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Original article

Effects of 12 weeks of barefoot running on foot strike patterns, inversion−eversion and foot rotation in long-distance runners

Pedro A. Latorre-Román [a], Felipe García-Pinillos [a], Víctor M. Soto-Hermoso [b], Marcos Muñoz-Jiménez [a,*]

[a] *Department of Didactics of Corporal Expression, University of Jaén, Jaén 23071, Spain*
[b] *Department of Sports Sciences, University of Granada, Granada 18071, Spain*

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Abstract

Purpose: The purpose of this study was to determine the effects of 12 weeks of barefoot running on foot strike patterns, inversion−eversion and foot rotation in long-distance runners.
Methods: Thirty-one endurance runners with no experience in barefoot running were randomized into a control group and an experimental group who received barefoot training. At pre-test and post-test, all subjects ran at low and high self-selected speeds on a treadmill. Data were collected by systematic observation of lateral and back recordings at 240 Hz.
Results: McNemar's test indicated significant changes ($p < 0.05$) in the experimental group at both high and low speed running in foot strike patterns, reducing the percentage of high rearfoot strikers and increasing the number of midfoot strikers. A significant increase ($p < 0.05$) of external rotation of the foot and a decrease of inversion occurred at comfortable speed in the experimental group.
Conclusion: Twelve weeks of barefoot running, applied progressively, causes significant changes in foot strike pattern with a tendency toward midfoot or forefoot strikes, regardless of running speed and significant changes in foot rotation at low speed, while the inversion was reduced in left foot at low speed with a tendency toward centered strike.

Keywords: Endurance; Footwear; Kinematics; Training; Unshod

1. Introduction

Barefoot running has become very popular in recent years and remains a hotly debated topic among runners. Many coaches consider barefoot training to have an effect on muscle strength and to be important for performance and for preventing injuries.[1] Transitioning from shod to unshod or minimalist shoes is only described by a few studies and footwear manufacturers as a way to prevent injuries.[2]

The debate about the pros and cons of barefoot running is current. Eslami et al.[3] suggested variations that increase the risk of injury and they found significant variations in forefoot adduction/abduction and rearfoot eversion patterns. For their part, Sinclair et al.[4] found that barefoot running and minimalist running increased rearfoot eversion and tibial internal rotation. In contrast, some authors, such as Lieberman et al.,[5] advocated the benefits of barefoot running and suggested that barefoot runners with forefoot strike (FFS) have an impact force on the ground 3 times lower than barefoot and shod runners with rearfoot strikes (RFS). Squadrone and Gallozzi[6] also suggested that barefoot runners experienced significantly lower local peak pressure in the midfoot and heel when unshod. Transitioning RFS to FFS may reduce patellofemoral pain[7] and pain associated with anterior chronic compartment syndrome of effort.[8] At this point, it would be interesting to transition runner's foot strike pattern (FSP) from RFS to midfoot strike (MFS) or FFS.[9]

Tam et al.[10] indicated that an unexplored area of the theory of barefoot running is the process in which biomechanical adaptations occur and if these are universally learned. Despite this, only few researchers have documented the period of change for a group of inexperienced barefoot or minimalist runners and its effects on FSP, inversion−eversion or foot rotation variables.[11−15]

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* Corresponding author.
E-mail address: mmj00006@red.ujaen.es (M. Muñoz-Jiménez).

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The study by Utz-Meagher et al.[15] showed significant results of reduction of total peak force and lower foot angles at foot strike with only 2 weeks of barefoot training. There was a significant need for research regarding adaptation of FSP after specific barefoot training. Although several researchers have identified significant related changes, such as those connected with minimalist footwear,[15,16] the time used seems to be insufficient for verifying long-term changes or changes in barefoot running (without any type of shoes). It remains to be determined how training based on barefoot running can help modify the traditionally shod runners' strike toward MFS or FFS. Studying the difference in FSP, inversion−eversion and foot rotation following a sufficiently lengthy controlled and progressive barefoot running training program could enhance our knowledge.

In light of the above information, the main objective of this study was to determine what changes in foot strike, inversion−eversion and foot rotation are produced after a 12-week program of barefoot running with progressive volume at the end of the athlete's daily training session.

