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ORIGINAL RESEARCH

CHANGES IN LOWER EXTREMITY MOVEMENT AND POWER ABSORPTION DURING FOREFOOT STRIKING AND BAREFOOT RUNNING

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ABSTRACT

Purpose/Background: Both forefoot strike shod (FFS) and barefoot (BF) running styles result in different mechanics when compared to rearfoot strike (RFS) shod running. Additionally, running mechanics of FFS and BF running are similar to one another. Comparing the mechanical changes occurring in each of these patterns is necessary to understand potential benefits and risks of these running styles. The authors hypothesized that FFS and BF conditions would result in increased sagittal plane joint angles at initial contact and that FFS and BF conditions would demonstrate a shift in sagittal plane joint power from the knee to the ankle when compared to the RFS condition. Finally, total lower extremity power absorption will be least in BF and greatest in the RFS shod condition.

Methods: The study included 10 male and 10 female RFS runners who completed 3-dimensional running analysis in 3 conditions: shod with RFS, shod with FFS, and BF. Variables were the angles of plantarflexion, knee flexion, and hip flexion at initial contact and peak sagittal plane joint power at the hip, knee, and ankle during stance phase.

Results: Running with a FFS pattern and BF resulted in significantly greater plantarflexion and significantly less negative knee power (absorption) when compared to shod RFS condition. FFS condition runners landed in the most plantarflexion and demonstrated the most peak ankle power absorption and lowest knee power absorption between the 3 conditions. BF and FFS conditions demonstrated decreased total lower extremity power absorption compared to the shod RFS condition but did not differ from one another.

Conclusions: BF and FFS running result in reduced total lower extremity power, hip power and knee power and a shift of power absorption from the knee to the ankle.

Clinical Relevance: Alterations associated with BF running patterns are present in a FFS pattern when wearing shoes. Additionally, both patterns result in increased demand at the foot and ankle as compared to the knee.

Key words: barefoot running, biomechanics, running, strike pattern

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Informed consent for participation in the study was approved by the University and Medical Center Institutional Review Board at East Carolina University.

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INTRODUCTION

Running barefoot is not a new concept; yet relatively few people choose to run barefoot (BF) on a regular basis. BF running has been used as a training method for years partially due to the belief that it improves performance and strengthens the intrinsic and extrinsic muscles of the foot.[1] A number of recent studies focusing on BF running have demonstrated distinct differences in lower extremity mechanics and muscle activity when compared to shod running.[2-11] BF running has received much attention due to these differences and how they may be related to injury or performance. When running BF, there is a significant reduction in the impact peak of the vertical ground reaction force (GRF) with a subsequent increase in impulse.[5] These changes likely contribute to a reduction in the high mechanical stresses that occur during repetitive strides.[5] For example, in a related concept, subjects with knee osteoarthritis walking BF have a significant reduction in joint loads at their knees and hips compared to walking in their normal shoes.[12]

While benefits have been suggested, there are potential risks associated with running BF. Many believe the risks are due to decreased external protection of the sole of the foot and lower reduction of shock transmission when compared to running with shoes.[5] Although forces are reduced under the heel in BF runners, forces are increased under the forefoot, both of which are the result of associated changes in foot strike pattern. Repetitive impact forces from running may cause discomfort and further result in other lower limb overuse or stress injuries.

Running shoes provide many benefits to runners such as protection of the sole of the foot from the hard ground and unpredictable surfaces.[13] Traditionally, sport shoes have been designed in an attempt to augment specific sports performances and to help prevent athletic injuries. For example, cushioned running shoes provide lower extremity shock attenuation while motion control running shoes decrease rearfoot eversion.[14] Running shoes have been shown to reduce impact peak of the GRF by 22% when compared to running BF.[15] While running shoes are associated with a number of beneficial effects, a large number of injuries to the foot have been associated with poorly-fit running shoes.[16] This has led researchers and shoe companies to investigate the need for shoe designs with less motion control or cushion (minimalist footwear).

Recently, shoe companies have begun developing shoes that are designed to mimic BF running by making them lighter and thinner. One such shoe was effective in imitating the BF condition and at the same time provided a small amount of protection.[1] However, peak vertical GRFs were higher in minimalist shoes compared to BF which may be due to comfort and the runners' ability to increase push off force when compared to BF running.

