x/day Marble drill 1x/day
Week 4	≥30%	Jump drill 3x/day Walk in Place 2x/day Marble drill 1x/day

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231 In the subsequent testing sessions (MID and POST), the weekly training logs  
 232 were reviewed. An exit questionnaire was given to each participant after the last testing  
 233 session (POST). The main question was whether they encounter any pain or injury  
 234 during the training.

235 Data Analysis

236 Changes in running distances wearing the normal and minimalist shoes over the  
 237 4-week training period were analyzed. The preferred running speeds in the two types of  
 238 shoes during the 3 testing sessions were recorded. Lumbar kinematics and muscle  
 239 activation data were computed during the stance phase of the dominant leg during the  
 240 running trials. The stance phases were identified with the aid of the foot pressure sensor



1 241 data; specifically from the initial foot contact to when the forefoot lost contact with the  
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4 242 running surface.  
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7 243 For lumbar kinematics, mean sagittal lumbar posture, peak lumbar flexion, peak  
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9 244 lumbar extension, and lumbar range of motion were computed. The mean sagittal  
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11 245 lumbar posture was the time-averaged lumbar posture during the stance phase; a  
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13 246 positive angular value indicates lumbar flexion. Mean lumbar muscle activation during  
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15 247 the stance phase was computed for both the contralateral and the ipsilateral paraspinal  
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17 248 muscles. The EMG signals from the lumbar paraspinal muscles were first filtered with  
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19 249 a 2<sup>nd</sup> order Butterworth band-pass filter (cut-off frequencies: 35-500 Hz) then full-wave  
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21 250 rectified. The mean muscle activation magnitudes were normalized to the highest 500  
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23 251 millisecond average activation magnitude obtained during the MVIC trials, and  
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25 252 reported as percentages of the MVIC. This duration was chosen to correspond with the  
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27 253 approximate duration of the stance phase (350-500 ms) for the running speeds used in  
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29 254 this study. For each running trial, 10 stance phases were identified; the lumbar  
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31 255 kinematic and muscle activation magnitude variables were obtained by averaging over  
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33 256 the 10 stance phases from each trial. The average values from 3 running trials for each  
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35 257 subject were used for statistical analysis.  
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#### 44 258 Statistical Analysis

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47 259 One-way repeated measures ANOVA tests were used to compare the  
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49 260 participants' preferred running speeds, lumbar kinematic, and muscle activation  
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51 261 variables during the 4-week training program (PRE, MID, and POST). Biomechanical  
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53 262 data obtained from the 3.1 m/s and the preferred running speeds were analyzed  
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55 263 separately. Post-hoc comparisons with Bonferroni correction were conducted when the  
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264 main effect was significant. All statistical procedures were conducted using SPSS®  
 265 22.0 (International Business Machines Corp. New York, USA). Significance level was  
 266 set at 0.05.

267 Results

268 The reported weekly mileage per footwear condition during the 4-week protocol  
 269 is presented in Table 3. The percentage of total running distance in the minimalist shoes  
 270 gradually increased from 18.8% to 54.9% during the 4 weeks. A significant difference  
 271 was detected in the preferred running speed ( $p=0.007$ ) that at the MID the preferred  
 272 running speed was significantly slower than at PRE (PRE vs. MID,  $3.25\pm 0.33$  vs.  
 273  $3.13\pm 0.31$  m/s,  $p=0.016$ ). No other differences in running speed were detected.

274

275 **TABLE 3.** Recorded weekly distance ran by participants in minimalist and their  
 276 normal running shoes.

	Week 1	Week 2	Week 3	Week 4
<b>Running Distance (km)</b>				
Total in minimalist shoes	$3.6 \pm 3.4$	$4.2 \pm 2.2$	$7.1 \pm 2.9$	$7.8 \pm 4.0$
Average per run in minimalist shoes	$2.6 \pm 2.0$	$3.8 \pm 2.0$	$4.3 \pm 1.4$	$4.7 \pm 1.5$
Total in normal shoes	$14.5 \pm 7.4$	$12.5 \pm 6.4$	$9.8 \pm 6.3$	$6.4 \pm 3.8$
Average per run in normal shoes	$6.3 \pm 2.5$	$5.4 \pm 2.1$	$5.8 \pm 4.8$	$5.1 \pm 3.6$
% of total distance in minimalist shoes	18.8%	31.3%	42.1%	54.9%

