

# Three-Dimensional Biomechanical Analysis of Rearfoot and Forefoot Running

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**Background:** In the running community, a forefoot strike (FFS) pattern is increasingly preferred compared with a rearfoot strike (RFS) pattern. However, it has not been fully understood which strike pattern may better reduce adverse joint forces within the different joints of the lower extremity.

**Purpose:** To analyze the 3-dimensional (3D) stress pattern in the ankle, knee, and hip joint in runners with either a FFS or RFS pattern.

**Study Design:** Descriptive laboratory study.

**Methods:** In 22 runners (11 habitual rearfoot strikers, 11 habitual forefoot strikers), RFS and FFS patterns were compared at 3.0 m/s (6.7 mph) on a treadmill with integrated force plates and a 3D motion capture analysis system. This combined analysis allowed characterization of the 3D biomechanical forces differentiated for the ankle, knee, and hip joint. The maximum peak force (MPF) and maximum loading rate (LR) were determined in their 3 ordinal components: vertical, anterior-posterior (AP), and medial-lateral (ML).

**Results:** For both strike patterns, the vertical components of the MPF and LR were significantly greater than their AP or ML components. In the vertical axis, FFS was generally associated with a greater MPF but significantly lower LR in all 3 joints. The AP components of MPF and LR were significantly lower for FFS in the knee joint but significantly greater in the ankle and hip joints. The ML components of MPF and LR tended to be greater for FFS but mostly did not reach a level of significance.

**Conclusion:** FFS and RFS were associated with different 3D stress patterns in the ankle, knee, and hip joint, although there was no global advantage of one strike pattern over the other. The multimodal individual assessment for the different anatomic regions demonstrated that FFS seems favorable for patients with unstable knee joints in the AP axis and RFS may be recommended for runners with unstable ankle joints.

**Clinical Relevance:** Different strike patterns show different 3D stress in joints of the lower extremity. Due to either rehabilitation after injuries or training in running sports, rearfoot or forefoot running should be preferred to prevent further damage or injuries caused by inadequate biomechanical load. Runners with a history of knee joint injuries may benefit from FFS whereas RFS may be favorable for runners with a history of ankle joint injuries.

**Keywords:** running biomechanics; 3D motion analysis; joint stress; maximum peak force; loading rate; forefoot strike; rearfoot strike

Running is one of the most popular sports throughout the world. Basically, 2 types of foot-strike pattern are known to runners. More than 85% of shod runners use the rearfoot strike (RFS) pattern, where the heel is the first part of the foot to contact the ground.<sup>9,14</sup> Other runners perform the forefoot strike (FFS) pattern, with the mid- or forefoot first hitting the ground.<sup>10</sup> Extrinsic factors can influence the preferred strike pattern. For example, on a steep incline, runners tend to FFS, whereas RFS is favored in descending

running.<sup>4,21</sup> The different strike patterns lead to different strains within the lower limb joints.

Articular cartilage is adapted to enormous compressive forces, and as long as the stress levels are within a physiological range, there is no permanent impairment on the structural integrity. However, damage caused by overuse, with inadequate biomechanical loading and repetitive joint injuries, will accumulate over time and promote cartilage degeneration, ultimately leading to osteoarthritis.<sup>3</sup> Detrimental stress levels may also cause other structural or functional deficits, such as medial tibial stress syndrome, which has been shown to occur at a higher incidence in rearfoot runners than in forefoot runners.<sup>6</sup> Biomechanical research

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aims to identify patterns with adverse motion-related joint forces. As a consequence of such research, the modification of individual running techniques may serve to reduce or prevent acute and chronic joint overuse and degeneration.

Several studies have shown a connection between high loading and cartilage damage on a cellular level. In vitro analyses have demonstrated that the compression of cartilage with high magnitudes of forces and a high velocity of loading, including inadequate shear stress, induce irreversible cartilage damage, including cell death and formation of fissures, within the extracellular matrix.<sup>13,16,18-20,22,29</sup> This problem is even more relevant for patients with previous joint injuries associated with joint instability and incongruity of the articulating surfaces. These functional and anatomic changes, in turn, are associated with increased peak contact stress and stress rates within the joints.<sup>17,26</sup> Thus, inadequate compressive forces and excessive shear stresses and loading rates (LRs) should be minimized to retain the integrity of the joint structures in the long term.

The purpose of this study was to analyze joint kinetics in runners performing either an FFS pattern or an RFS pattern. As FFS is considered the more natural foot-strike pattern,<sup>15</sup> we hypothesized that FFS is associated with less inadvertent joint stresses than RFS and thus may be favorable for runners. These 2 common foot-strike patterns have previously been compared with regard to the ground reaction force (GRF) related to joint compression and shear stress.<sup>1</sup> However, a differential analysis for the ankle, knee, and hip joint in terms of a 3-dimensional (3D) analysis of forces has not been performed so far. A recent study by Rooney and Derrick<sup>24</sup> focused on the loading pattern of runners in different joints of the lower limb, but that study investigated only axial forces. Our experimental setup included a multimodal analysis combining a treadmill with integrated force plates and a 3D motion-capturing system, which allowed us to separately analyze the different joints of the lower extremity in a 3D pattern. Our multimodal approach analyzed the stress profiles in the different joints by decoding the joint reaction forces (JRF) and LR of RFS and FFS in their 3 ordinal components.

