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Mechanical Advantages and Disadvantages of a Lower Limb Using Forefoot to Heel Strike Landing †

Takayuki Koike [1,*] and Norimasa Yamada [2]

[1] Department of Innovative Engineering, Faculty of Science and Technology, Oita University, 700 Dan-Noharu, Oita-City 870-1192, Japan
[2] Department of Sport and Physical Education, School of Health and Sport Sciences, Chukyo University, 101 Tokodachi, Kaizu-cho, Toyota, 470-0393, Japan; nyamada@sass.chukyo-u.ac.jp
* Correspondence: t-koike@oita-u.ac.jp; Tel.: +81-97-554-7720
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Abstract: A previous study reported that habitually barefoot Kenyan distance runners tend to use a mid-foot strike or a forefoot-heel strike (FHS). Current findings indicate FHS helps enhance Kenyans' running performance. However, no study has investigated how FHS modulates leg stiffness (k_{leg}) and altered running velocity with changes in k_{leg}. Because vertical displacement of the centre of mass and k_{leg} during hopping are applicable to the running process, this study investigated how FHS affects k_{leg} and hopping frequency ($f_{hopping}$) during hopping. Subjects hopped at 2.2 Hz with normal hopping (NH-2.2Hz) and at a comfortable frequency with FHS (FHS-CF). According to each subject's comfortable frequency at FHS-CF, they were divided into higher (HG, 2.49 ± 0.11 Hz) and lower (LG, 2.16 ± 0.19 Hz) groups. With FHS-CF, the flight duration in HG was significantly shorter than that in LG. k_{leg} in HG was greater than that in LG. Negative work in the first half of the stance phase and positive work in the second half of the stance phase at all three joints were smaller in HG than in LG. The touchdown angle was larger and angular displacements at the joints were smaller in HG than in LG. The findings indicate that when hoppers used FHS, they increased their preferred $f_{hopping}$ by stiffening their leg joints during the stance phase and jumping with a lower height than in normal hopping; additionally, it is important to increase the touchdown joint angle for a stiffened joint.

Keywords: hopping; forefoot-heel strike; preferred hopping frequency; leg stiffness; mechanical joint work

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1. Introduction

A recent anthropometrical study reports that Kenyan distance runners who live in the Rift Valley Province and habitually run barefoot tend to use either a forefoot-heel strike (FHS) or a mid-foot strike, while habitually shod runners use a heel–toe strike (HTS) [1]. This indicates that habitual differences in footwear influence foot-strike skills, FHS is used to dissipate impact force during barefoot running, and Kenyan habitual barefoot runners change from HTS to FHS to attain high-speed running. Consequently FHS may be a reason to achieve high-speed running. However, although previous studies [2] investigated the relationship between the foot strike patterns and waveforms of the ground reaction force (GRF), there is no study investigating how FHS affects kinetic variables in the whole leg during running or running velocities obtained from the centre of mass of the body (COM).

Previous studies investigated the relationship between running velocities and kinetic variables using a spring–mass model using body mass on a linear leg spring [3,4], with leg stiffness (k_{leg}) representing the relationship between internal forces, such as muscular force, and external forces, such as GRF. The optimal k_{leg} determines preferred hopping frequencies ($f_{hopping}$) as 2.2 Hz [5] and stride frequencies during running as 1.16 steps/sec [6]. When both frequencies increase by 65%, k_{leg} for both increases twofold [6], indicating that findings obtained for hopping are applicable to running. The relationship between k_{leg} and $f_{hopping}$ is also reported in other studies [5,7]. However, there is no study investigating how k_{leg} is modulated during FHS-hopping and consequently, how it affects the preferred $f_{hopping}$. This study aimed to investigate how hoppers change their preferred $f_{hopping}$ with changes in k_{leg} when using FHS.

