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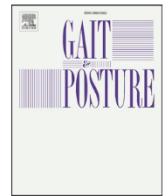
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Full length article



Effect of different forefoot rocker radii on lower-limb joint biomechanics in healthy individuals

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ABSTRACT

Introduction: Previous studies showed that rocker shoes with a stiff forefoot rocker profile significantly reduce peak plantar flexion moment at the ankle (PFM) and peak ankle dorsiflexion (DF). Both parameters are related to Achilles tendon and Plantar Fascia unloading. The shape of an outsole with a forefoot rocker is described with multiple rocker design parameters. The aim of this research is, to determine the relation between different forefoot rocker radii on peak DF and peak PFM at a self-selected walking speed.

Methods: 10 participants walked in standard shoes and three experimental pairs of shoes with different forefoot rocker radii. Lower extremity kinematics and kinetics were collected while walking on an instrumented treadmill at preferred walking speed and analysed with Statistical Parametric Mapping (SPM) ($\alpha = .05$; post-hoc $\alpha = .05/6$).

Results: Peak value analyses showed significant decreases in peak DF, peak PFM, and peak ankle power generation for the rocker conditions. No relevant significant differences were found in spatio-temporal parameters and total work at the ankle joint. SPM showed a significant decrease (% gait cycle) in DF (40–69 %), PFM (7–15 %; 41–68 %; 69–81 %), ankle power (10–15 %; 32–51 %; 55–64 %; 64–67 %; 72–80 %) and foot-to-horizontal angle (FHA) (0–4 %; 40–62 %; 92–100 %) and an increased shank-to-vertical angle (SVA) (44–84 %) for the rocker conditions.

Conclusion: The results of this study suggest that rocker shoes with a proximally placed apex significantly reduce DF and PFM during the third rocker compared with control shoes. This effect is mainly explained by a change in the FHA. Smaller radii cause the largest reductions in DF and PFM, so therefore, a uniform standardisation of the forefoot rocker radius is essential.

1. Introduction

Patients with lower-leg disorders like Achilles tendinopathy (AT) might benefit from conservative interventions to reduce the symptoms of pain or the mechanical load [1]. Load management by using different types of foot orthoses [2] is therefore a common treatment in AT. Shoes with forefoot rocker profiles are commonly used in patients with lower-leg disorders in order to reduce (peak) dorsiflexion angle (peak DF) and (peak) plantarflexion moment (peak PFM) [3] and with that to reduce force on the Achilles tendon during gait. Moreover, use of shoes with forefoot rocker profiles might also reduce traction on the plantar fascia [4].

The shape of a shoe sole with a forefoot rocker can be described in multiple rocker design parameters [5–7]. The rocker axis can be

characterised by an apex position and apex angle (Fig. 1A). Forefoot rockers can be described with a rocker angle [8], basically a straight line between the apex and the shoe front, but also with a radius (Fig. 1B). Where it is logical to describe a smooth curve with a rocker radius [9], a smooth curve was also described with a rocker angle [5].

Where the forefoot apex position is quantified as percentage of the shoe length, there is no uniform definition of the forefoot rocker radius. Research into rocker radii is only described in roll-over shoes (Fig. 1C). It was shown that smaller radii compared to larger radii lead to both reduced peak ankle plantarflexion in loading response and reduced dorsiflexion during terminal stance [10–13]. Other research focused primarily on the effects of one rocker shoe configuration on biomechanical gait parameters and plantar pressure [3,14–18]. It has already been shown that a rocker profile causes a reduced PFM leading to

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reduced positive ankle power during push-off [14], but the magnitude of the reduction in relation to a specific forefoot rocker radius is not known. Although various studies have assessed the effects of different rocker apex positions and apex angles on kinematics and kinetics or plantar pressure [5,19,20], research about the effects of different forefoot rocker radii on gait parameters is lacking. For proper decision making about the design of the rocker profile, knowledge on the effects of different forefoot rocker radii on kinetics and kinematics of the lower-limb is essential.