## METHODS

### Participants

Voluntary male runners (N = 22), performing at least 1 running session a week (at least 1 hour or 10 miles a week), were recruited from a triathlon squad. The participants had no reported lower limb injuries within the past

6 months and no other orthopaedic, cardiovascular, or neurological diseases. There was no leg length discrepancy and no malalignment of the lower limb in any participant. Among the study population, 11 participants were self-rated habitual rearfoot strikers (hRF group; age = 30.9 ± 7.0 years, weight = 85.0 ± 11.0 kg, height = 1.86 ± 0.07 m) and 11 were self-rated habitual forefoot strikers (hFF group; age = 28.5 ± 8.0 years, weight = 79.1 ± 9.0 kg, height = 1.83 ± 0.09 m). No statistically significant differences were detected between the groups ( $P > .05$ ). An institutional ethics committee approved the study, and written informed consent was obtained from all participants.

### Data Acquisition

Three-dimensional kinematic and kinetic data were obtained using a Qualisys (Qualisys AB) motion capture system, including 8 Oqus 300 cameras and 1 Oqus 100 camera sampling at 200 Hz. The cameras were arranged around an instrumented split-belt treadmill with integrated force plates (Bertec Corporation) sampling at 1000 Hz. Framewise camera synchronization was ensured by the capturing software Qualisys QTM 2.8.

Spherical reflective markers were placed on 38 locations of the pelvis and lower limbs in a standardized pattern according to anatomic palpation guidelines.<sup>27</sup> The marker positions defined by skeletal landmarks included the anterior and posterior iliac spines, the greater trochanters, the medial and lateral femoral epicondyles, and the medial and lateral malleoli. Clusters of 4 markers were positioned laterally on each thigh and lower leg. Foot markers were attached on the shoes above the first, second, and fifth metatarsal head and on the aspect of the Achilles tendon insertion above the calcaneus. The knee and hip markers and the thigh-cluster served as tracking markers for the thigh. The ankle markers and the lower-leg cluster served as tracking markers for the lower leg. The pelvis was tracked by the pelvis markers.

### Protocol

Prior to starting, a warm-up phase on the treadmill was provided as desired by the participant, including a 5-minute adaption phase.<sup>33</sup> After a preceding 10-second static standing trial, the habitual foot-strike pattern of each participant was recorded by motion capture of a 30-second run at 3.0 m/s (6.7 mph). Then, the participants were instructed as to the differences between RFS and FFS, according to previous studies.<sup>28,30,31</sup>

The habitual strike pattern and intentional RFS or FFS patterns were quantified by determining the strike index

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Ethical approval for this study was obtained from the Friedrich-Alexander-University Erlangen-Nürnberg (FAU).

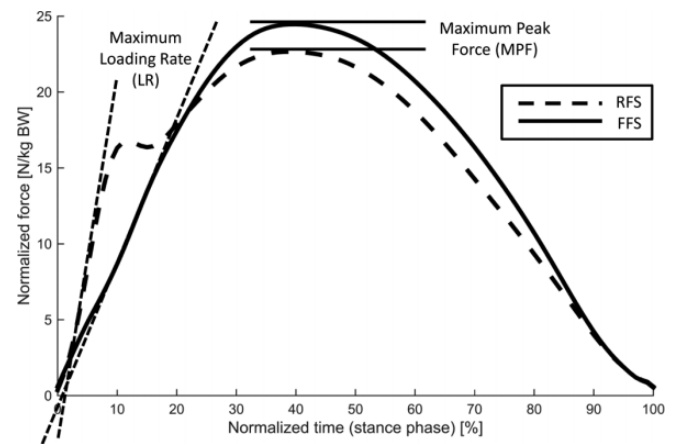
(SI). The SI was defined as the center of pressure (COP) location at the initial contact of the foot to the ground and was reported as a percentage of the imaginary line segment between the center of the ankle joint and the first metatarsal head. RFS was defined as the COP being posterior to the center of the ankle joint (indicated by negative SI values) or less than or equal to 20% of the line segment between the ankle joint and the first metatarsal head. Correspondingly, FFS was defined as the COP being anterior to the 20% of the described distance. According to previous studies,<sup>1,28</sup> the definition of FFS also included those participants with a midfoot strike pattern, since the biomechanical aspects of the FFS and midfoot strike closely resemble one another. After determining the SI, we classified each participant into either the hRF group ( $n = 11$ ) or the hFF group ( $n = 11$ ). This classification fit with the runner's self-assessment in all cases.

Next, each participant was asked to intentionally simulate both the RFS and FFS patterns separately ( $n = 44$  simulations). The measurement for evaluating the intentional RFS and FFS started with a 10-second static standing trial, followed by 2 running trials performing RFS or FFS at 3.0 m/s, respectively. Allowing an additional adaption phase of 5 minutes to the final speed, the motion capturing for each trial lasted for 1 minute. Between the trials, a recovery phase was provided as desired by the participant. All recording sessions were performed by the same investigator. The individual running shoes the participants wore in this study were all characterized by a moderate heel-to-toe drop (mean,  $9.2 \pm 2.4$  mm). There were no additional biomechanical insoles or foot orthoses fitted into the participants' running shoes.

## Data Analysis

Data preprocessing was performed in Visual 3D (C-Motion) and included the following steps: The offset of the force plates was corrected during the airborne phase. Using the marker positions detected in the static standing trial and the individual's body height and weight, a virtual biomechanical model of each participant was generated, resulting in 7 lower body segments (feet, lower legs, thighs, and pelvis). The marker and force data were filtered using a Butterworth low-pass filter with frequency cutoffs of 12 and 30 Hz, respectively. The strike-events "ground contact" and "toe off" were detected based on a threshold of 80 N on the vertical GRF. The stance phases were defined by normalizing the time between these 2 events to 101 points using a cubic spline interpolation, which results in a stance phase that is represented by 100%. JRFs were extracted using inverse dynamics<sup>23,32</sup> and were normalized to body weight. In addition, the duration of the stance time and the location of the COP in relation to the marker positions were detected.