Previous studies have investigated the relationship between k_{leg} and $f_{hopping}$ under normal hopping (NH) in which the foot is plantarflexed at touchdown [5], showing that k_{leg} increases with increased ankle stiffness (k_{ankle}) and joint stiffness (k_{joint}) increases with increased touchdown joint angle [7,8]. k_{leg} during hopping while wearing a spring-loaded ankle-foot orthosis with plantarflexion resistance is similar to that obtained while wearing the orthosis with no resistance; moreover, knee joint stiffness (k_{knee}) increased to compensate for the decrease in biological k_{ankle} due to the plantar flexion resistance [9]. Furthermore, since the displacements of leg spring and joint decrease as k_{leg} and k_{joint} increase, there is negative and positive work at each joint (W_{joint}^- and W_{joint}^+, respectively), calculated by integrating the negative and positive periods of instantaneous joint power over each landing, indicating the work in each joint (W_{joint}) indirectly considered k_{joint} in each joint. This study will provide several interesting findings that differ from the previous studies because foot orientation in FHS is more dorsiflexed than in NH. Therefore, in the present study, it was hypothesized (1) that k_{leg} will increase with increases in preferred $f_{hopping}$ and (2) that this would be due to increased and decreased k_{knee} and mechanical work to compensate for decreases and increases in k_{ankle} and mechanical work, respectively, during FHS hopping.

2. Methods

2.1. Subjects and Measurements

Thirteen healthy subjects (seven men, six women, mean age 22.1 ± 1.4 [standard deviation, SD] years) gave informed consent prior to participation according to our institutional review board. One male subject was excluded due to an inability to match $f_{hopping}$ to the metronome beat. Subjects were instructed to perform NH and FHS hopping tasks with their arms akimbo on a force platform (AMTI, Watertown, MA, USA), which measures GRF and ground reaction moments, and matching the metronome beat set at 2.2 Hz in NH, which is considered as comfort hopping frequency in NH [4,7] (NH-2.2 Hz). Further, during FHS hopping, each subject was instructed to hop at a comfortable frequency (FHS-CF). The duration of the hopping tasks was 60 s; kinetic and kinematic data were measured from 10 to 15 s for data analysis. GRF and moments were sampled at 1000 Hz and stored in a PC via an Analog–Digital converter (Kyowa, Tokyo, Japan). GRF data were low pass filtered at 25 Hz using a fourth order Butterworth filter. Sagittal plane kinematics in right halves of lower limbs and the trunk were captured using a high-speed camera (120 fps, Photron, Tokyo, Japan). The kinematic data were synchronized with vertical GRF (Fz) higher than 20 N when the subject initially landed on the platform. Digitized reflective markers were mounted on the right halves of the subject's body using digitization software [10].

2.2. Data Analysis and Statisitical Analysis

The digitized and transformed 2-D coordinates of each marker were used to calculate the centre of mass for each segment and COM by an anthropometric parameter and to estimate joint torque (τ_{joint}) using standard inverse dynamics [11]. To precisely calculate τ_{joint} and k_{leg} in each stance phase, GRF and kinematic data in each stance phase of hopping were extracted. k_{leg} and k_{joint} were estimated by the slope of the curve between the vertical displacement of COM and Fz and the curve between angular displacement and torque in each joint during the first half of the stance phase (left hand of Figure 1). k_{leg} was calculated using the following equation:

$$k_{leg} = Fz_{max}/\Delta COM_{max} \quad (1)$$

where Fz_{max} indicates the maximum value of Fz and ΔCOM_{max} indicates the maximum value of vertical displacements in COM. k_{joint} was calculated using the following equation:

$$k_{joint} = \Delta\tau_{joint}/\Delta\theta_{joint} \tag{2}$$

where $\Delta\tau_{joint}$ indicates the maximum value of extensor torque and $\Delta\theta_{joint}$ indicates the angular displacement in each joint. Kinetic variables, such as k_{leg}, Fz and τ_{joint}, were normalized by dividing by the subject's body mass, thus removing the influence of body mass on the kinetic variables.

As mentioned in the introduction, the work in each joint (W_{joint}) indirectly considered the stiffness in each joint. The work was calculated using the following equation:

$$W_{joint} = \int_{T1}^{T2} \tau_{joint} \times \ \omega_{joint} \ dt \tag{3}$$

where ω_{joint} indicates the angular velocity of a joint and T1 and T2 indicate intervals of integrating joint power. τ_{joint} in the three joints exerted extensor torque, while ω_{joint} showed flexor and extensor direction in the first and second periods, respectively, of the stance phase. Negative and positive powers were obtained in the first and second halves of the stance phase. Therefore, negative and positive works (W_{joint}^{-} and W_{joint}^{+}, respectively) were obtained in each joint by integrating the negative and positive powers, respectively.