The aim of this research is, therefore, to determine the relation between different forefoot rocker radii and both peak DF and peak PFM at a self-selected walking speed. Moreover, foot-to-horizontal angle (FHA) [21] and shank-to-vertical angle (SVA) are analysed as well to clarify possible sagittal ankle angle effects (Fig. 2). Also, ankle power and work will be analysed to assess ankle contribution during gait.

2. Methods

2.1. Participants

Based on a priori power analysis on data of Sobhani et al. [16] ten healthy adults was sufficient to provide a statistical power of 80 % to detect 0.17 Nm/kg decrease in peak PFM. Participants had to fit the shoe sizes of the experimental female shoe (EU37). Inclusion criteria were therefore female gender and age ≥ 18. Exclusion criteria were the use of custom inlays and self-reported diseases or injuries that influence gait. Written informed consent was obtained before starting the experiments. The local Medical Ethics Committee approved this research (METC 2018.060).

2.2. Shoe conditions

To limit the number of experimental shoes, we chose one size (EU37) of lightweight medium width athletic shoes (Katy, Dr Comfort, Mequon, WI, USA) in this study. In the control condition a non-adjusted shoe was used and in the experimental condition the original outsoles were replaced with rocker profiles. Subjects walked on a control shoe and on three comparable shoes with modifications to the forefoot rocker radius (Fig. 3).

A thin (5 mm) layer of EVA (63 durometers, shore A) and a 30 mm thick stiff sole (Polyamide 12; 80 durometers, shore D) was used for the rocker profiles. All shoes had the same inlay (25 durometers, shore A, thickness: 6 mm). Three different radii were used. Selected radii were based on previous research [9]: 160 mm, 185 mm and 210 mm (respectively R16, R18.5 and R21). The length of the shoe sole was 260 mm. The apex position of all rocker shoes was, based on previous suggestions [7], placed at a proximal position (55 % of the shoe length, referenced to the heel) and had a neutral apex angle of 90°. The rocker shoes were stiff to maintain the curvature during gait and prevent toe dorsiflexion. Although rocker profiles with larger radii require less sole thickness, to remain all rocker parameters (including outsole thickness) except radius constant, in this research R18.5 and R21 had a thicker toe

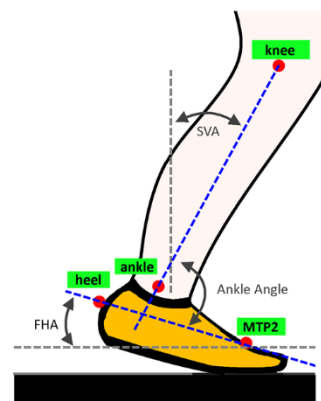


Fig. 2. Schematic view of a foot and shank and both Shank-to-Vertical angle (SVA) and Foot-to-Horizontal angle (FHA) and their relation to the sagittal ankle angle.

part of the shoe (depicted as *d* in Fig. 1D). The weight for each shoe was 240, 588, 556 and 558 g for Control, R16, R18.5 and R21 respectively. The weight difference between the control shoe and the experimental shoes was not supplemented for, because we expect negligible weight effects during the stance phase. The small weight difference between the experimental shoes are explained by variations in internal structure of the outsole.

2.3. Technical procedure

All measurements were performed at the GRAIL (Gait Realtime Analysis Interactive Lab; Motekforce Link, Amsterdam) of the Department of Rehabilitation Medicine, University Medical Center Groningen. An instrumented treadmill and a ten-camera motion capture system (Vicon Bonita 10, Oxford, UK; Fs = 100 Hz) were used to measure the kinematics by tracking 22 reflective markers placed according to the lower-limb Human Body Model 2 [22]. Analogue force data were captured by two force plates (Motekforce Link; Amsterdam; Fs = 1000 Hz) incorporated in the treadmill. Both kinetic and kinematic data were synchronised and normalised to 100 % gait cycle and for body mass (kg).

2.4. Experimental procedure

Only the dominant foot (foot used to kick a ball) was taken into account in the data analysis. Preferred walking speed while walking on the control shoes was determined by taking the mean speed of 60 s self-paced walking on the GRAIL [23] after a 60 s familiarization period. In all conditions the treadmill speed was fixed to this preferred walking speed. Measurements started with the control condition, followed by the experimental conditions in a randomized order defined by a custom-made script in Matlab (R2016b). Each measurement contained 60 s of familiarization followed by 60 s of recording.