Further data processing was done in MATLAB (R2014b, MathWorks Inc). The values for the stance time, the location of the COP and the time-dependent force curves of the JRF were averaged for the right and the left side of all steps of a single trial. The average JRF was determined for each joint separately and the 3D components, including the vertical (V), anterior-posterior (AP), and medial-lateral (ML) axis of the JRF, were calculated. Figure 1 exemplarily shows the time-



**Figure 1.** Time-dependent force pattern obtained from one representative participant performing a forefoot strike (FFS) and a rearfoot strike (RFS). MPF and maximum LR were determined and used for statistical analyses. BW, body weight.

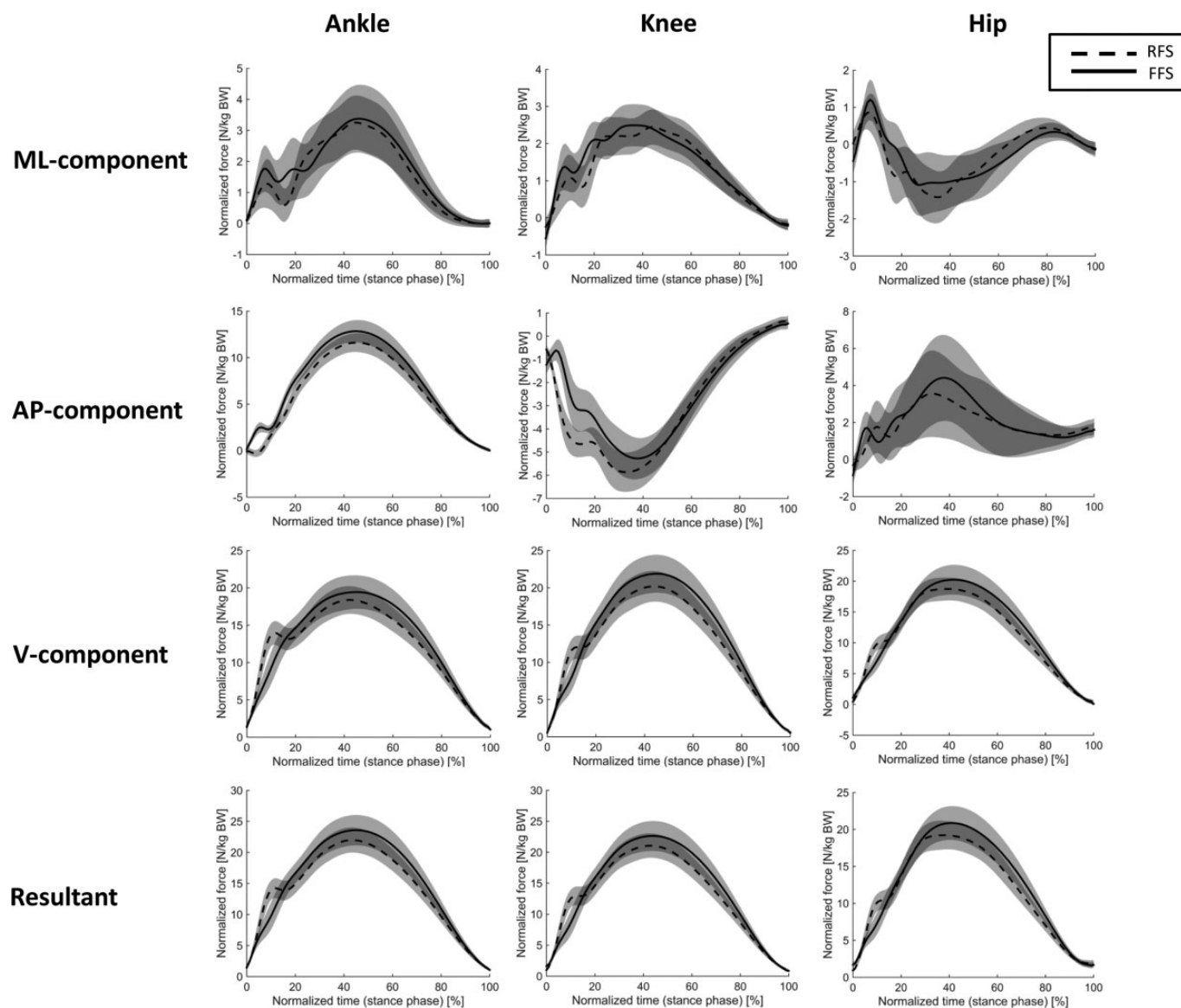
dependent force graphs that are typical for RFS and FFS. The analysis of the 2 strike patterns was based on the detection of the maximum peak force (MPF) and the instantaneous LR for each joint in all 3 ordinates: The magnitude of the MPF represents the absolute stress value on the joint in the respective direction. The maximum LR represents the greatest slope of the time-dependent JRF graph, which is obtained by differentiation of the graph as a function of time.

## Statistics

Statistical analysis was performed using GraphPad Prism 6 (GraphPad Software Inc). The differences of the mean values of the group- and strike-dependent variables were analyzed by 2-way analysis of variance multiple comparison followed by Tukey posttests ( $\alpha = .05$ ). For intraindividual comparison, group-independent paired  $t$  tests for the 24 variables of the force data were performed using a Bonferroni correction ( $\alpha = .0023$ ).