BF running is associated with a change to midfoot strike or forefoot strike (FFS) pattern.[17] Running with a FFS pattern results in decreased loading rates and decreased work at the knee when compared to running with a rearfoot strike pattern (RFS).[18] While work at the knee is decreased in a FFS pattern, work at the ankle is increased.[23] Further, a FFS pattern reduces both the magnitude and the rate of loading of the skeletal forces on the tibia produced during BF running.[16] While FFS reduces stress in the lower extremity during initial contact it places increased demand on the achilles tendon and plantar fascia which may lead to pathologies in these structures.[16] Conversely, RFS runners have a greater work demand at the knee when compared to FFS.[18] For these reasons, it is often recommended that runners with knee pain or pathology adopt a midfoot or FFS pattern. However, it is not currently known whether running BF changes biomechanical factors of the lower extremity differently than adopting a FFS pattern while in shoes.

The purpose of this study is to compare the lower extremity biomechanics of shod RFS running to those occurring during shod FFS and BF conditions. The authors hypothesized that compared to the shod RFS condition: 1. Shod FFS and BF conditions will demonstrate increased plantarflexion, knee flexion and hip flexion angles at initial contact, 2. Shod FFS and BF conditions will demonstrate an increased joint power absorption in the plantarflexors and decreased joint power absorption in the knee and hip extensors and 3. Total lower extremity joint power will be lowest in the BF condition and highest in the shod RFS condition.

Table 1. *Subject Demographics (mean +/– sd).*

Gender	Age (years)	Body Mass (kg)	Height (m)
Male (n=10)	25.40 ± 2.01	79.99 ± 9.53	1.81 ± 0.07
Female (n=10)	24.10 ± 1.37	58.59 ± 5.79	1.63 ± 0.07

METHODS

Runners for this study were recruited and randomly selected from the University and local running clubs. The study included a total of 10 male and 10 female runners ranging in age from 20-30 at the time of data collection (Table 1). All runners were experienced runners who ran at least 6 miles per week and at least 3 days per week. All subjects ran with a RFS pattern when wearing shoes and did not regularly train or run in BF or FFS conditions. Subjects were excluded from this study if they had any cardiovascular or neurological compromise, current lower extremity musculoskeletal injury or pain, joint replacement or joint fusion. Each subject gave their written informed consent for participation in the study, which was approved by the University and Medical Center Institutional Review Board.

Subjects eligible for participation in the study completed a 3-dimensional running analysis. Two standing calibration trials were collected during which static joint (bilateral greater trochanters, right medial and lateral knee, right medial and lateral maleoli, right medial and lateral forefoot) and segment tracking (distal, proximal and lateral calcaneus, shank, thigh and pelvis) retroreflective markers were placed on the right lower extremity. One static trial was performed while the subjects were wearing New Balance 825 running shoes with the posterior and lateral heel cut out. These are a neutral shoe with a single density midsole. All subjects wore the same shoes during both of the shod trials. The second static trial was performed with the subject BF.

The static joint makers were used to establish joint centers and segment coordinate systems. The static joint markers were removed before dynamic data collection, and subjects were allowed to run along the runway as many times as necessary to feel comfortable with the markers and the lab environment. The subjects were asked to run along a 20 meter runway at a speed of 3.35 m/s (±5%). Running speed was measured using photocells 6 meters apart. A fixed pace was chosen to reduce differences in lower extremity biomechanics related to speed. All runners were comfortable running at this pace, particularly since it was over a short distance and there was time provided for rest between trials. Kinematic data were collected at 240 Hz with an 8-camera Qualisys® motion analysis system (Qualisys® Inc., Gothenburg, Sweden). Three-dimensional coordinates for each maker were reconstructed and filtered at 12 Hz. Two forces plates (AMTI®, Watertown, MA) mounted in the floor of the runway recorded ground reaction forces (GRF) at a sampling frequency of 1200 Hz. The GRF data was filtered at 50 Hz with a second-order recursive Butterworth filter (C-motion® Inc., Bethesda, MD).