2. Materials and methods

2.1. Subjects

Thirty-nine recreational athletes from 3 different athletics clubs in Spain (Table 1) were randomly placed in either an experimental group (EG, $n = 20$) or a control group (CG, $n = 19$) and participated voluntarily in this study. The inclusion criteria were: (1) participants were shod runners with no experience of barefoot running; (2) no injuries in the past 3 months and no damage or pain that may interfere with the proper monitoring of the training protocol without shoes; and (3) a minimum sport level (participated in regional or national athletics championships in the past 4 years). Each participant signed an informed consent to take part in this study. There were only 2 athletes of the EG who left the program; in the CG, 6 athletes left, all for personal reasons. The study was conducted in adherence with the standards of the Declaration of Helsinki[17] and following the European Community guidelines for Good Clinical Practice,[18] as well as the Spanish legal framework for clinical research on humans.[19] The Bioethics Committee of the University of Jaén (Spain) approved the study and process of informed consent.

2.2. Procedures

Participants were asked to run consistently at their comfortable training speed, denoted as low speed (LS), and their competition running speed as high speed (HS), as chosen by themselves,[20] on a mechanical treadmill (Salter E-Line PT-320; Salter International, Barcelona, Spain). Participants did not perform any heavy physical exertion for 72 h prior to data collection. Tests were performed with the subjects' usual training shoes to attain their most typical performance. Before beginning the tests, the subjects were given 8 min to habituate to the treadmill and to determine their training or competition speed. A period of 8 min was chosen because previous studies on human locomotion have shown that accommodation to a new condition occurs within this period.[21,22] The 10-min period following this warm-up was recorded for data collection. Four steps were analyzed for each runner at all conditions (LS and HS). Participants were instructed to run continuously without stops in each trial. Once the participants had confirmed their comfortable running speed, the main researcher recorded the speed displayed on the treadmill screen (average = 10.58 ± 2.01 km/h). The subjects then increased the speed to their competition running pace and once this was successfully reached, the researcher recorded the athletes' HS (average = 16.51 ± 3.51 km/h). In the post-test, athletes repeated the tests at the same paces that were recorded in the pre-test.

Table 1
Sociodemographic data of participants in this study (mean ± SD).

	Control group	Experimental group	*p*
Age (year)	36.84 ± 11.73	32.38 ± 10.56	0.277
Body mass index (kg/m^2)	22.93 ± 2.46	21.90 ± 2.36	0.246
Annual championships (time)	10.60 ± 7.93	11.55 ± 7.05	0.745
Running distance (km/week)	61.53 ± 12.81	55.27 ± 18.58	0.304

2.3. Intervention procedures

For the EG, the training consisted of the inclusion of a progressive volume of barefoot running in the athlete's usual weekly training (6 sessions). This was performed at the end of their training session and on grass (as explained below). As the weeks went by, the volume and frequency of barefoot running were increased. Before starting the protocol a meeting was held with the athletes in the EG to explain the training and exercise requirements and to answer any questions. The CG performed the same exercises as the EG but without any barefoot or unshod exercise. During Weeks 1 and 2 of training, athletes in the EG were instructed to run barefoot for 10 min in 50% of the weekly sessions (i.e., in 3 of their 6 sessions). During the 3rd and 4th weeks, the barefoot training was increased to 75% of the weekly sessions. In Weeks 5 and 6, subjects ran barefoot for 15 min in 75% of the weekly training sessions. In Weeks 7 and 8, subjects ran barefoot for 20 min in 50% of their weekly training and 4 × 80 m sprint races were added. In Weeks 9 and 10, participants ran barefoot for 20 min in 75% of their weekly training and performed 4 × 80 m sprint races. In the last 2 weeks (11th and 12th), runners performed 40 min of barefoot running once a week and 20 min in the other 2 training sessions. The principal investigator reviewed the barefoot training procedures. They were advised to decrease the intensity of training or even abandon it when pain or injury occurred. During the barefoot running training protocol participants were not allowed to change their running shoes.