## RESULTS

The determination of the SI revealed significant differences between the intentional FFS and RFS ( $P < .001$ ). Interestingly, there was a trend that the respective non-habitual strike pattern was exaggerated. Thus, hFF runners landed farther posterior than hRF runners when performing intentional RFS, and hRF runners landed farther anterior than hFF runners when performing intentional FFS. The negative values of the mean SI of hFF runners performing RFS indicated that the COP at the initial landing phase was slightly behind the ankle joint, whereas hRF runners landed slightly anterior to the center of the ankle joint (SI: hRF group =  $2.1\% \pm 12.4\%$ , hFF group =  $-7.0\% \pm 12.7\%$ ;  $P = .65$ ). Correspondingly, when performing FFS, the COP of the hRF group at the initial ground contact was located more anterior than that of the



**Figure 2.** Overview of the time-dependent force patterns as ensemble graphs of all participants. The dashed lines represent the mean values of rearfoot strike (RFS) and the solid lines represent those of forefoot strike (FFS). The shaded range adjoining the graphs represent the respective standard deviation. AP, anterior-posterior; BW, body weight; ML, medial-lateral; V, vertical.

hFF group (SI: hRF group =  $90.6\% \pm 23.8\%$ , hFF group =  $87.1\% \pm 21.0\%$ ;  $P = .97$ ).

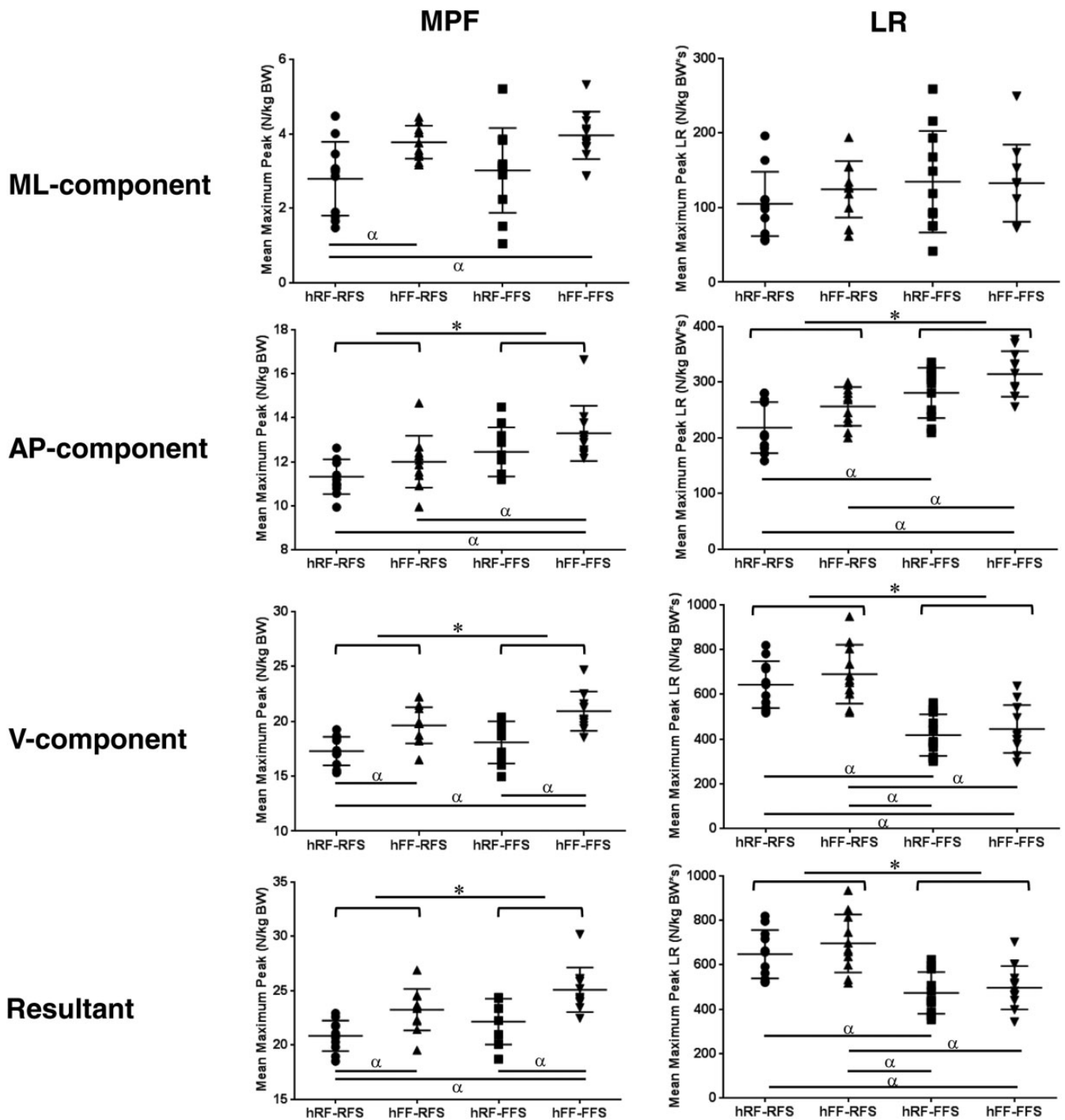
Interestingly, the participants in the hFF group generally had a statistically significantly shorter ground contact time compared with those in the hRF group, which was observed for both FFS and RFS (RFS: hRF group =  $259 \pm 20$  ms, hFF group =  $236 \pm 20$  ms,  $P = .03$ ; FFS: hRF group =  $243 \pm 16$  ms, hFF group =  $220 \pm 19$  ms,  $P = .03$ ).