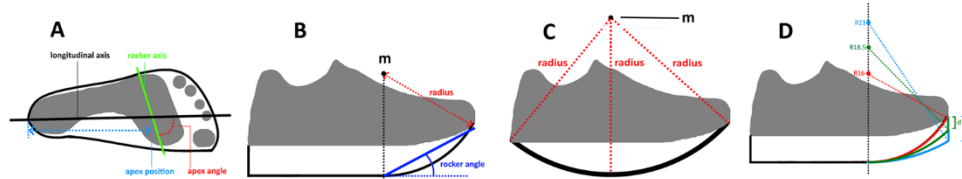


Fig. 1. A: Schematic view of the rocker axis (green). The apex position is marked with the blue arrowed line. The apex angle is marked as the angle between the longitudinal axis and the rocker axis. The rocker axis normally follows the MTP-axis. B: Schematic view of a forefoot rocker angle (blue) and a forefoot rocker radius (red). The center (m) of the rocker radius lays just above the apex position. C: Roll-over rocker [13] with a heel-to-toe rocker. This is a rocker

profile where the heel and toe rocker share the same antero-posterior center (m), resulting in a fully rounded sole profile with one radius. D: Schematic view of the experimental shoe with three different forefoot rocker radii (R16 (red), R18.5 (green) and R21 (blue)). All rockers have the same apex position (55 % shoe length; marked with the dotted black line), and outsole thickness (30 mm). For R21 and R18.5 the radius leaves a thicker toe part of the shoe (d). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).



Fig. 3. From left to right: Experimental shoes R16, R18.5, R21 and the control shoe. The holes in the internal structure of the experimental outsoles are for weight reduction. All experimental outsoles had a thickness of 35 mm and a toe spring of 20 mm.

2.5. Data analysis

Data of twelve steps per condition were filtered with a fourth order zero-lag Butterworth low-pass filter with a 4 Hz cut-off frequency and averaged using a custom-made Matlab script. Per condition peak values for DF, PFM and ankle power as well as ankle work were determined during terminal stance and pre-swing (time region of interest). SVA and FHA during the stance phase were determined based on the marker trajectories of the shank and the foot markers respectively and calculated with a custom made Matlab script.

2.6. Statistical analysis

Means and standard deviations of ten subjects were determined to describe study population characteristics and spatio-temporal parameters. Repeated measures ANOVA was used to estimate the effect of shoe condition ($p < .05$) on the discrete gait parameters (spatio-temporal parameters, peak DF, peak PFM and ankle work) and corrected with a Bonferroni post-hoc procedure (IBM Statistics 23). Continuous gait parameters were analysed using 1-dimensional Statistical Parametric Mapping (SPM) [24]. All SPM analyses were conducted with a custom-made Matlab script (R2016b) and using the open-source software package spm1D 0.4 (www.spm1d.org). Repeated measures analyses of variance (ANOVA) were performed on all four conditions with post hoc paired t-tests to compare shoe conditions [25]. The significance level for all statistical tests was set a priori to .05. The significance level of the six post hoc paired t-tests was Bonferroni corrected and set at .0083 (0.05/6).

3. Results

The subjects had a mean (\pm SD) age of 20.8 (\pm 2.4) years, bodyweight of 67.5 (\pm 10.5) kg, and body height of 164.4 (\pm 3.1) cm. The right foot was dominant in all. Average walking speed was 1.19 (\pm .18) m/s with a range from 0.94 to 1.55 m/s. Significant main effects were found for cadence and step length (Table 1). Post-hoc tests revealed significantly higher cadence for R18.5 compared with R21. No significant differences were found in step length.

Significant rocker shoe effects are found for peak DF ($F_{27,3} = 14.064$, $p < .001$), peak PFM ($F_{27,3} = 90.782$, $p < .001$), peak ankle power generation ($F_{27,3} = 36.605$, $p < .001$), positive ankle work ($F_{27,3} = 22.238$, $p < .001$), and negative ankle work ($F_{27,3} = 38.861$, $p < .001$) (Table 1). Furthermore, post-hoc tests revealed significantly lower peak PFM and negative work for R16 when compared with R18.5 ($p = .03$; $p = .006$) and R21 ($p = .001$; $p = .012$). Total ankle work is significantly lower for R21 when compared with the control shoe, but not between rockers.