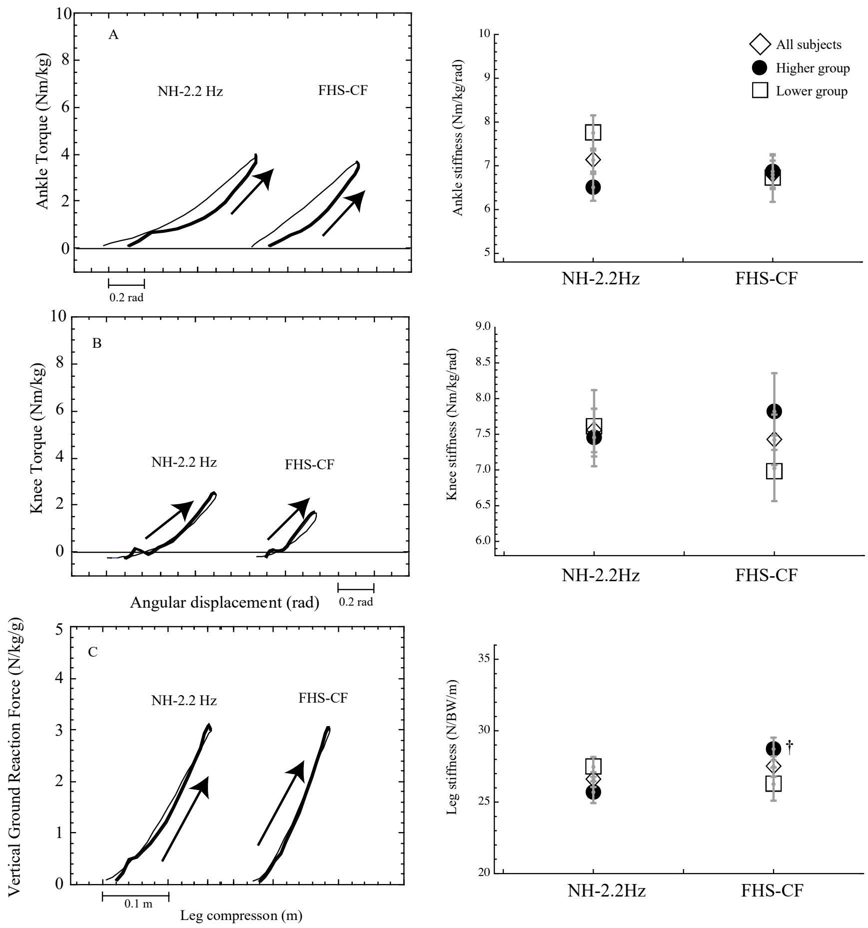

Figure 1. Representative examples of Fz-vertical displacement and torque-angular displacement curves and change in the mean and standard deviation of leg and joint stiffness in each hopping trial. The thick line indicates the first half of the stance phase, and the direction of vectors indicates the change in the curves during the first half of the stance phase. Open diamond (◇), black circle (●), and open square (□) indicate mean and SD values of the stiffness obtained from all subjects and Higher and Lower groups, respectively. The dagger (†) indicates a significant difference from the Lower Group ($p < 0.05$).

One-way analysis of variables with repeated measures with the two hopping tasks was applied to test for significant difference for each individual variable, with an α of 0.05. Based on each subject's preferred hopping frequency in FHS-CF, subjects were equally divided into higher and lower groups (see details in results); the Friedman test was applied to compare the hopping trials and the groups. Significant main effects were followed by the Mann–Whitney test.