All subjects ran in each of 3 running conditions: RFS, FFS and BF, performing 10 trials of each. The order of running conditions was established by flipping a coin to determine the shod or BF condition. Each foot strike pattern within the shoe condition was determined second. All runners were naturally RFS and employed a RFS pattern in the shod condition. In the BF condition, each runner was instructed to run down the runway without any instruction as to how to foot strike. In the FFS condition, subjects were simply instructed to "run on your toes".[18] No training was provided for the runners for either the FFS or BF conditions. A total of 10 successful trials for each condition using the right lower extremity were collected for each subject. Subjects had a chance to rest in between each trial. A trial was considered acceptable if the subject ran without altering their stride characteristics over the force plates within the given velocity range, and their entire right foot hit one of the force plates.

Pelvis, thigh, shank, and foot segments were created. All data were time synchronized at the time of collection through system hardware. Data were further analyzed between initial contact and toe off and

Table 2. *Strike Indices during all conditions.*				
		RFS	FFS	BF
Mean		12.7%	65.8%	45.7%
Range		0-30%	48-91%	17-83%
Footstrike patterns				
	RFS	20	0	8
	Midfoot	0	12	9
	FFS	0	8	3

RFS= Shod rearfoot strike condition; FFS= Shod forefoot strike condition; BF= Barefoot running condition
*Definitions of footstrike patterns: RFS= 0-33%; Midfoot= 34-66%; FFS= 67-100%

normalized to 100 data points, each representing 1% of the stance phase of running. Utilizing Visual 3-D software (C-motion® Inc., Bethesda, MD), joint rotations were calculated via Cardan sequencing where motion about the X-axis was defined as flexion/extension at the hip and knee and plantarflexion/dorsiflexion for the ankle. Motion about the Y-axis was defined as abduction/adduction at the hip and knee, and internal rotation/external rotation at the ankle. Finally, motion about the Z-axis was defined as internal rotation/external rotation at the hip and knee, and inversion/eversion at the ankle. Mean curves from 10 trials were created for each condition for hip, knee, and ankle motion in the sagittal plane. Joint powers were calculated using standard inverse dynamics.

STATISTICAL METHODS

After collection, all trials were analyzed in order to determine if strike pattern matched the assigned condition. Strike index was used to verify strike pattern in each condition. Strike index was defined as the position of the center of pressure relative to the long axis of the foot. A value of 0% represents an extreme heel strike and 100% represents extreme toe striking. For the purposes of this study, RFS was defined as 0-33%, 34-66% was considered midfoot strike and 67-100% was considered FFS. The dependent variables were the angle of plantarflexion, knee flexion, and hip flexion at initial ground contact and peak negative sagittal plane joint power (absorption) at the hip, knee and ankle during stance. A series of one-way ANOVAs were employed to compare variables of interest ($\alpha \leq 0.05$). If significant differences were determined in each one-way ANOVA, post-hoc paired t-tests ($\alpha \leq 0.05$) were utilized to determine specific differences.

RESULTS

Strike indices were different between conditions (Table 2). A significant difference ($p = 0.00$) was found in ankle angle at initial contact. Individual comparisons revealed the RFS pattern resulted in a dorsiflexed position (14.85° ± 6.15°) while the FFS pattern resulted in a more plantarflexed position (−12.46° ± 6.67°) (Figure 1). The BF condition demonstrated a dorsiflexed position (0.03° ± 7.29°) compared to shod FFS condition and less ankle dorsiflexion when compared to the shod RFS condition. There were no differences between conditions in knee ($p = 0.84$) or hip angles ($p = 0.19$) at initial contact (Table 3).

When comparing peak ankle power absorption, all conditions were significantly different ($p = 0.00$) with the FFS condition (−9.58 ± 2.21 W/kg) resulting in the greatest ankle power absorption and the shod RFS condition resulting in the least (−5.72 ± 2.33 W/kg)