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1 278 During the prescribed 3.1 m/s running speed, significant differences were  
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4 279 detected in mean lumbar posture, peak flexion, peak extension, and contralateral  
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6 280 paraspinal muscle activation between the 3 testing sessions (Table 4). Post-hoc  
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8 281 comparisons showed that the mean lumbar posture was significantly less flexed when  
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10 282 compared to before training (PRE vs. POST,  $1.9 \pm 15.3^\circ$  vs.  $-6.0 \pm 13.3^\circ$ ,  $p=0.001$ ). Peak  
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12 283 lumbar flexion angle was significantly lower after training (PRE vs. POST,  $8.6 \pm 15.7^\circ$   
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14 vs.  $-0.3 \pm 13.7^\circ$ ,  $p<0.001$ ; MID vs. POST,  $7.6 \pm 15.1^\circ$  vs.  $-0.3 \pm 13.7^\circ$ ,  $p=0.001$ ). Peak  
15 284  
16 lumbar extension angle increased significantly after training (PRE vs. POST,  $4.8 \pm 14.3^\circ$   
17 285  
18 vs.  $6.7 \pm 11.8^\circ$ ,  $p<0.001$ ; MID vs. POST,  $6.7 \pm 11.8^\circ$  vs.  $12.6 \pm 12.4^\circ$ ,  $p=0.033$ ). There was  
19 286  
20 no significant change in the overall lumbar range of motion before, during, and after  
21 287  
22 training. The contralateral lumbar paraspinal muscle activation significantly differed  
23 288  
24 among the 3 time points. Post-hoc comparison showed that there was a significant  
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26 reduction of muscle activation after two weeks of training (PRE vs. MID,  $47.0 \pm 34.0\%$   
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28 vs.  $24.9 \pm 8.2\%$ ,  $p=0.049$ ). No significant difference in muscle activation was observed  
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30 in the ipsilateral paraspinal muscle.  
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299 **TABLE 4.** Comparison of lumbar kinematic and paraspinal muscle activation pre, mid,  
 300 and post the 4-week training.

	3.1 m/s running speed				Preferred running speed			
	PRE	MID	POST	<i>p</i> value	PRE	MID	POST	<i>p</i> value
Mean lumbar posture (degree)	1.9 ± 15.3	0.4 ± 13.0	-6.0 ± 13.3*	0.001	2.3 ± 15.5	0.9 ± 13.9	-5.7 ± 14.2*	0.002
Peak lumbar flexion (degree)	8.6 ± 15.7	7.6 ± 15.1	-0.3 ± 13.7*†	<0.001	9.1 ± 16.3	8.0 ± 15.4	-0.3 ± 14.7*†	<0.001
Peak lumbar extension (degree)	4.8 ± 14.3	6.7 ± 11.8	12.6 ± 12.4*†	0.005	4.4 ± 14.7	6.7 ± 12.5	12.4 ± 13.5*†	0.007
Overall lumbar ROM (degree)	13.3 ± 2.4	14.3 ± 6.1	12.3 ± 4.4	0.496	13.5 ± 2.4	14.7 ± 6.0	12.1 ± 4.6	0.325
Contralateral lumbar muscle activation (% of MVIC)	47.0 ± 34.0	24.9 ± 8.2*	29.4 ± 11.3	0.039	41.6 ± 28.6	23.4 ± 6.2	30.3 ± 11.6	0.047
Ipsilateral lumbar muscle activation (% of MVIC)	26.5 ± 15.8	17.0 ± 4.1	25.5 ± 17.2	0.225	28.8 ± 22.5	16.7 ± 3.8	25.9 ± 17.8	0.262

\*indicates a significant difference from PRE condition.

†indicates a significant difference from the MID condition.

For the preferred running speed, significant differences were detected in mean lumbar posture, peak lumbar flexion, peak lumbar extension, and contralateral paraspinal lumbar muscle activation between the 3 testing sessions (Table 4). Post-hoc comparisons showed that the mean lumbar posture was significantly less flexed when compared to before training (PRE vs. POST, 2.3±15.5° vs. -5.7±14.2°, p=0.002). Peak lumbar flexion angle was significantly lower after training (PRE vs. POST, 9.1±16.3°