SPM analysis with repeated measures ANOVA revealed significant differences between shoe conditions in the ankle angle, and ankle moment during the terminal stance, pre-swing and initial swing (40–69 % gait cycle, $p < .001$) (Fig. 4; top). Post hoc analyses show significant differences between the experimental conditions and the control condition (Fig. 4; bottom). Moreover, R16 has a smaller ankle dorsiflexion in terminal stance, and a larger ankle plantarflexion in pre-swing compared to the other rocker conditions.

Analysis of the sagittal ankle moments between the shoe conditions indicate three significant regions (7–15 %, $p < .001$; 41–68 %, $p < .001$;

Table 1

Mean values, standard deviations, and results of the repeated measures ANOVA for spatio-temporal parameters, kinetics and kinematics. Significant p-values ($\alpha = 0.05$) are marked in bold. Post-hoc significant differences are marked with a (vs. Control shoe), b (vs. R16), c (vs. R18.5), d (vs. R21).

Variables	Control shoe	R16	R18.5	R21	F	p
Spatio-Temporal						
Cadence (steps/min)	110.4 (9.1)	111.1 (9.2)	111.1 (8.9) ^d	110.4 (8.8) ^c	4.078	.016
Step length (m)	0.65 (0.06)	0.64 (0.05)	0.64 (0.05)	0.65 (0.05)	5.681	.004
Step width (m)	0.14 (0.03)	0.14 (0.02)	0.14 (0.02)	0.14 (0.03)	.051	.984
Stance time (s)	0.81 (.08)	0.77 (.06)	0.77 (.06)	0.81 (.10)	1.446	.262
Ankle						
Peak dorsiflexion angle (°)	13.89 (2.49) ^{b,c,d}	9.80 (3.65) ^a	10.62 (2.95) ^a	10.91 (2.70) ^a	14.064	<.001
Peak plantar flexion moment (Nm/kg)	1.54 (.15) ^{b,c,d}	1.25 (.15) ^{a,c}	1.31 (.16) ^{a,b}	1.39 (.16) ^{a,b}	90.782	<.001
Peak power generation (W/kg)	3.71 (.93) ^{b,c,d}	2.80 (.79) ^a	2.81 (.74) ^a	2.81 (.68) ^a	36.605	<.001
Positive work (J/kg)	0.37 (.08) ^{b,c,d}	0.30 (.07) ^a	0.30 (.06) ^a	0.30 (.06) ^a	22.238	<.001
Negative work (J/kg)	-0.16 (.02) ^{b,c,d}	-0.11 (.02) ^{a,c}	-0.12 (.02) ^{a,b}	-0.13 (.02) ^{a,b}	38.861	<.001
Total work (J/kg)	0.20 (.05) ^d	0.19 (.05)	0.18 (.05)	0.17 (.06) ^a	5.128	.006

69–81 % gait cycle, $p = .0016$) (Fig. 4; middle). During terminal stance (region of interest) all rocker conditions reduced ankle PFM. Moreover, rocker conditions show significant differences between each other (R16 < R18.5 < R21 < Control).

Analysis of the ankle power between shoe conditions indicate four regions with significant differences (10–15 %, $p < .001$; 32–51 %, $p < .0001$; 55–64 %, $p < .0001$; 64–67 %, $p = .0161$; 72–80 % gait cycle, $p < .001$) (Fig. 4; bottom): during loading response, exit from mid-stance, terminal stance–pre-swing and initial swing. Post hoc analyses show that ankle power generation is decreased for all rocker conditions during loading response compared with the control condition. During terminal stance all rocker conditions have reduced ankle power absorption compared with the control condition. The power absorption of R16 is significantly more reduced than R18.5 and R21. During terminal stance and pre-swing, the ankle power generation is reduced for all rocker conditions. Moreover, where all rocker conditions have no differences in peak ankle push-off power, R16 has significantly lower ankle power generation after peak push-off compared with R18.5 and R21. Also, power absorption during terminal stance differs between all conditions (R16 < R18.5 < R21 < Control).