Figure 2 provides an overview of the time-dependent force patterns in their 3D components, which were obtained from the 22 participants performing either RFS or FFS. In particular, the vertical and resultant JRF normalized to the body weight typically show the characteristic “double-peak curve” for RFS and “single-peak curve” for FFS. The diagrams illustrate the differences in the magnitude of the

force values between the 3 ordinal components, with the vertical component being considerably higher than the AP and ML components. The average magnitudes of V-MPF and V-LR were 92% and 96%, those of AP-MPF and AP-LR were 33% and 46%, and those of ML-MPF and ML-LR were 11% and 24% compared with the respective resultant JRF.

For analyzing the strike patterns, the mean maximum values of MPF and LR were separately determined for the ankle, knee, and hip joints in their 3D components and their resultant values (Figures 3-5, respectively). A number of significant strike-specific (RFS vs FFS) and group-specific (hRF vs hFF) differences were found.

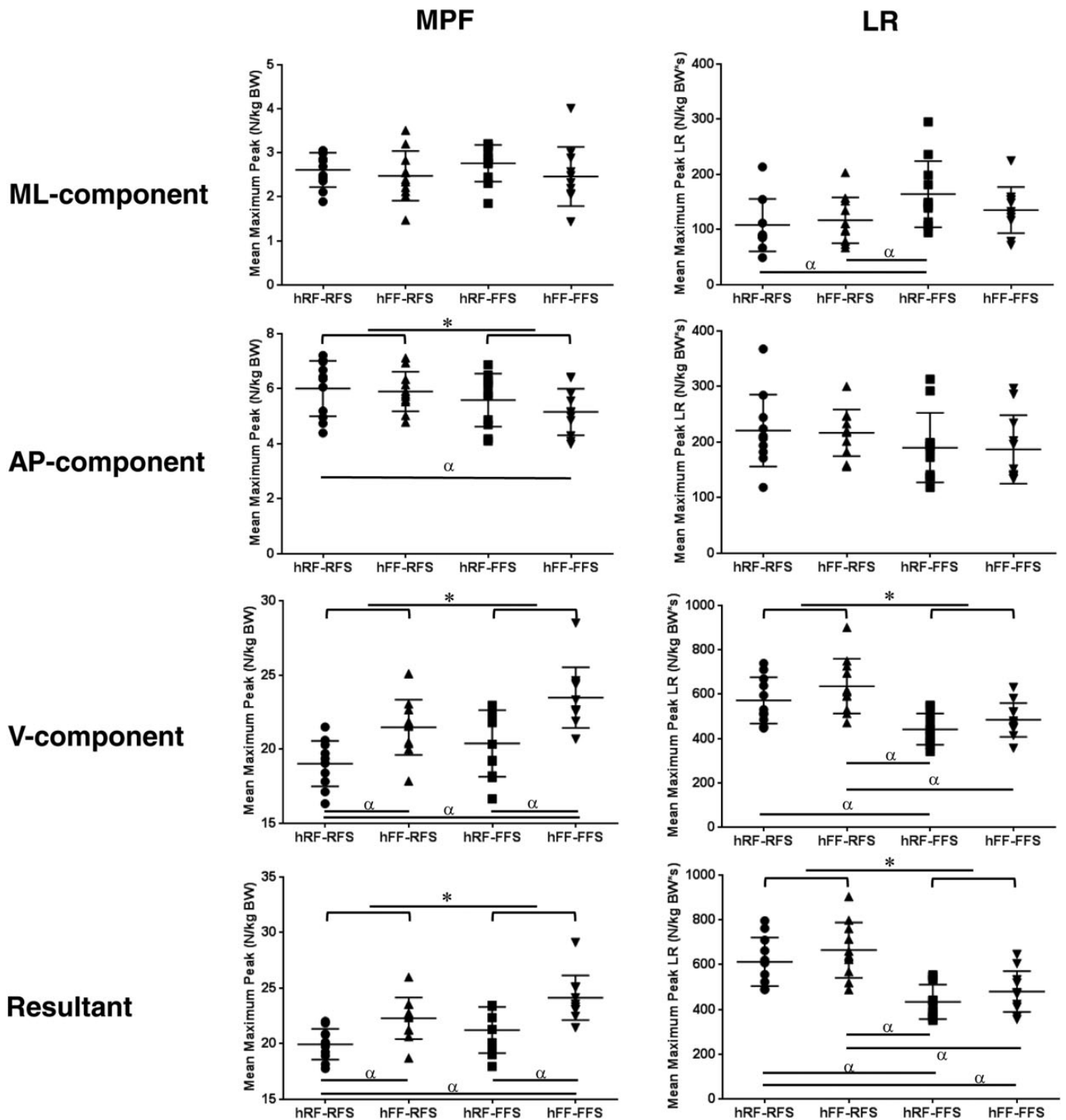
In the ankle joint (Figure 3), FFS was associated with higher AP-MPF ( $P < .0001$ ), V-MPF ( $P < .0001$ ), and resultant



**Figure 3.** Analysis of the maximum peak force (MPF) and loading rate (LR) occurring in the ankle joint. Shown are the mean maximum values determined for all 3-dimensional components and the resultant vector. Dot-plot diagrams show the means and standard deviations. Significant differences between the groups (habitual rearfoot [hRF], habitual forefoot [hFF]) and respective strike patterns (rearfoot strike [RFS], forefoot strike [FFS]) are denoted by “α” ( $P < .05$ ; analysis of variance followed by Tukey posttest). Differences between the 2 strike patterns (FFS vs RFS) are denoted by an asterisk ( $P < .0023$ ;  $t$  test with Bonferroni correction). AP, anterior-posterior; BW, body weight; ML, medial-lateral; V, vertical.