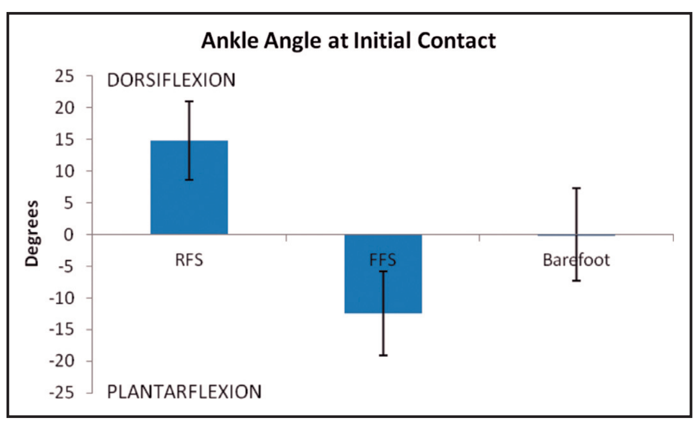

Figure 1. *Ankle Angle at Initial Contact across the four conditions.*

Table 3. *ANOVA results and individual comparisons.*

	FFS (mean±sd)	RFS (mean±sd)	BF (mean±sd)	p-value
Kinematics				
Ankle Angle at IC (°)	−12.46 ± 6.67‡	14.85 ± 6.15*†	0.03 ± 7.29	<0.01
Knee Angle at IC (°)	−12.73 ± 6.40	−12.57 ± 7.00	−13.63 ± 5.05	0.84
Hip Angle at IC (°)	26.19 ± 10.39	26.04 ± 9.86	20.76 ± 11.25	0.19
Kinetics				
Ankle Power (W/kg)	−9.58 ± 2.21‡	−5.72 ± 2.33*†	−6.58 ± 1.70	<0.01
Knee Power (W/kg)	−6.24 ± 2.66‡	−13.48 ± 4.56*†	−7.93 ± 2.73	<0.01
Hip Power (W/kg)	−1.07 ± 0.75‡	−2.63 ± 1.58*	−1.83 ± 1.72	0.01
Total Power (W/kg)	−16.88 ± 3.48	−21.83 ± 5.46*†	−16.35 ± 3.11	<0.01

IC=Initial Contact, *p≤0.05 for RFS vs. FFS, † p≤0.05 for RFS vs. RF, ‡ p≤0.05 for FFS vs. RF

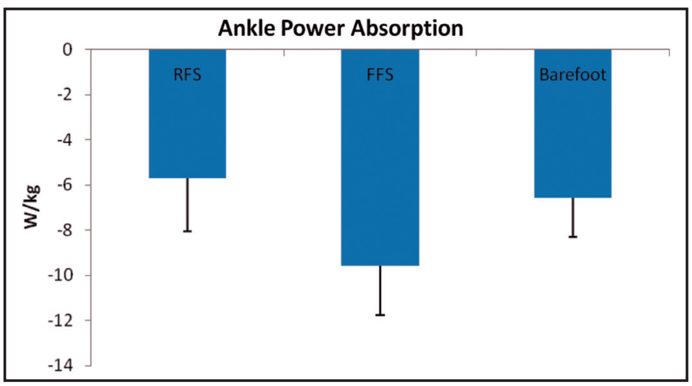

Figure 2. *Peak ankle power absorption across all conditions.*

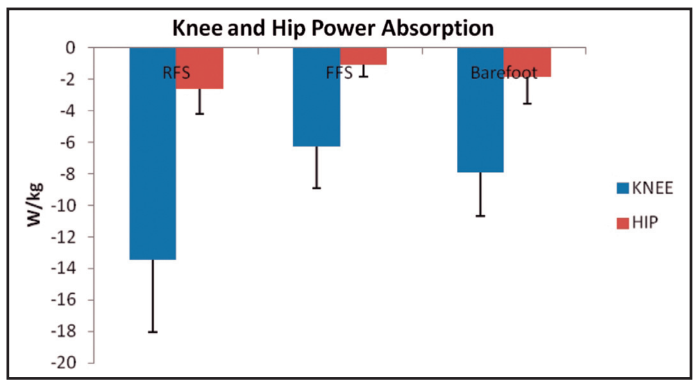

Figure 3. *Peak Knee and hip power absorption across all conditions.*

(Figure 2). The BF condition (−6.58 ± 1.70 W/kg) was significantly different from the other 2 conditions (Table 3).