2.4. Data analysis

Anthropometric parameters that were analyzed included height (cm), measured with a stadiometer (Seca 222; Seca GmbH, Hamburg, Germany), body mass (kg), recorded with a bariatric scale (Seca 634), and the body mass index = weight (kg)/height (m)^2. The method used to ascertain the type of foot strike is similar to that used by Altman and Davis.[23] Recordings of athletes were performed from lateral and back views with 2 camcorders with a rate of 240 Hz (Casio Exilim EX-F1; CASIO, Tokyo, Japan). In both cases, cameras were placed 2 m away from the treadmill at ground level. Marks were placed on the floor to indicate the exact point of camera placements. Video data were collected using 2-dimensional photogrammetric techniques (VideoSpeed Version 1.38; ErgoSport, Granada, Spain). Four steps of each athlete at HS and LS conditions were measured wearing their usual running shoes.

Following Lieberman[24] and Muñoz-Jimenez et al.,[25] the variables observed were as follows. (1) Foot strike type at initial contact with the ground: FFS as the ball of the foot landing before the heel, MFS as the landing of the heel and sole simultaneously and rearfoot or heel strike, and RFS as the landing heel before the ball of the foot. In the current study, 2 other strike patterns were assessed to discriminate the severity of the strike in rearfoot and forefoot. These were high RFS (HRFS) as the landing with the second half of the heel (the landing from back of the heel) and high FFS (HFFS) as the only contact with the ball of the foot with the ground (no contact with the heel, running on tiptoe) observed from the lateral view recording of the camera. (2) Inversion or eversion of the foot at the moment of first contact with the ground. (3) External, internal, or over external foot rotation in stance phase (Fig. 1) observed from the posterior view recording of the camera.

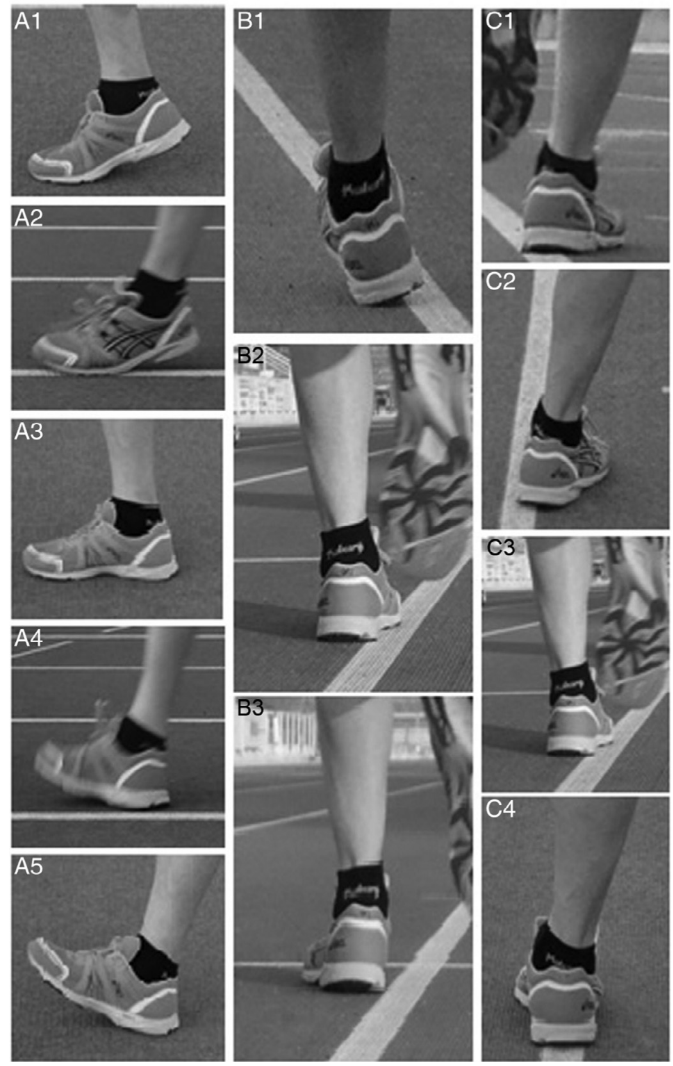

Fig. 1. Examples of foot strike patterns, inversion or eversion, and foot rotation: high forefoot strike (A1), forefoot strike (A2), midfoot strike (A3), rearfoot strike (A4), and high rearfoot strike (A5); inversion (B1), centered (B2), eversion (B3); over external rotation (C1), external rotation (C2), no rotation (C3), and internal rotation (C4).