3. Results

Table 1 shows kinematic and kinetic variables including preferred $f_{hopping}$ and k_{leg} in FHS-CF. Since there were individual differences in the preferred $f_{hopping}$, subjects were divided into a higher frequency group (Higher GP), which was > 2.2 Hz as determined by the mean – SD of the frequency, and lower frequency group (Lower GP), with a mean – SD values < 2.2 Hz. Consequently, as shown in Table 2, while the frequency obtained from all subjects was 2.31 ± 0.11 Hz, the frequency in the Higher and Lower GPs was 2.49 ± 0.15 Hz and 2.19 ± 0.13 Hz, respectively. The contact duration for Higher GPs at FHS-CF was the same as that at NH-2.2Hz. In addition, the flight duration of Higher GP at FHS-CF was significantly shorter than that at NH-2.2 Hz. k_{leg}, k_{ankle}, and k_{knee} were also compared between Higher GP and Lower GP. In the Higher GP, k_{leg} in FHS-CF significantly increased compared to that at NH-2.2 Hz and that in FHS-CF in Lower GP (Figure 1). However, there were no significant changes in k_{ankle} or k_{knee} between differences in hopping task or groups. Figure 2 shows W_{joint}^{+} and W_{joint}^{-} at the ankle, knee, and hip joints. In Higher GP, although W_{ankle}^{+} and W_{ankle}^{-} in FHS-CF was significantly lower than at NH-2.2 Hz, no significant difference in the mechanical work between FHS-CF and NH-2.2 Hz was found for the other joints. In FHS-CF, both W_{joint}^{+} and W_{joint}^{-} were significantly lower in Higher GP than in Lower GP.

Table 1. Individual mean and SD values of temporal parameters during FHS-CF.

Subject Number	1	3	4	5	6	7	8	9	10	11	12	13
f(hops/sec)	2.479 ± 0.265	2.157 ± 0.075	2.169 ± 0.057	2.485 ± 0.089	2.156 ± 0.179	2.636 ± 0.167	2.338 ± 0.055	1.906 ± 0.066	2.401 ± 0.067	2.557 ± 0.111	2.031 ± 0.078	2.310 ± 0.161
Group	H	L	L	H	L	H	H	L	H	H	L	L

'f' means hopping frequency, 'H' and 'L' mean that hoppers hopped with frequencies above and below 2.2 hops/sec, respectively.

Table 2. Kinematics and kinetics summary obtained from Higher and Lower groups.

Variables	NH-2.2 Hz				FHS-CF			
	Higher Group		Lower Group		Higher Group		Lower Group	
Hopping frequency (hops/sec)					2.49 ± 0.15		2.16 ± 0.13	
1st Peak Fz (N/BW) **	0 ± 0.00		0 ± 0.00		0.81 ± 1.38		1.33 ± 1.49	
2nd Peak Fz (N/BW)	3.24 ± 0.29		3.44 ± 0.47		3.09 ± 0.38		3.24 ± 0.66	*
Contact duration (sec)	0.30 ± 0.03		0.29 ± 0.03		0.28 ± 0.03		0.28 ± 0.04	
Aerial times (sec)	0.16 ± 0.03		0.18 ± 0.03	*	0.13 ± 0.04	1	0.20 ± 0.05	*
COM downward displacement (m)	0.13 ± 0.01		0.12 ± 0.02		0.11 ± 0.01	1	0.13 ± 0.01	*
Ankle displacement (rad)	0.59 ± 0.10		0.57 ± 0.07		0.45 ± 0.08	1	0.54 ± 0.07	*
Knee displacement (rad)	0.42 ± 0.07		0.39 ± 0.09		0.36 ± 0.07	1	0.50 ± 0.08	1,*
Hip displacement (rad)	0.18 ± 0.05		0.16 ± 0.06		0.17 ± 0.06		0.25 ± 0.06	
Ankle angle at touchdown (rad)	2.20 ± 0.12		2.16 ± 0.12		2.08 ± 0.09	1	2.06 ± 0.12	
Knee angle at touchdown (rad)	2.79 ± 0.08	*	2.68 ± 0.12		2.78 ± 0.09	*	2.72 ± 0.13	
Hip angle at touchdown (rad)	3.08 ± 0.13		3.00 ± 0.12		3.08 ± 0.13	*	2.99 ± 0.14	

"1" means significant difference from NH-2.2 Hz in same group ($p < 0.05$). * an asterisk means that the value was significantly larger than the other group. BW means subjkect's body weight, Fz means vetical ground reaction force. ** two asterisks mean that no statistical comparison was conducted because of a lower number of samples.