All conditions were significantly different when comparing peak knee (p = 0.00) and hip (p = 0.01) power absorptions, the FFS condition (knee = −6.24 ± 2.66 W/kg, hip = −1.07 ± 0.75 W/kg) resulted in the least power absorptions and the shod RFS condition resulted in the greatest (knee = −13.48 ± 4.56 W/kg, hip = −2.63 ± 1.58 W/kg) (Figure 3). The BF condition was significantly different from both conditions at the knee (−7.93 ± 2.73 W/kg) and different from the FFS condition only at the hip (−1.83 ± 1.72 W/kg) (Table 3).

Total joint power absorption differed between conditions (p = 0.00) with the shod RFS condition demonstrating the largest magnitude absorption (−21.83 ± 5.46 W/kg) compared to the FFS (−16.88 ± 3.48 W/kg) and the BF conditions (−16.35 ± 3.11 W/kg) (Figure 4).

DISCUSSION

The purpose of this study was to compare lower extremity mechanics that occur during running with

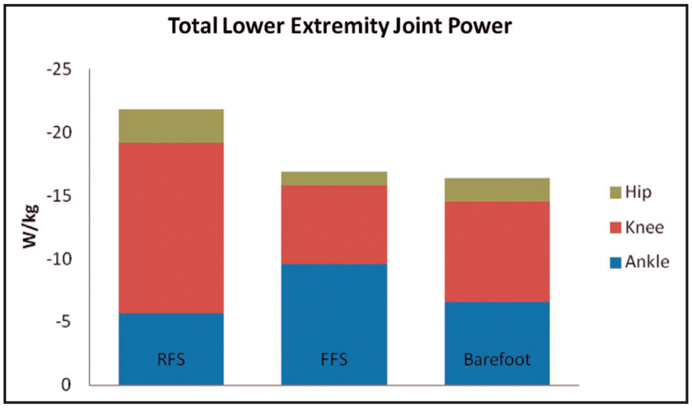

Figure 4. *Total Power absorption across all conditions.*

a RFS pattern compared to those that occur when running with a FFS pattern and those occurring in a BF condition. In general, FFS and BF conditions demonstrated similar mechanical changes when compared to the shod RFS condition. Specifically, BF and FFS runners demonstrated increased plantarflexion at initial contact, increased peak ankle power absorption and decreased peak knee and hip power absorption. This is consistent with what has been previously shown in FFS runners and BF runners.[17,18]

In both FFS and BF running the forces at initial contact are transmitted through the comparably smaller midfoot bones and muscles rather than through the calcaneus, talus and tibia directly. While a structurally sound foot may be able to absorb these forces effectively, it is likely that different foot types may respond differently to these increased forces to the forefoot. Foot type was not assessed in the current study so it is unclear which specific foot types would be more vulnerable. The difference between FFS and RFS ankle angle at initial contact was much greater than the difference between BF and RFS. This results in a much greater shortening of the gastrocnemius and soleus, which may require the muscle to work harder due to the compromised length tension relationship.[19] Additionally, because of the eccentric to concentric transition that occurs at midstance,[20] the muscles of the calf may be further stressed during midstance.

There was no increase in knee flexion angle at initial contact in the BF or FFS conditions. While the values in the current study are lower than previously reported,[18] they are consistent with the findings presented in recent reports that examined BF runners.[17] If the ankle is in more plantarflexion at initial contact, the knee would be in more flexion in order to establish the strike position closer to the projection of the center of mass (COM). If runners are not habitual FFS or BF runners, they may not change the knee angle, resulting in a strike further anterior to the COM projection. Manipulation of strike position relative to the COM independent of strike pattern (FFS versus RFS) may help clarify if strike pattern or strike position is the more important factor in changes in lower extremity mechanics. For example, increasing stride frequency decreases anterior strike position and increases knee position at initial contact.[21] These changes are present without a change in foot strike pattern. Finally, the decrease in the passive tension in the gastrocnemius may result in more extension of the knee at initial contact in inexperienced FFS or BF runners. Modification of the complex interactions of stride frequency, stride length, foot strike pattern, and lower extremity mechanics as they relate to running performance and injury is not yet fully understood. Simply instructing runners to "run on your toes" or "on the ball of your foot" may not result in the desired strike pattern and perhaps place some individuals at risk for injury if the change in strike pattern is incomplete or incompatible with the runner's lower extremity structure.