2.5. *Statistical analyses*

Descriptive statistics are represented as mean ± SD. Student's *t* test was used for determining significant differences between EG and CG in sociodemographic variables. Analysis of the effect of the intervention was performed by McNemar's test. Reliability intra- and interobserver were calculated using Kappa of Cohen. The significance level was set at $p \leq 0.05$. Data analysis was performed using the statistical package SPSS (Version 21.0; IBM Corp., Armonk, NY, USA).

3. Results

Kappa of Cohen was used to calculate the reliability intra- and interobserver. The intraobserver reliability was obtained for foot strike (κ = 0.904, proportion of agreement = 95%), inversion (κ = 0.732, proportion of agreement = 85%), and the rotation (κ = 0.898, proportion of agreement = 90%). The average $\kappa = 0.844 \pm 0.090$ is considered a very good value.[26]

The interobserver reliability was obtained for foot strike ($\kappa = 0.801 \pm 0.090$, proportion of agreement = 90%), inversion ($\kappa = 0.727 \pm 0.110$, proportion of agreement = 85%), and rotation ($\kappa = 0.810 \pm 0.080$, proportion of agreement = 90%). The average $\kappa = 0.780 \pm 0.090$ is considered a good value.[26]

3.1. *Inversion and eversion*

Differences were found in left foot at LS in the EG. Values were from 66.7% of inversion in pre-test to 33.3% in post-test; and centered strike value from 33.3% in pre-test to 66.7% in post-test, respectively ($p = 0.031$) (Table 2).

3.2. *Foot rotation*

There were no changes in foot rotation for the CG ($p \geq 0.05$) whereas the EG obtained significant changes in the right and left feet at LS ($p \leq 0.05$). Left foot values changed from 5.6% in pre-test to 5.5% in post-test, from 33.3% in pre-test to 55.6% in post-test, and from 61.1% in pre-test to 38.9% in post-test for over external rotation, external rotation, and no rotation, respectively ($p = 0.046$). In the right foot, values changed from 5.5% in pre-test to 22.2% in post-test, from 55.6% in pre-test to 61.1% in post-test, and from 38.9% in pre-test to 16.7% in post-test for over external rotation, external rotation, and no rotation, respectively ($p = 0.030$). No significant changes appeared at HS ($p \geq 0.05$) (Table 2).

Table 2
Variables in inversion/eversion of the foot, foot rotation and foot strike patterns at low and high speeds in the control and experimental groups.

	Control group					
	Left foot			Right foot		
	Pre[a]	Post[a]	p[b]	Pre[a]	Post[a]	p[b]
LS						
INV	6 (46.2)	8 (61.5)	0.687	9 (69.2)	6 (46.2)	0.375
Centered	7 (53.8)	5 (38.5)		4 (30.8)	7 (53.8)	
HS						
INV	6 (46.2)	9 (69.2)	0.375	10 (76.9)	8 (61.5)	0.625
Centered	7 (53.8)	4 (30.8)		3 (23.1)	5 (38.5)	
LS						
Over external FR	3 (23.0)	2 (15.4)	0.392	2 (15.4)	2 (15.4)	1.000
External FR	5 (38.5)	7 (53.8)		8 (61.5)	8 (61.5)	
No rotation	5 (38.5)	4 (30.8)		3 (23.1)	3 (23.1)	
HS						
Over external FR	3 (23.0)	2 (15.3)	0.261	3 (23.1)	2 (15.4)	0.513
External FR	6 (46.2)	6 (46.2)		8 (61.5)	10 (76.9)	
No rotation	4 (30.8)	5 (38.5)		2 (15.4)	1 (7.7)	
LS						
HRFS	8 (61.5)	2 (15.4)	0.102	8 (61.5)	3 (23.1)	0.106
RFS	4 (30.8)	9 (69.2)		4 (30.8)	8 (61.5)	
MFS	1 (7.7)	2 (15.4)		1 (7.7)	2 (15.4)	
HS						
HRFS	7 (53.8)	7 (53.8)	0.549	7 (53.8)	5 (38.5)	0.532
RFS	5 (38.5)	4 (30.8)		5 (38.5)	7 (53.8)	
MFS	1 (7.7)	2 (15.4)		1 (7.7)	1 (7.7)	