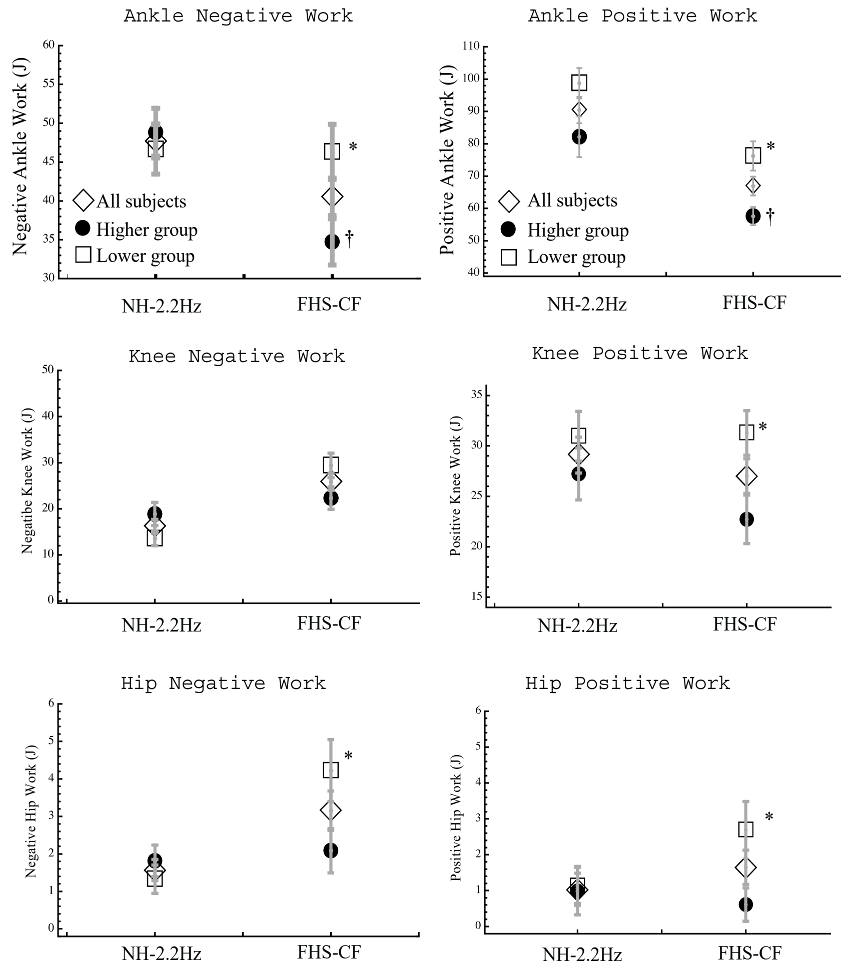

Figure 2. Change in the mean and SD values of negative and positive work at the ankle, knee, and hip joints in each hopping trial. The dagger (†) indicates a significant difference from NH-2.2Hz ($p < 0.05$). An asterisk (*) means the Lower group was significantly greater than the Higher group.

Table 2 shows the mean and SD value of the two peaks in Fz. At FHS-CF, the first peak of Fz at touchdown in Higher GP was smaller than that in Lower GP, although there were no significant differences in the peak between the groups. The second peak of Fz at mid-stance was significantly smaller in Higher GP than in Lower GP. In both Higher and Lower GPs, the touchdown angle at the ankle joint at FHS-CF was significantly smaller than that at NH-2.2 Hz. At FHS-CF, the touchdown angle at the knee and hip joints in Higher GP was significantly greater than that in Lower GP. For the Higher GP, angular displacements at the ankle and knee joints at FHS-CF were significantly decreased compared to that at NH-2.2 Hz. The displacement of FHS-CF obtained from Higher GP was significantly lower than that in Lower GP.

4. Discussion

The main findings of this study were that, based on the preferred hopping frequency $f_{hopping}$ at FHS-CF, when subjects were divided into Higher GP and Lower GP, in the Higher GP, the $f_{hopping}$ obtained at FHS-CF was higher than that obtained at NH-2.2 Hz. k_{leg} at FHS-CF was higher than that at NH-2.2Hz in higher GP, and at FHS-CF, k_{leg} in Higher GP was also lower than that in Lower GP. The results support the hypothesis of this study and correspond with previous studies stating leg stiffness k_{leg} increases with $f_{hopping}$ [5,7]. While the previous studies reported that downward displacement of COM decreased and contact duration shortened as $f_{hopping}$ increased with k_{leg}, the current study showed that although the displacement decreased, the flight duration also decreased.