SPM Analysis of the FHA indicate three regions with a significant main effect of the conditions (0–4 % gait cycle, $p = .0293$; 40–64 % gait cycle, $p < .001$; 92–100 % gait cycle, $p = .008$) (Fig. 5; top). Post hoc analyses show that at initial contact all rocker conditions reduce FHA. During terminal stance–pre-swing, all rocker conditions show a decreased FHA (toe-down) compared to the control. Moreover, R16 has

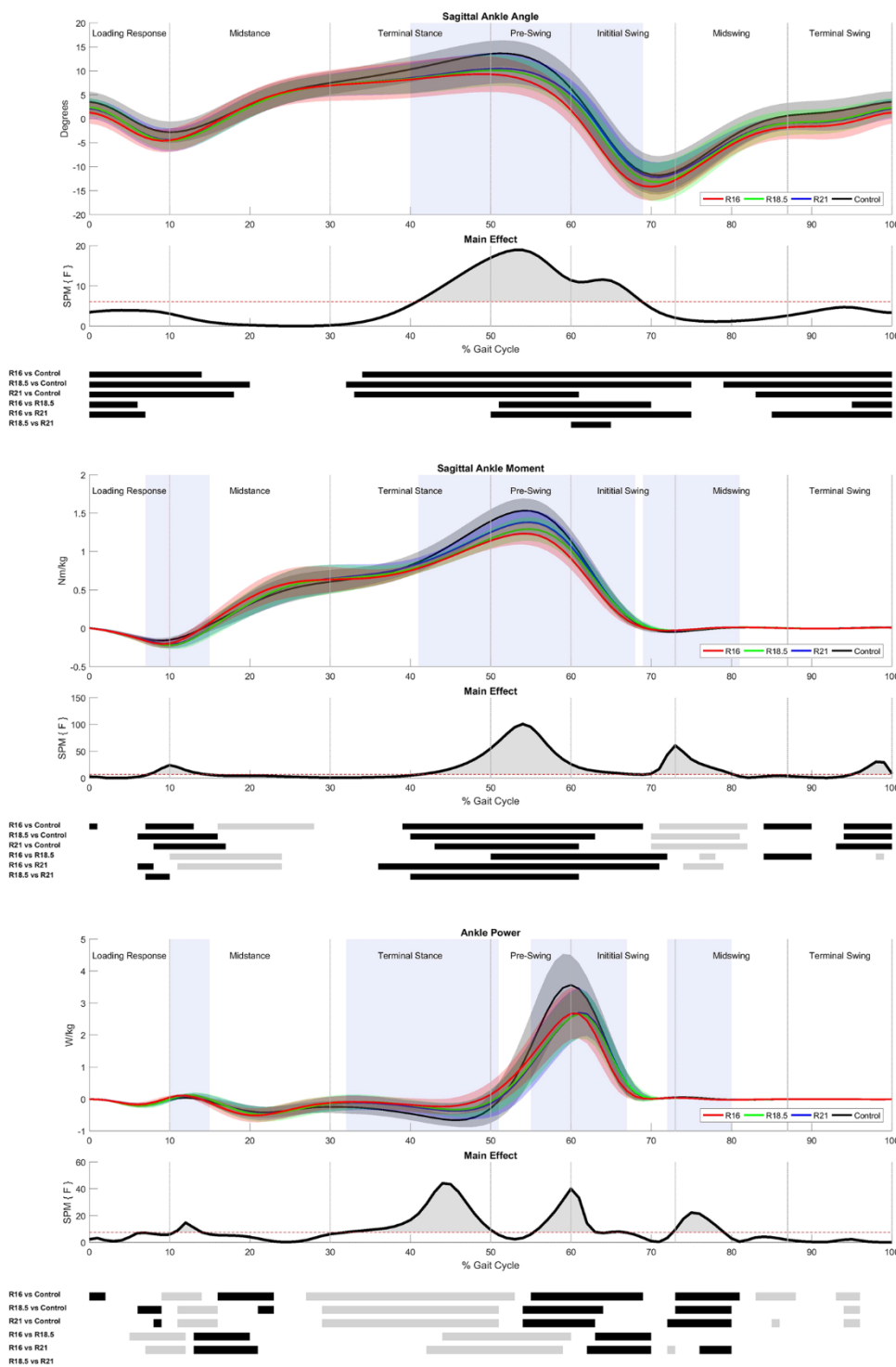


Fig. 4. Sagittal ankle angle, moment and ankle power mean and SD patterns for all shoe conditions. The blue areas indicate statistical significant differences between conditions, followed by the time-dependent F-values of the SPM (main statistical test; analysis of variance) for all subjects (dashed red line; $\alpha \leq .05$). Grey areas indicate regions with significant differences. Below each graph the post-hoc tests between all shoe conditions. Solid black (decrease) and grey bars (increase) span the region of the gait cycle where significant ($\alpha \leq .0085$) differences were observed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

a lower FHA when compared with R18.5 and R21 during pre-swing. No significant differences between R18.5 and R21 were found in terms of FHA during the gait cycle.

Analysis of the SVA shows a significant main effect at 44–84 % gait cycle ($p < .001$) (Fig. 5; bottom). Post hoc analysis indicate reduced SVA of R16 and R18.5 when compared with the control condition during terminal stance.

4. Discussion

To the best of our knowledge this is the first study that evaluated the

effects of different forefoot rocker radii on biomechanics in gait. We showed that rocker shoes reduce peak DF and peak PFM in line with previous research [14,15]. It is thought that this effect reduces Achilles tendon stretch and force during the stance phase of gait respectively. Moreover, the radius of the forefoot rocker determines how large these reductions are, the smaller the forefoot rocker radius the larger the reductions in peak DF and PFM.

Reduction in DF during terminal stance and pre-swing are found in each rocker condition. Analysis of SVA showed that during the stance phase significant differences were found between conditions, however small ($<2^\circ$) and therefore not clinically relevant. This is in line with gait