	Experimental group					
	Left foot			Right foot		
	Pre[a]	Post[a]	p[b]	Pre[a]	Post[a]	p[b]
LS						
INV	12 (66.7)	6 (33.3)	0.031	12 (66.7)	8 (44.4)	0.289
Centered	6 (33.3)	12 (66.7)		6 (33.3)	10 (55.6)	
HS						
INV	13 (72.2)	9 (50.0)	0.130	14 (77.8)	10 (55.6)	0.219
Centered	5 (27.8)	9 (50.0)		4 (22.2)	8 (44.4)	
LS						
Over external FR	1 (5.6)	1 (5.5)	0.046	1 (5.5)	4 (22.2)	0.030
External FR	6 (33.3)	10 (55.6)		10 (55.6)	11 (61.1)	
No rotation	11 (61.1)	7 (38.9)		7 (38.9)	3 (16.7)	
HS						
Over external FR	2 (11.1)	2 (11.2)	0.560	3 (16.6)	6 (33.3)	0.261
External FR	7 (38.9)	8 (44.4)		10 (55.6)	10 (55.6)	
No rotation	9 (50.0)	8 (44.4)		5 (27.8)	2 (11.1)	
LS						
HRFS	10 (55.6)	2 (11.1)	0.020	10 (55.6)	2 (11.1)	0.020
RFS	6 (33.3)	10 (55.6)		6 (33.3)	10 (55.6)	
MFS	2 (11.1)	6 (33.3)		2 (11.1)	6 (33.3)	
HS						
HRFS	11 (61.1)	4 (22.2)	0.020	10 (55.6)	4 (22.2)	0.029
RFS	5 (27.8)	7 (38.9)		5 (27.8)	7 (38.9)	
MFS	2 (11.1)	7 (38.9)		3 (16.6)	7 (38.9)	

[a] Values presented as frequency (%).
[b] Comparison between pre- and post-test.
Abbreviations: FR = foot rotation; HRFS = high rearfoot strike; HS = competition running speed; INV = inversion; LS = comfortable running speed; MFS = midfoot strike; RFS = rearfoot strike.

3.3. Foot strike patterns

McNemar's test shows no differences between pre- and post-tests at any speed (LS or HS) ($p \geq 0.05$). The EG results were significant in all foot strike variables studied ($p < 0.05$). In left and right feet at LS, 55.6% of runners were HRFS in pre-test, changed to 11.1% in post-test; 33.3% of RFS changed to 55.6%; and 11.1% of MFS changed to 33.3% in post-test ($p = 0.020$). At HS in left foot, percentages changed from 61.1% of HRFS to 22.2%, from 27.8% of RFS to 38.9%, and from 11.1% of MFS strike to 38.9% in pre- and post-tests, respectively ($p = 0.020$). Right foot at HS results changed from 55.6% of HRFS to 22.2%, from 27.8% of RFS to 38.9%, and from 16.6% of MFS to 38.9% in pre- and post-tests, respectively ($p = 0.029$) (Table 2).

4. Discussion

The main finding of the present study was that a 12-week barefoot running program, progressively performed, could cause significant change in FSP with a tendency to MFS regardless of running speed, significant changes in the inversion toward a centered strike and significant changes in foot rotation at LS. To our knowledge, this study is the first to analyze changes in FSP using barefoot running as planned training, because most of the studies have focused on cross-sectional analyses.[6,27] The kinematic differences between shod and barefoot running have been studied by many authors.[6,28–30] De Wit et al.[28] have suggested that foot strike with the metatarsal heads while wearing running shoes is more difficult because of the elevated heel design of the running shoes. This elevated heel causes a greater demand in the degree of plantar flexion and the tibial angle is more vertical. That is why it is more difficult to see changes in foot strike from RFS to MFS or FFS with common running shoes. This could be optimized by means of barefoot running training. Currently to our knowledge there are no studies that have shown changes in the FSP of running with common running shoes using a barefoot running training program.

At pre-test, the FSP of athletes in the EG were 88.9% of the total RFS at LS and 86.1% at HS. These data justified the progressive implementation and soft surface of the barefoot running training because Lieberman et al.[5] mentioned that the impact force and loading rates are higher in barefoot runners who have RFS in the shod condition. They also observed FSP in habitually shod runners while barefoot running, suggesting that impact attenuation tactics do not occur immediately and may predispose the novice barefoot runner to higher injury risk for a period of time. To prevent injuries, there must be a period of adaptation to barefoot running and a progressive training of load and duration.