However, in Lower GP, the flight duration increased as the displacement increased. The facts indicate that hoppers are able to increase the $f_{hopping}$ by decreasing the hopping height when using FHS.

When hoppers use a spring-loaded ankle-foot orthosis with plantar flexion resistance, their k_{leg} increased by increasing k_{knee} to compensate for the decreases in biological k_{ankle} due to the orthosis; consequently, $f_{hopping}$ increased [3]. Hence, it was hypothesized that preferred $f_{hopping}$ is enhanced by increasing k_{knee}. However, this hypothesis was rejected because, in Higher GP, k_{knee} did not vary in other hopping trials. This may be explained by a previous study which showed that k_{knee} increased by antagonistic activation between the plantar flexor, which is antagonistically activated against the spring for plantar flexor resistance, and the knee extensor [9]; in the current study, antagonistic activation may not have occurred because the muscular force in plantar flexion was decreased due to dorsiflexion movement that stretches the plantar flexor muscles and reciprocally deactivates them.

Furthermore, the W_{joint}^+ and W_{joint}^- at the lower extremity that indirectly represents modulation of joint stiffness showed that, in FHS-CF, W_{ankle}^+ and W_{ankle}^- decreased; however, work in Higher GP, with the exception of W_{knee}^-, was smaller than that in Lower GP. The reductions in the W_{joint} were caused by the decreases in extensor torque and/or angular displacement at the joints. Therefore, subjects in Higher GP hopped with their leg joints stiffened during the stance phase. The findings not only suggest that FHS enables increased $f_{hopping}$ with increasing k_{leg} by stiffening the ankle joint during the whole stance phase but also support the findings of previous studies that k_{leg} during hopping primarily depends on k_{ankle} [5].

In addition, the W_{joint} at the leg joints explains muscular activation and work at the leg extensor muscles across joints. Thus, the decreased or unchanged W_{joint} suggests the force for jumping exerted by leg extensor muscles is decreased. The 2nd peak of Fz occurred mid-stance during FHS-CF in Higher GP and was lower than that in Lower GP; indicating that the muscular force required for jumping exerted by subjects in Higher GP was lower than that in Lower GP. Meanwhile, in Lower GP at FHS-CF, the peak value of the impact force was larger, and furthermore, W_{joint}^+ and W_{joint}^- were greater compared with Higher GP. Concerning the exerting force and leg work, when humans hop on damped surfaces that absorb impact force, positive work for exerting jumping force is increased, and thus the peak value of Fz is increased as damping coefficients increase [12]. The authors explained this was due to humans compensating for the absorbed impact force, essentially used for jumping, by increasing their positive work for exerting a jumping force. The findings showing increases in W_{joint}^+ and W_{joint}^- at the leg joints in Lower GP at FHS-CF indicate it is difficult for subjects to increase their $f_{hopping}$ because they absorb the impact force by softening their leg joints and then exerted the force for leg extension for jumping; thus, this is consistent with earlier studies. Hence, stiffening the leg joints to utilize the impact force for jumping is enhanced at the preferred $f_{hopping}$ at FHS-CF.

The findings of this study may explain why distance runners that use FHS such as Kenyan runners are able to run with higher speed. We found that when subjects use FHS and stiffen their leg joint during the whole stance phase, it enables them to hop with a low jumping height, reducing W_{joint} of three leg joints and consequently, increase their preferred $f_{hopping}$. The findings are consistent with earlier studies investigating not only the higher stride frequency in Kenyan runners compared to others [13], but also that k_{leg} is increased with increases in stride frequency [6]. Therefore, Kenyan runners stiffen the leg joint and reduce W_{joint} during the stance phase.

In summary, when hoppers use FHS, a lower hopping height is needed to increase their preferred hopping frequency. To attain the low hopping height, it is necessary to stiffen the leg joint and exert less mechanical work during the stance phase, and the knee and hip joints are extended at touchdown. Furthermore, Kenyan runners run with a higher stride frequency by stiffening their leg joints during the stance phase.

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