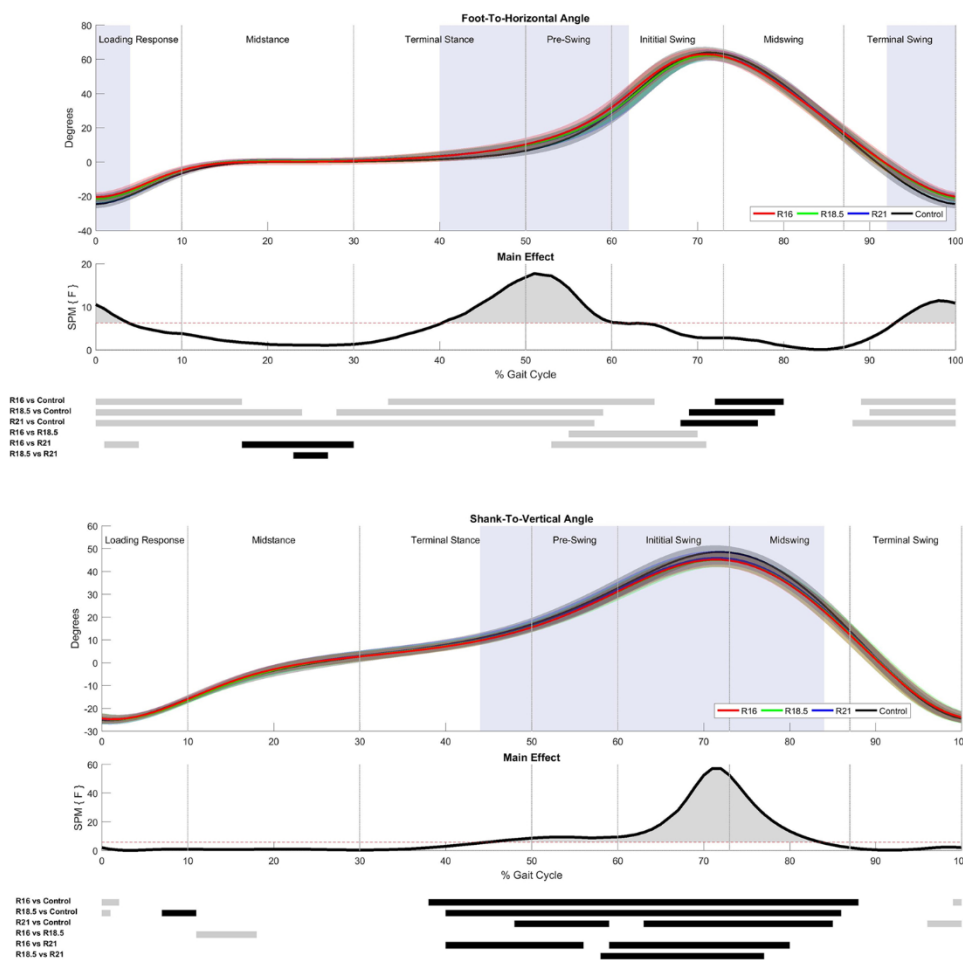


Fig. 5. Foot-to-Horizontal angle (FHA) Shank-to-Vertical angle (SVA) SD patterns for all shoe conditions. The blue areas indicate statistical significant differences between conditions, followed by the time-dependent F-values of the SPM (main statistical test; analysis of variance) for all subjects (dashed red line; $\alpha \leq .05$). Grey areas indicate regions with significant differences. Below each graph the post-hoc tests between all shoe conditions. Solid black (decrease) and grey bars (increase) span the region of the gait cycle where significant ($\alpha \leq .0085$) differences were observed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

with a well tuned ankle foot orthosis where SVA during the stance phase of gait remains unaffected as well [26]. Apparently humans seem to control their gait pattern in such a way that the SVA remains almost unaffected. However, the FHA decreases (toe-down) after the application point of the GRF passes the apex. Moreover, FHA during the third rocker (Fig. 5) is smaller when a smaller radius is applied. As FHA and SVA together determine the sagittal ankle angle (Fig. 2), changes in DF can mainly be explained by changes in the FHA. In other words, rocker radius has a direct effect on the FHA and therefore affects DF.

Reductions in peak PFM can be explained by a reduced sagittal ankle moment arm of the ground reaction force. This is caused by an earlier onset of the heel rise as the apex is placed proximal to the MTP region and an increased FHA during the third rocker (Fig. 5) when a smaller radius is applied. R16 increases FHA at the end of the third rocker, therefore reducing PFM more when compared with R21. This implies that rocker shoes with smaller radii reduce PFM more when compared with rocker shoes with large radii. Post-hoc analyses showed that ground reaction force peaks during the third rocker remained unchanged between conditions.