1 310 vs.  $-0.3 \pm 14.7^\circ$ ,  $p < 0.001$ ). The peak lumbar extension angle increased significantly after  
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4 311 training (PRE vs. POST,  $4.4 \pm 14.7^\circ$  vs.  $12.4 \pm 13.5^\circ$ ,  $p < 0.001$ ; MID vs. POST,  $6.7 \pm 12.5^\circ$   
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6 312 vs.  $12.4 \pm 13.5^\circ$ ,  $p = 0.046$ ). There was no significant change in the overall lumbar range  
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8 313 of motion before, during, and after the training. The contralateral lumbar paraspinal  
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10 314 muscle activation significantly differed among the 3 time points. The post-hoc  
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12 315 comparison detected a trend of reduction in contralateral paraspinal muscle activation  
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14 316 after two weeks of training (PRE vs. MID,  $41.6 \pm 28.6\%$  vs.  $23.4 \pm 6.2\%$ ,  $p = 0.072$ ). No  
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16 317 significant difference in muscle activation was observed in the ipsilateral paraspinal  
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18 318 muscle.  
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## 24 319 Discussion

27 320 Biomechanical evaluations aimed at identifying risk factors, prevention, and  
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29 321 treatment strategies pertinent to running-related injuries have traditionally focused on  
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31 322 the more common injuries such as knee pain and tendinopathy. In comparison, research  
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33 323 regarding the biomechanics of lumbar spine during running is lacking. This is an  
34  
35 324 important void in the current knowledge base that needs to be addressed, because lower  
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37 325 back dysfunctions are relatively common in distance runners.(Gonzalez, et al., 2006;  
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39 326 Walter, et al., 1989; Yoder, 2013) Also, preliminary evidence suggested that  
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41 327 dysfunction or weakness of the lumbar-pelvis-hip musculoskeletal complex can lead to  
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43 328 injuries in other parts of the body.(Brumitt, 2011; Hammill, Beazell, & Hart, 2008)  
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49 329 Our primary finding was that the runners gradually adopted a more extended  
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51 330 lumbar posture over the 4 weeks of training. During running, lumbar flexion has been  
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53 331 shown to dominate the initial loading phase of stance followed by more extension from  
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55 332 midstance to toe-off.(Saunders, Schache, Rath, & Hodges, 2005; Schache, Blanch,  
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57 333 Rath, Wrigley, & Bennell, 2002; Schache, Blanch, Rath, Wrigley, & Bennell, 2005;  
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1 334 Schache, et al., 2001) Lumbar flexion during the initial loading phase is thought to aid  
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4 335 in the attenuation of the impact forces.

