Gait & Posture 107 (2023) 23–27

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Impact of pronated foot on energetic behavior and efficiency during walking

Wataru Kawakami [a], Yoshitaka Iwamoto [a,b], Junpei Sekiya [a], Mitsuhiro Ota [a], Yosuke Ishii [a,b], Makoto Takahashi [a,b,*]

[a] Graduate School of Biomedical and Health Sciences, Hiroshima University, Hiroshima, Japan
[b] Center for Advanced Practice and Research of Rehabilitation, Graduate School of Biomedical and Health Sciences, Hiroshima University, Hiroshima, Japan

ARTICLE INFO

Keywords:
Pronated foot
Walking efficiency
Energy
Foot biomechanics

ABSTRACT

Background: The longitudinal arch of the foot acts like a spring during stance and contributes to walking efficiency. Pronated foot characterized by a collapsed medial longitudinal arch may have the impaired spring-like function and poor walking efficiency. However, the differences in the energetic behavior during walking between individuals with pronated foot and neutral foot have not been considered.

Research question: How does the energetic behavior within the foot and proximal lower limb joints in pronated foot affect walking efficiency?

Methods: Twenty-one healthy young adults were classified into neutral foot and pronated foot based on the Foot Posture Index score. All subjects walked across the floor and attempted to have the rearfoot and forefoot segments contact separate force plates to analyze the forces acting on isolated regions within the foot. Kinematic and kinetic data were recorded by a three-dimensional motion capture system. The hip, knee, ankle, and mid-tarsal joint power was quantified using a 6-degree-of-freedom joint power method. To qualify total power within all structures of the foot and forefoot, we used a unified deformable segment analysis. Additionally, we calculated the center of mass power to quantify the total power of the whole body

Results: There is no difference in the mid-tarsal joint work between the pronated foot and neutral foot. On the other hand, pronated foot exhibited greater net negative work at structures distal to the forefoot during walking. Additionally, pronated foot exhibited less net positive work at the ankle and center of mass during walking compared to neutral foot.

Significance: Individuals with pronated foot generate the mid-tarsal joint work by increasing the work absorbed at structures distal to the forefoot, which results in reduced energy efficiency during walking. That energy inefficiency may reduce positive work at the ankle and affect the walking efficiency in individuals with pronated foot.

1. Introduction

Human walking is accomplished by the positive and negative mechanical work performed on the center of mass (COM) [1]. This mechanical work is performed by physiological tissues, including contributions from both active muscle contractions and passive soft tissue deformations, and affects the kinetic and potential energy of the body [2]. To maintain consistent walking speed, any mechanical energy dissipation within a walking cycle must be compensated by an equal amount of positive work [3]. During steady walking, it has been found that positive and negative work are exchanged, and the required net work is zero [2]. Therefore, it is important to reduce the energy loss and active work from the muscles for economical walking.

Elastic energy storage and return is known to contribute to walking efficiency by reducing active work demands on muscles [4,5]. The mid-tarsal joint which is the major joints spanning the medial longitudinal arch acts elastically during stance, compressing and recoiling in response to the load. The elastic behavior of the mid-tarsal joint has been described as a spring-like function, which allows mechanical energy to be stored and subsequently released during each stance [6]. Therefore, the midtarsal joint has been believed to have a significant role in walking efficiency. The spring-like function of the mid-tarsal joint has

* Correspondence to: 2-3, Kasumi 1-chome, Minami-ku, Hiroshima 734-8553, Japan.
E-mail address: biomec@hiroshima-u.ac.jp (M. Takahashi).

https://doi.org/10.1016/j.gaitpost.2023.09.003
Received 14 April 2023; Received in revised form 13 August 2023; Accepted 6 September 2023
Available online 15 September 2023
0966-6362/

been considered as passive and active process. In the passive process, the plantar fascia plays a key role for spring-like function. The plantar fascia exhibits viscoelastic behavior under tension, thereby contributing to the elastic recoil of the mid-tarsal joint. It has been reported that the plantar fascia provides between 8 % and 17 % of the mechanical energy required for a stride [6,7]. On the other hand, the intrinsic and extrinsic foot muscle contribute to the active process of spring-like function. The intrinsic foot muscles have been shown to undergo active lengthening and shortening during stance, which contribute to power absorption in early to mid-stance and power return and generation in late stance [8,9]. The extrinsic foot muscles provide both power absorption and generation capabilities during stance through their long tendons and connecting passive structures [10].