The reduced peak ankle power generation during the third rocker is explained by a reduced PFM in combination with a reduced plantarflexion angular velocity. This might not be beneficial for walking, however net work between most of the conditions remains unchanged. Furthermore, R16 causes an increase in PF angular velocity at push-off compared with R18.5 and R21 which explains the slightly higher ankle power peak of R16. This finding suggests that smaller radii, despite their lowest PFM, can compensate for this loss by stimulating plantarflexion angular velocity during push-off.

For external validity, it is important that the rocker radius is stand-

ardised. A radius of 160 mm is relatively small with 300 mm shoe length, but relatively large with 200 mm shoe length. Therefore, considering the radius (R) relative to the shoe length (L) improves comparison between different shoe sizes. However, agreement on standardisation is so far not available. For this study, radii of 160, 185 and 210 mm were used with a total shoe length of 260 mm. The relative radius (R/L) of R16, R18.5 and R21 was therefore 0.62, 0.71 and 0.81 respectively. However, solely the magnitude of R/L is not enough to optimize the biomechanical effect of the rocker shoe during the gait. In combination with the forefoot apex position the arc length of the rocker curve and therefore the angle of the tangent of the rocker curve at the end of the sole (α_{TO}) can be determined. This relation can be summarized as followed (Eq. (1)):

$$\frac{R}{L} = \frac{1 - apex}{\sin(\alpha_{TO})} \quad (1)$$

where apex is the forefoot apex position (ratio of shoe length), R the forefoot rocker radius (mm), L the distance of the heel to the tip of the shoe (mm) and α_{TO} the angle of the tangent of the forefoot rocker curve relative to the horizontal at the end of the sole. This angle can be related to the rocker angle of conventional rocker shoes (Fig. 1B). For this study α_{TO} is 47° , 39° and 34° for R16, R18.5 and R21 respectively.