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6 336 In order to provide effective intervention to runners with running-related lower  
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8 337 back pain, it is important to establish how different running styles may affect spinal  
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10 338 mechanics. Changes in lumbar kinematics in response to foot strike pattern during  
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12 339 running were first reported by Delgado et al.(Delgado, et al., 2013) The authors  
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14 340 reported a small reduction (from 22.1 to 20.9°) in overall lumbar range of motion after  
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16 341 acute changes of foot strike pattern. Contrary to their findings, we observed no changes  
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18 342 in the lumbar range of motion, but an overall tendency of most runners adopting a more  
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20 343 extended lumbar posture after **running training with minimalist footwear and technique**  
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22 344 **instruction.** Specifically, the runners in our study generally exhibited a gradual  
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24 345 reduction in peak lumbar flexion angle over the course of the training (Figure 2). The  
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26 346 discrepancy in the results perhaps stemmed from the different methodology. In the  
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28 347 previous study the peak lumbar spinal angles were recorded over combined swing and  
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30 348 stance phases, while in this study we focused on the stance phase. Also, we did not  
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32 349 explicitly instruct the runners on the foot strike location during the running trials, but  
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34 350 allowed the runners to naturally adapt to running with the minimalist footwear over  
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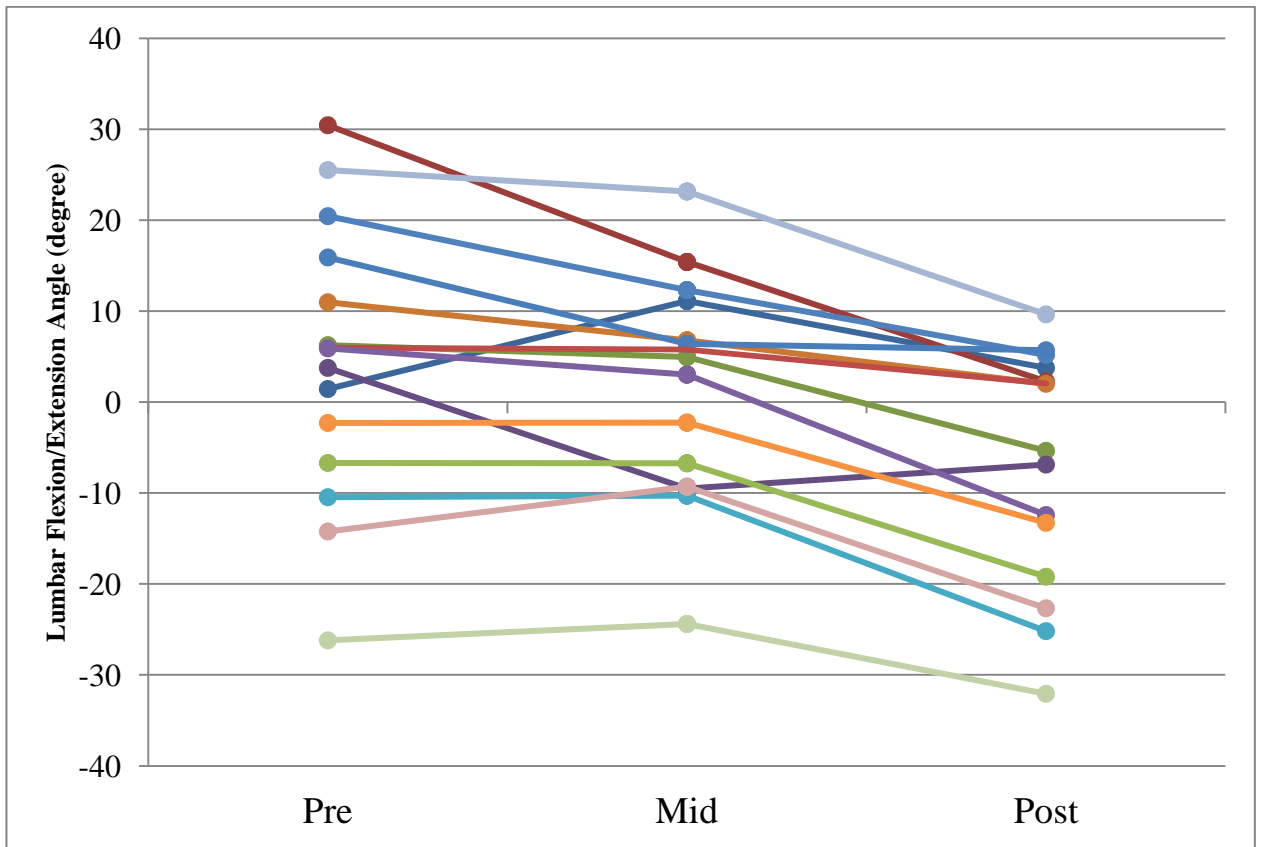
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358 **FIGURE 2.** Changes of mean lumbar posture during the stance phase of running for  
 359 each participant Pre, Mid, and Post the 4-week training



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362 The observed more upright running posture after training was accompanied by  
 363 reduced contralateral paraspinal muscle activation. Previous studies have shown that  
 364 the greatest activation of the lumbar paraspinal muscle group occurs during forward  
 365 trunk flexion and is reduced during extension.(Kienbacher, et al., 2015) The observed  
 366 reduction in the contralateral muscle activation during stance is compatible with the  
 367 reduced need to stabilize the lumbar spine against gravity in the more upright posture  
 368 and the potential reduction of impact shock after training.

369 Appropriate muscle activation during running facilitates adequate coordination  
 370 between the lumbar spine, pelvis and hip complex, helps to stabilize the spine in

1 371 response to the ground reaction force during the stance phase of running. However,  
2  
3 372 excessive lumbar paraspinal muscle activation may be a sign of dysfunction, and the  
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5 373 increased muscular force can lead to increased loading on the spine. Previous EMG  
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7 374 studies of lumbar muscle activation demonstrated that during locomotion, patients with  
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9 375 LBP showed continuous activation in contrast to the more phasic activation pattern  
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11 376 observed in those without LBP.(Kuriyama & Ito, 2005; van der Hulst, et al., 2010) This  
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13 377 indicates that patients with LBP exhibit altered paraspinal muscle activation patterns,  
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15 378 perhaps as a guarding response that also increases the stiffness of the spine. Such  
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17 379 increased loading from the paraspinal muscle contraction may also be related to the  
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19 380 chronic back pain symptoms and interferes with recovery. While we could not  
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21 381 definitively imply the observed reduction of paraspinal muscle activation as beneficial,  
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23 382 it is possible that such change can be clinically meaningful. Future intervention study  
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25 383 on runners with running-related lower back pain is needed to investigate the clinical  
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27 384 utility of minimalist running for treating this condition.