Meanwhile, in individuals with pronated foot, it has been demonstrated that the cross-sectional area and thickness of intrinsic foot muscles and plantar fascia are smaller compared to those with neutral feet [11]. Additionally, these differences have been found to be more pronounced with increasing severity of the pronation alignment [12]. These altered plantar structures in individuals with pronated foot can be considered to affect the spring-like function and thus walking efficiency. Indeed, Otman et al. reported that individuals with collapsed longitudinal arch exhibit increased energy cost and oxygen consumption during walking, and that use of appropriate arch support can improve these outcomes [13]. These findings indicate that reduced walking efficiency in individuals with pronated foot may be attributed to increased energy loss at distal foot structure due to impaired the spring-like function of the mid-tarsal joint. Additionally, more severe pronated alignment has been reported to be correlated with lower walking speed, stride length, and step width [14]. To maintain steady walking speed, increased energy loss at distal foot structure may need to be compensated by greater active work at proximal lower limb joints. We hypothesized that individuals with pronated foot exhibit 1) increased energy loss at distal foot structure due to the impaired spring-like function of the mid-tarsal joint, 2) increased active work at proximal lower limb joints, and 3) reduced walking efficiency. To verify our hypothesis, we investigated the differences in the energetic behavior within the foot and proximal lower limb joints between the neutral and pronated foot. Addressing these issues will advance our understanding the effect of foot structure on walking efficiency and enable innovative approaches to improve walking efficiency in individuals with pronated foot.

2. Methods

2.1. Subjects

Twenty-one healthy young adults without any disease or current illness that would affect walking participated in this study. Foot posture was evaluated using the Foot Posture Index (FPI) [15]. Based on the FPI score, all feet were classified into neutral foot (FPI score = 0 to +5) and pronated foot (FPI score ≥ 6). The FPI was evaluated by a single experienced assessor. Prior to the experiment, the intent and purpose of this study were explained to all subjects, and informed consent was obtained prior to their participation. This study was approved by the Ethical Committee for Epidemiology of Hiroshima University [Approval no. E-467-4].

2.2. Instrumentation and procedures

A three-dimensional motion capture system that included ten infrared cameras (Vicon Motion Systems, Oxford, UK, sampling frame rate 100 frames/s) recorded positional data and eight force plates (Tec Gihan TF-400-A, Uji, Japan, sampling frame rate 1000 Hz) acquired ground reaction forces (GRF).

Prior to measurement, a total of 67 reflective markers were attached to the following landmarks on both sides of each subject according to previous studies [16,17]: the temple, lateral end of the superior nuchal line, tragus, acromion, olecranon, ulnar styloid process, superior edge of the iliac crest, anterior superior iliac spine, posterior superior iliac spine, superior aspect of the greater trochanter, medial and lateral epicondyles of the femur, midpoint between the greater trochanter and the lateral epicondyle of the femur, medial and lateral tibial condyles, medial and lateral malleoli, midpoint between the lateral knee joint line and the lateral malleolus, superior apex of calcaneus, apex of calcaneal tuberosity, peroneal tubercle, sustentaculum tali, medial prominence of navicular bone, lateral centroid of cuboid bone, medial aspect of 1st metatarsal base, lateral aspect of 5th metatarsal base, midway between 2nd and 3rd metatarsal heads, centroid of hallux nail, superior aspect of 1st metatarsal head.