Our results show that smaller forefoot rocker radii lead to larger reductions in peak DF and peak PFM. Theoretically it is possible to create a quarter of a circle as rocker curve, however with an apex position of 50 % this will lead to a sole thickness of 50 % of the shoe length as well. Therefore, the smallest possible radius is constrained to functional and cosmetic terms. With the use of Eq. (1) and some functional assumptions, it is possible to give a clear view of the minimal radius of the forefoot rocker. Assuming an α_{TO} to be at least 42° (the mean toe-off

angle with the control shoe found in this study) and a normal apex position of 66 % shoe length will result in a forefoot rocker with a relative radius of .52. Relative radii smaller than .52 might reduce PFM and increase ankle power at toe-off, however this is at the expense of sole thickness.

In this study we kept sole thickness constant, which led to a larger offset (d) at R21 and R18.5. This additional offset d might have influenced our results and other effects might be expected when d was kept zero. Theoretically it can be assumed that if the offset d is larger than 0, this would lead to a decrease in ankle moment arm during terminal stance as the ankle joints moves closer to the GRF. This would mean that the reductions in PFM for R18.5 and R21 are larger in this study than when d would be zero. On the other hand, the larger offset might affect balance. Although no balance problems were reported by the subjects, the effects of offsets d of 8 and 14 mm are expected to be small in this study. However, clinical footwear should reduce the offset as much as possible.

In this study, between shoe-effects can mainly be explained by the forefoot rocker radius, because all other rocker and shoe parameters of the experimental shoes remained constant with negligible weight difference. Moreover, the large number of twelve steps per participant for peak data and SPM analyses accounts for individual walking variability. Weight differences between the experimental shoes and the control shoe were not corrected for, however, walking pattern was not substantially affected in terms of spatio-temporal parameters (Table 1). However, future studies should focus on minimizing weight differences to prevent potentially affecting swing and therefore stance phase biomechanics.

The time to become familiarized with a shoe was limited, yet measurements started when subjects established a stable gait pattern to measure immediate effects. Even though the scope of this study was to determine immediate effects of the forefoot rocker radius it is also interesting for future studies to examine the long-term effect, because it might decrease individual walking variability, with a reduced standard deviation in SPM as a consequence. In this study young healthy female adults participated, however similar effects are expected to be found in patients suffering from Achilles Tendinopathy, as previous research showed similar effects in DF and PFM of rocker profiles in healthy and patients with AT [3,27].

To date, clinicians do not specify (all) rocker design parameters. This study showed that negative effects on ankle power with rocker shoes with a proximally placed apex can partially be compensated by a smaller forefoot rocker radius. Moreover, while all rocker shoes in this study provide significant DF and PFM reductions, choosing smaller forefoot rocker radii are clinically more relevant as they reduce these parameters to a larger extent. The outcome for this research was not to provide the optimal shoes for patients, but the insight that smaller radii are more beneficial in off-loading the Achilles tendon. For clinical purposes, the sole thickness will always be minimized and a heel curve will be added. The findings from this study can improve prescriptions for rocker shoes in terms of forefoot rocker radius and is a next step in quantifying rocker design parameters in rocker shoe prescriptions. Future studies concerning forefoot rocker radii should use other shoe sizes, apex positions and apex angles to determine the influence of and relation between these three parameters.

5. Conclusion

This study showed that rocker shoes with proximal apex positions and small rocker radii induce larger reductions in DF and PFM, compared with larger rocker radii. As both effects are beneficial in off-loading the Achilles tendon the results have to be converted from 'study-shoes' to shoes for persons with Achilles Tendinopathy or for athletes to support load management. Therefore, shoe design should have small rocker radii at a proximal apex position to optimally offload the Achilles tendon. A uniform standardisation of the forefoot rocker radius is essential.

Declaration of Competing Interest

The authors report no declarations of interest.

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