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29 385         Fifteen out of 17 runners were able to complete the training, and none of them  
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31 386 reported any running-related injuries during the training period. Our 4-week training  
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33 387 intervention protocol was designed around a gradual progression of runners' weekly  
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35 388 training mileage in the minimalist shoes. Some previous study protocols were longer at  
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37 389 10-12 weeks.(Miller, Whitcome, Lieberman, Norton, & Dyer, 2014; Ridge, et al.,  
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39 390 2013) The extended durations in those studies were necessary for identifying  
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41 391 musculoskeletal structural adaptations to the adjusted stress from the altered running  
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43 392 pattern. On the other hand, the focus of the current study was to identify movement  
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45 393 pattern adjustments rather than structural adaptations. Furthermore, the end point of our  
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1 394 program was to allow the runners to incorporate minimalist footwear running into only  
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4 395 30-50% of their total weekly mileage and not a full conversion.  
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6 396 In the current study, the minimalist running training was designed as a  
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8 397 supplement to the runner's typical running routine with the inclusion of footwear  
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10 398 variability, postural cues and strengthening exercises. In other words, the minimalist  
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12 399 style running was used as an exercise drill to induce changes in running movement  
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14 400 pattern, which we observed to be transferrable to the runners' normal shod running.  
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16 401 This could imply that some learning occurred due to the running training used in this  
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18 402 study. We believe that this finding is clinically important as it is often unrealistic to ask  
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20 403 a runner to completely shift to a different running style or footwear. In fact, results  
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22 404 from a number of previous studies have shown that even successful complete transition  
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24 405 to minimalist running can induce potential damage to the foot and lower  
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26 406 extremity.(Ridge, et al., 2013; Ryan, Elashi, Newsham-West, & Taunton, 2014) While  
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28 407 researchers and clinicians continue to debate about the benefits and injury risks  
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30 408 associated with minimalist running,(Jenkins & Cauthon, 2011; Perkins, et al., 2014) it  
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32 409 is likely safer to utilize the minimalist style running as a supplemental training to  
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34 410 induce beneficial movement pattern changes and not to emphasize a complete  
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36 411 transition.  
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45 412 This study has a number of limitations. The biomechanical testing was done on  
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47 413 a treadmill, which may not reflect the activities of the lumbar spine and paraspinal  
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49 414 muscle during overground running as the treadmill afforded some cushioning. Also,  
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51 415 direct measurement of ground reaction force was not done. Since foot strike impact  
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53 416 attenuation has been proposed as an important factor to running-related lower back  
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55 417 dysfunctions,(Hamill, et al., 2009) future studies should examined the ground reaction  
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1 418 impact attenuation and energy absorption of the lower extremity and spinal joints.  
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3 419 While surface EMG provide a reliable method of quantifying trunk muscle activity  
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5 420 during running locomotion,(Smoliga, Myers, Redfern, & Lephart, 2010) they are  
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7 421 unable to differentiate between activity in the different depth of muscles that comprise  
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9 422 the lumbar paraspinal group.(Stokes, Henry, & Single, 2003) Lastly, it is important to  
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11 423 recognize that individual response to training differs. A recent study has shown that  
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13 424 only certain runners respond to barefoot running training in a manner consistent with  
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15 425 injury prevention.(Tam, Tucker, & Astephen Wilson, 2016) Future research should  
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17 426 focus on the feasibility and the clinical benefits of minimalist style running in clinical  
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19 427 populations.  
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#### 26 428 Conclusion

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29 429 Our results demonstrated that a 4-week running training with minimalist  
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31 430 footwear and techniques instruction can induce significance changes to lumbar spine  
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33 431 biomechanics during running. Specifically, the participants ran with a less flexed, and  
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35 432 more upright lumbar posture after training. Correspondingly, we observed a trend of  
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37 433 reduction of the contralateral lumbar paraspinal muscle activation. These effects were  
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39 434 observed when the runners ran wearing their regular running footwear. Our findings  
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41 435 demonstrated that including minimalist style running into a runners' training may  
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43 436 induce beneficial changes to the lumbar kinematics and paraspinal muscle activation  
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45 437 during their normal shod running.  
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