Interestingly, the FFS and BF conditions did not result in changes compared to the RFS condition when considering hip angle at initial contact. While runners during the BF condition demonstrated a trend toward decreased hip flexion, these differences were not significant. Decreased hip flexion is consistent with modification of the position of the COM projection more posteriorly under the body. Because trained BF runners strike in less plantarflexion than FFS, they would be less likely to strike anteriorly. With no concurrent increase in knee angle at initial contact, the hip would need to remain in less flexion, bringing the COM posteriorly and allowing the forefoot to contact the ground. This may contribute to the concurrent increase reported in peak vertical ground reaction force in FFS.[18] This increase in vertical GRF combined with the more vertical orientation of the lower extremity segments in FFS and BF running, there is potentially increased compressive forces compared to torsional forces in the ankle, knee and hip joints. Additionally, this may partially explain the reported decrease in the deceleration component of the posterior GRF.

The FFS pattern and BF conditions both reduced the peak knee extensor power. FFS demonstrated the greatest reduction in magnitude. These findings are consistent with what has been previously reported in research performed on forefoot strikers.[17,18] Comparatively, the FFS conditions demonstrated the greatest reduction in knee extensor power. It is important to note that these changes in knee power occurred independent of changes in knee position at initial contact. Since there were no changes in knee position and similar magnitude of the vertical GRF, the differences in knee power suggest that the line of the vertical GRF may be passing closer to the knee joint center throughout the stance phase. Therefore, it may be important to evaluate contact forces in the joints of the lower extremities during BF and FFS running. Further, changes in the moment arm of the vertical GRF have implications for extensor demand and metabolic cost.[22]

Plantarflexion power (absorption) was significantly greater in FFS and BF conditions when compared to the shod RFS condition. FFS had the greatest increase in ankle power absorption. This is likely present due to the fact that running in the BF condition resulted in a more midfoot strike pattern that reduces the load on the plantarflexors. In fact, running BF resulted in an average strike index of 45.7% but only 60% of the runners in this condition actually adopted a midfoot or FFS pattern. This suggests that while BF running, on average, results in a different strike pattern, a number of runners still maintain a RFS pattern. Therefore, a switch to running BF may not sufficient to make comprehensive changes in the lower extremity mechanics in all runners. Running BF without subsequent changes in strike pattern is unlikely to result in reduction of injury or other benefits. In contrast, 100% of the subjects ran with a midfoot or FFS pattern in the FFS condition with an average strike index of 65.8%. It is important to note that none of the subjects in the current study were experienced or trained BF runners. Further study of whether trained BF runners demonstrate similar strike patterns as those observed in the current study will help to clarify the potential changes associated with BF running.

A midfoot strike pattern potentially places the perpendicular position of the vertical GRF further from the ankle joint center compared to FFS. While this may reduce the vertical impact through the long axis of the metatarsals, it is likely to increase the torsional forces imparted on the midfoot and forefoot as a result of changing the "gear ratio" as described by Braunstein et al.[23] These torsional forces are most commonly directed toward dorsiflexion of the metatarsals on the cuboid and cuneiforms. The morphology of these plane joints help to establish stability in the midfoot. However, it is not known how these joints respond to repetitive dorsiflexion stress associated with midfoot and forefoot strike patterns. This may partially explain some of the recent evidence associating strike pattern and metatarsal stress fractures in BF runners.[24]

CONCLUSION

When compared to RFS running, FFS and BF running conditions both resulted in reduction of total lower extremity power absorption particularly at the knee and a shift in power absorption from the knee to the ankle. While these reductions may be beneficial in isolation, the increase in power absorption at the distal segments may result in increased risk of injury at the foot and ankle. Special care should be taken when adopting a FFS or BF running style in an attempt to improve performance or reduce lower extremity injury risk. Both FFS and BF running appear to result in significant changes in lower extremity and power absorption when compared to RFS running. In fact, these differences are more pronounced in the FFS condition as compared to the BF condition. Therefore, it may not be necessary to run BF or in minimalist shoes in order to gain potential benefits. However, the larger increase in ankle power in FFS running may be potentially injurious. Long-term prospective studies are necessary to determine what benefits may be present as a result of FFS or BF running styles or how these running patterns may affect injured runners or runners with chronic problems such as osteoarthritis.

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