MPF ( $P < .0001$ ) compared with RFS. Interestingly, for both strike patterns (RFS and FFS), the hFF group was characterized by significantly higher V-MPF ( $P < .0001$ ) and resultant MPF ( $P < .0001$ ) than the hRF group. Concerning the LR in

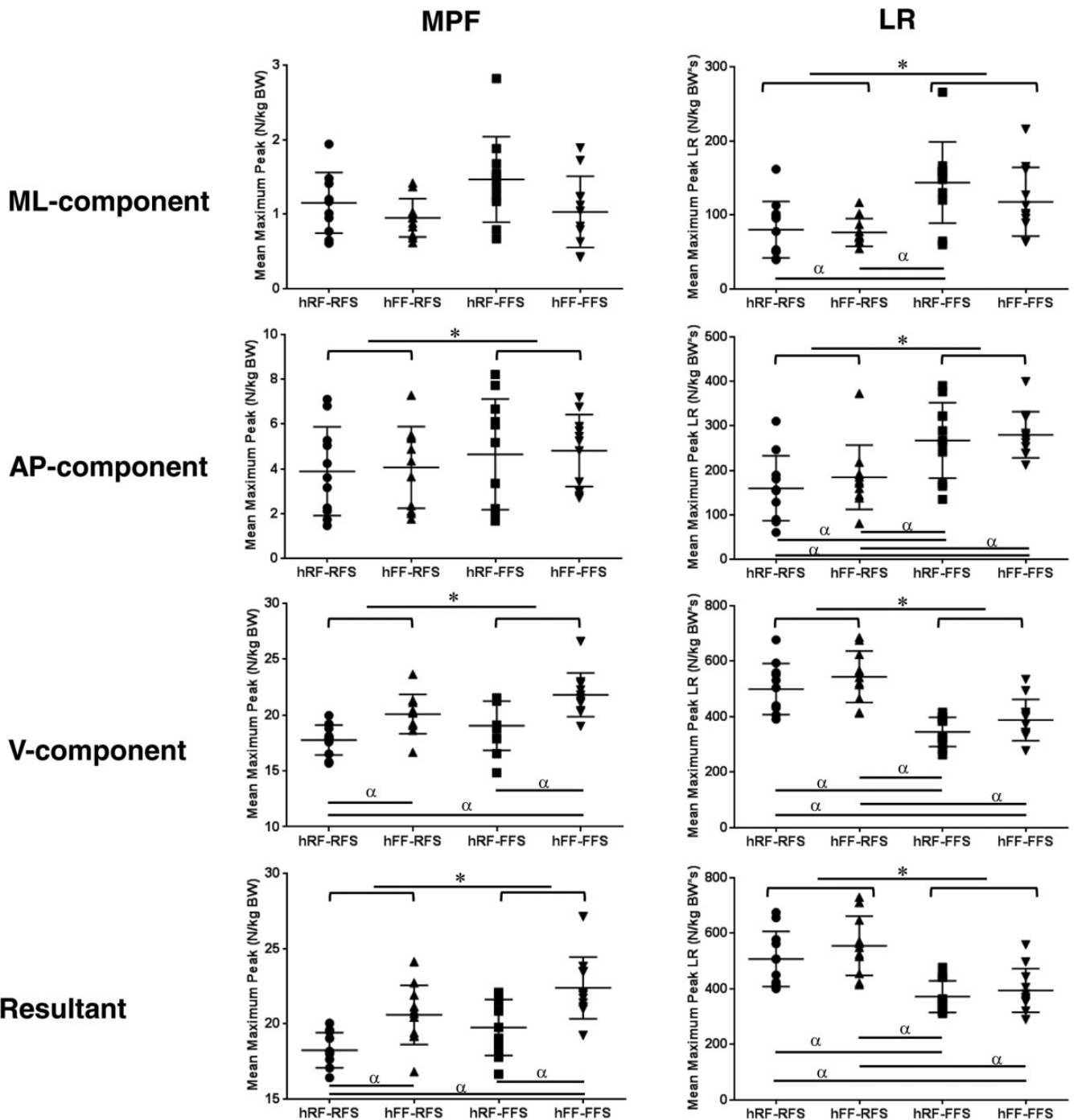
the ankle joint, FFS was associated with higher AP-LR ( $P < .0001$ ) but significantly lower V-LR ( $P < .0001$ ) and resultant LR ( $P < .0001$ ) compared with RFS. No group-specific differences were detected for the LR in the ankle joint.



**Figure 4.** Analysis of the maximum peak force (MPF) and loading rate (LR) occurring in the knee joint. Shown are the mean maximum values determined for all 3-dimensional components and the resultant vector. Dot-plot diagrams show the means and standard deviations. Significant differences between the groups (habitual rearfoot [hRF], habitual forefoot [hFF]) and respective strike patterns (rearfoot strike [RFS], forefoot strike [FFS]) are denoted by “ $\alpha$ ” ( $P < .05$ ). Differences between the 2 strike patterns (FFS vs RFS) are denoted by an asterisk ( $P < .0023$ ). AP, anterior-posterior; BW, body weight; ML, medial-lateral; V, vertical.