At LS, significant changes were produced in FSP in the EG: an average of 2 feet for 55.6% of HRFS in pre-test became 11.1% in post-test, MFS changed from 11.1% to 33.3% in pre- and post-tests. At HS, HRFS went from 58.3% to 22.2% in pre- and post-tests, and MFS from 13.8% to 38.9% in pre- and post-tests. Studies have indicated that, in most cases, habitual barefoot runners tend to adopt the FFS or MFS patterns,[5] but most participants used an RFS at endurance running speeds because running speed and other factors, such as training level, substrate mechanical properties, running distance and running frequency, influence the selection of FSP.[31] However, in this study, changes to MFS were produced both at LS and HS and, most importantly, runners achieved these barefoot adaptations when running shod. In similar studies with 12 weeks of progressive training with minimalist shoes simulating barefoot running, McCarthy et al.[13] and Miller et al.[32] found that the EG obtained significant changes to the adoption of an FFS when running shod. Using simulated barefoot training through minimalist shoes and a 4-week familiarization program, Warne and Warrington[33] found that during pre-test 30% of subjects adopted an FFS in the minimalist group. Following familiarization this increased to 80%. No change occurred in the habitually shod condition and a significant decrease occurred in heel pressures in minimalist footwear.

Furthermore, rearfoot eversion is associated with injury that is characteristic of shod runners. Barefoot and minimalist running increase eversion and tibial internal rotation[3,4,33] and in this study, the EG runners did not show eversion after barefoot running training.[34,35] Results show that there is lower prevalence of inversion in the left foot at LS increasing the percentage of a centered support. Following 7 weeks of minimalist shoes training, Schütte and Venter[14] did not find kinematic changes in the shod condition in inversion or eversion, in contrast to the barefoot condition, which significantly increases the inversion. In foot inversion at HS there is a tendency toward centered strike that is not statistically significant.

As for foot rotation, runners from the EG obtained an average of both feet of 5.5% in over external rotation in pre-test with a significant increase of 13.8% in post-test at LS; this leads to an incorrect alignment of the lower limb. Misalignments in the lower limbs and an excessive coronal and transverse plane motion of the ankle and tibia are linked to the development of a number of chronic injuries.[35,36]

As humans have evolved to run barefoot, a barefoot running style that minimizes impact peaks and provides increased proprioception and foot strength is hypothesized to help avoid injury, regardless of whether the runner is wearing shoes.[24] However, a recent review by Tam et al.[10] indicated that an unexplored area of the theory of barefoot running is the process by which biomechanical adaptations occur and whether these are universally learned.

While running barefoot, the hardness of the running surface may be a significant factor causing an alteration to a runner's footfall pattern; only 20% of the participants ran with an MFS or FFS pattern on the soft surface, whereas 65% of the participants ran with an MFS or FFS pattern when running on the hard surface. Out of the 80% of participants who maintained an RFS pattern on the soft surface, 43% of these participants ran with an MFS or FFS pattern on the hard surface.[37] Despite this consideration, in this study athletes who performed the barefoot running training on a soft, grassy surface could assimilate an MFS pattern. In addition, this type of surface is necessary for an adequate and progressive introduction to barefoot running because it has been shown that the acute response of most runners in barefoot running is an increase in impact forces and loading rates that are significantly higher than when running shod; these runners can suffer considerable risk unshod.[10] In this study, no injuries to participating athletes were recorded.

5. Conclusion

To summarize, data support that a 12-week program of barefoot running training, applied by progressively increasing the volume of barefoot running, causes significant changes to FSP with a tendency toward MFS, regardless of running speed. Progressive barefoot running training can help those athletes seeking an MFS or FFS. Future studies could monitor athletes to check if the changes obtained are consolidated or lost over time.

Authors' contributions

MMJ drafted the manuscript, participated in data collection, and reviewed the barefoot training procedures; FGP had collaborated in data collection and responding the reviewer questions; PALR collaborated in drafting the text, performed statistical analysis, and the design of the training protocol; VMSH did a part of statistical analysis and helped in the design of data collection protocol. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Competing interests

The authors declare that they have no competing interests.

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