In the knee joint (Figure 4), FFS was associated with lower AP-MPF ( $P < .0001$ ) but higher V-MPF ( $P < .0001$ ) and higher resultant MPF ( $P < .0001$ ) compared with RFS. For both FFS and RFS, the habitual strike pattern had

significant influence on V-MPF ( $P < .0001$ ) and resultant MPF ( $P < .0001$ ), with the hRF group having significantly lower values than the hFF group. The analysis of the LR in the knee joint revealed significantly lower values during

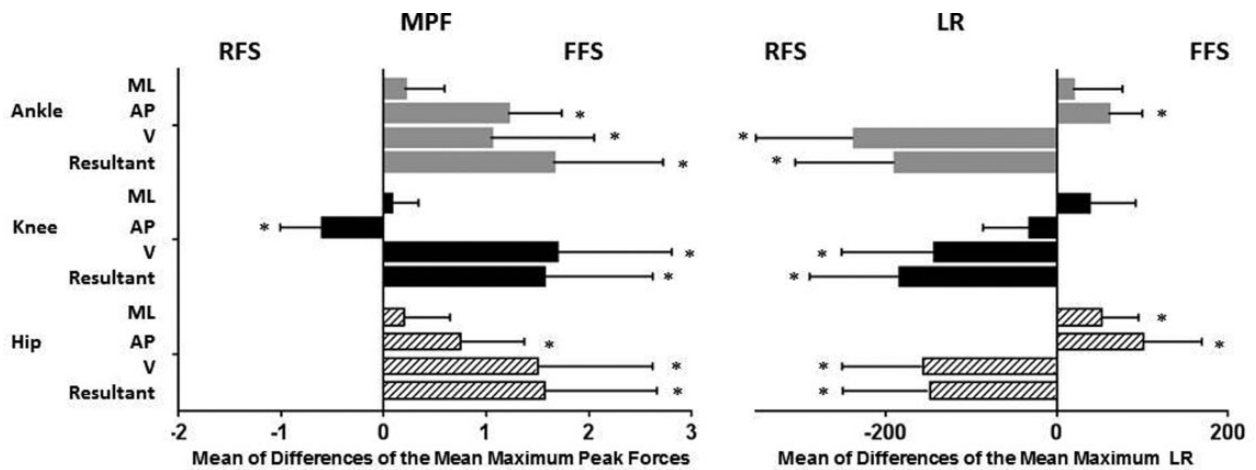


**Figure 5.** Analysis of the maximum peak force (MPF) and loading rate (LR) occurring in the hip joint. Shown are the mean maximum values determined for all 3-dimensional components and the resultant vector. Dot-plot diagrams show the means and standard deviations. Significant differences between the groups (habitual rearfoot [hRF], habitual forefoot [hFF]) and respective strike patterns (rearfoot strike [RFS], forefoot strike [FFS]) are denoted by “ $\alpha$ ” ( $P < .05$ ). Differences between the 2 strike patterns (FFS vs RFS) are denoted by an asterisk ( $P < .0023$ ). AP, anterior-posterior; BW, body weight; ML, medial-lateral; V, vertical.

FFS for V-LR ( $P < .0001$ ) and resultant LR ( $P < .0001$ ). Group-specific differences could not be detected in the knee joint.

In the hip joint (Figure 5), FFS was associated with higher AP-MPF ( $P < .0001$ ), V-MPF ( $P < .0001$ ), and

resultant MPF ( $P < .0001$ ) compared with RFS. For both strike patterns (FFS and RFS), the hRF group had significantly lower values for V-MPF ( $P = .0001$ ) and resultant MPF ( $P < .0001$ ). The analysis of the LR revealed significantly higher values during FFS for ML-LR ( $P < .0001$ ) and



**Figure 6.** Direct comparison of the mean maximum peak force (MPF) values and loading rates (LR) occurring in rearfoot strike (RFS) or forefoot strike (FFS) by showing the mean paired differences. The direct comparison was performed by paired *t* test of the mean MPF values and the mean maximum LR values (\* $P < .0023$ ; *t* test with Bonferroni correction). AP, anterior-posterior; ML, medial-lateral; V, vertical.

AP-LR ( $P < .0001$ ) but lower values for V-LR ( $P < .0001$ ) and resultant LR ( $P < .0001$ ). Group-specific differences were not detected for the LR in the hip joint.

Figure 6 summarizes the MPF and LR independent of the habitual strike pattern groups. The mean differences between RFS and FFS demonstrated generally higher MPF values during FFS in all 3 joints and all ordinates, except for AP-MPF in the knee joint. On the other hand, FFS was generally associated with lower LR values, except for AP-LR in the ankle and hip joints and ML-LR in the hip joint.

## DISCUSSION

To our knowledge, this is the first study investigating the 3D forces specifically for all 3 joints of the lower extremity by combining running on a treadmill with integrated force plates and simultaneous 3D motion capture analysis. The aim of this study was to establish individual recommendations for runners to reduce excessive compressive or shear stress focusing on the different joints. So far, most studies have compared the biomechanics pattern of RFS and FFS by only measuring the vertical forces based on the GRF without differentiating between the different joints.<sup>11,15,28</sup> Others have implemented the differentiation between different joints of the lower limb focusing primarily on axial contact forces in forefoot and rearfoot runners.<sup>24</sup> Generally, shear forces are much smaller than the vertical forces that arise during running and therefore may not contribute to an injury potential.<sup>1</sup> However, a more detailed analysis in a recent study combining 3D GRF and 3D motion analysis demonstrated relevant amounts of shear stress arising during running, in particular when performing FFS.<sup>1</sup> Indeed, the data of the current study confirmed that shear forces amount to relevant levels during running. Thus, both the AP and the ML components must not be neglected, as their average values are within the range of one-third to one-half of the resultant MPF and LR.

Shear forces may not necessarily induce acute cartilage damage or new injuries in otherwise healthy joints, since articular cartilage is well adapted to such shear force patterns within the physiological range.<sup>2,3</sup> However, for a previously injured joint with instability or pre-existing cartilage damage, such relatively small differences in shear forces within the detected range may gain relevance, particularly during the exposure to highly repetitive force patterns associated with excessive running.<sup>8</sup> Therefore, having the accumulation of microdamage during several training sessions and a longer time period in mind, it may be worthwhile to consider even minor differences in the biomechanical force pattern. Repetitive inadequate loading stress may induce not only cartilage damage but also other overuse syndromes such as medial tibial stress syndrome.

The study data demonstrated that running with FFS is associated with moderate but significant higher values for the MPF compared with RFS. This observation was found in all 3 joints of the lower extremity. In contrast, FFS was associated with lower values for the vertical and resultant LR compared with RFS in all 3 joints. Our findings basically confirm the data of the literature, with FFS leading to higher MPF and RFS leading to higher LR.<sup>11</sup> The higher vertical LR in RFS may be ascribed to the first impact peak occurring immediately in the early part of the stance phase by landing directly with the heel.<sup>1,11,15</sup> The higher vertical MPF in FFS may be a consequence of the reduced ground contact time when performing FFS. However, our joint-specific analysis in all 3 ordinates was able to reveal differences in the stress profile between joints. Interestingly, FFS led to a higher AP component of the MPF and LR in the ankle and hip joint. This finding is consistent with recent studies analyzing joint forces, which revealed that FFS is associated with higher joint stress in the ankle joint.<sup>25,30</sup> Based on these findings, it may be recommended for runners with unstable ankle joints or hip problems to perform RFS.



On the other hand, we were able to show that FFS was associated with significantly lower AP-MPF in the knee joint. This also confirms the results of recent studies that were based on calculations of joint angles and moments, which determined lower patellofemoral joint contact forces for FFS compared with RFS.<sup>12,28</sup> Thus, FFS may be favored for runners with unstable anterior cruciate ligaments, anterior knee pain, or patellofemoral cartilage degeneration. Indeed, data from a recent study favored a change from a rearfoot to a nonrearfoot strike pattern in patients with patellofemoral pain.<sup>5</sup>

In the hip joint, the shear force and LR pattern were comparable to those of the ankle; also, a higher MPF but lower vertical LR was found in the hip joint for FFS. However, due to the anatomic position of the hip joint close to the center of the body, biomechanical analysis of the hip joint is difficult to interpret, with only few and partly contradictory data in the literature so far.<sup>25,30</sup>

To date, there has been limited knowledge of either excessive MPF or excessive LR having a stronger detrimental influence on the metabolism and integrity of articular cartilage. A recent study compared the effect of maximum strain and impact velocity on cartilage explants and demonstrated detrimental effects on cell viability and integrity of the matrix.<sup>29</sup> In another study, loading of cartilage explants with a constant compression force but applying 2 different LRs revealed more severe matrix damage but a lower degree of cell death for the higher LR compared to the lower LR.<sup>7</sup> The results of these recent studies<sup>7,29</sup> indicate that the maximum peak stress and the strain rate exert different effects on cartilage damage: High forces rather promote chondrocyte death, whereas high LR (stress rate) induces damage to the extracellular matrix. As FFS results in higher MPF values and RFS in higher LR values, both strike patterns have a potential to injure cartilage. Further research is needed in this context to estimate if either MPF-induced cell death or LR-induced matrix damage plays a greater role in the induction of osteoarthritis.

Furthermore, we were able to detect an interesting group effect: The hFF group was associated with significantly higher force values for the vertical axis and resultant force in all 3 joints compared with the hRF group. This effect was observed in both the RFS and the FFS patterns. This finding is in agreement with previous studies, which found a greater peak vertical ground reaction force for habitual forefoot strikers.<sup>1,31</sup> There are 2 possible reasons for this finding: First, the average ground contact time of runners in the hFF group was significantly shorter than that of the hRF-group, which was independent of the RFS and FFS patterns. Thus, a shorter stance time and a more dynamic running style contributed to higher peak forces, at least in the vertical axis. A second reason for this finding can be ascribed to the observation that the participants exaggerated the nonhabitual strike. This was shown by the fact that participants in the hFF group landed more posterior to the heel than those in the hRF group when running RFS. Correspondingly, participants in the hRF group landed more anterior and closer to the toes than those in hFF group when running FFS. The differences in the SI may have contributed to lower MPF values in the hRF group. Similar group-specific differences

were reported in a recent study that demonstrated a significant correlation between the SI and the vertical force and LR.<sup>1</sup> Furthermore, the hRF runners may have to better focus on the FFS-running technique and thus better absorb impacts by an activated neuromuscular system.<sup>1</sup> The adoption of RFS by hFF runners may have elicited a more passive and rigid ground contact.

## CONCLUSION

This study demonstrates that FFS and RFS are associated with different biomechanical stress patterns in the ankle, knee, and hip joints. There is no global advantage of FFS compared with RFS on the joint stresses, and therefore our hypothesis that FFS is more beneficial for runners needs a more differential assessment. FFS was generally associated with higher MPF but significantly lower LR, at least in the vertical axis. Further research on the detailed mechanisms of cartilage damage, including cell death and matrix disruption, is necessary to assess the different biological impacts of the MPF and LR on the integrity of articular cartilage. Nevertheless, this study established 2 recommendations: RFS is associated with lower shear stress in the ankle joint and, thus, may be recommended for runners with unstable ankle joints. FFS is associated with lower AP forces in the knee joint and, thus, may be favorable for runners with anterior knee pain or an unstable anterior cruciate ligament.

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