After instrumentation, subjects walked on a flat 10 m walkway at a self-selected walking speed. The subjects walked across the floor and attempted to have the rearfoot and forefoot segments contact separate force plates to analyze the forces acting on isolated regions within the foot [18]. The subjects were instructed to walk as normally as possible, while the investigators adjusted the starting positions to ensure appropriate foot contact. Three successful trials were obtained.

2.3. Data analysis

Data analysis was performed using the analysis software Nexus 2.1.1 (Vicon Motion Systems, Oxford, UK). Kinematic and kinetic data were low-pass filtered using a fourth-order Butterworth filter with cut-off frequencies of 6 Hz and 100 Hz, respectively. The head, thorax, pelvis, thigh, shank, rearfoot, forefoot, and hallux segments were created based on the obtained marker points. The pelvis, thigh, and shank segments separated the hip and knee were defined according to previous studies [16,19], and shank, rearfoot, forefoot, and hallux segment separated by the ankle, mid-tarsal, and metatarsophalangeal (MTP) joints were defined according to Bruening et al. [17]. Anthropometric parameters for mass, COM, and moment of inertia for the head, thorax, pelvis, thigh, and shank segment were obtained from the report by Okada et al. [20], and the rearfoot, forefoot, and hallux segment were calculated according to previous studies [18,21]. The whole-body COM displacement was calculated using coefficients of each body segment’s inertia.

Analyses were conducted on the data during the stance phase. The initial contact and toe-off were identified according to the vertical GRF using a threshold of 20 N. Joint angles were calculated the distal segment expressed relative to the adjacent proximal segment using a right-handed orthogonal Cardan xyz sequence of rotations [22]. The hip, knee, ankle, and mid-tarsal joint power was quantified using a 6-degree-of-freedom (6DOF) joint power method [23]. This technique has been shown previously to yield a mathematically complete estimate of joint power. 6DOF joint power was calculated using the following equation:

$$P_{6DOF} = F_{jt} \bullet \Delta v_{jt} + M_{jt} \bullet \omega_{jt} \quad (1)$$

P_{6DOF} is the summation of power due to the dot product of the joint force (F_{jt}) and the relative translational velocity between the distal and proximal segment ends (Δv_{jt}), and power due to the dot product of joint moment (M_{jt}) and the joint angular velocity (ω_{jt}), where the F_{jt} and M_{jt} are derived from inverse dynamics analysis. P_{6DOF} at the hip, knee, and ankle joints were computed using data from combined two force plates, and mid-tarsal joint was calculated using data from anterior force plate.

To qualify total power within all structures of the foot, we used a unified deformable (UD) segment analysis [24]. The UD segment model is a hybrid segment composed of a rigid component (i.e., reference segment) and a distal deformable component. The UD analysis quantifies the total power due to all structures distal to a chosen reference segment. In this study, we set the rearfoot and forefoot as reference segments to qualify power profiles within the foot and forefoot. UD-based power profiles were calculated using the following equation:

$$P_{UD} = F_{GRF} \bullet V_{COP\_distal} + M_{free} \bullet \omega_{RF} \quad (2)$$

The total mechanical power of structures distal to a chosen reference segment (P) can be quantified by summing the dot product of the total deformation velocity of the distal deformable component (V_{COP_distal}) and GRF (F_{GRF}) with the dot product of the free moment (M_{free}) and angular velocity of the reference segment (ω_{RF}). V_{COP_distal} was computed as:

$$V_{COP\_distal} = V_{RF\_COM} + (\omega_{RF} \times r_{COP/RF}) \quad (3)$$

Where V_{COM_distal} and ω_{RF} represent the translational and rotational velocity of the reference segment, and $r_{COP/RF}$ represents the distance from the center of pressure to the reference segment COM. P_{UD} at rearfoot segment was computed using data from combined two force plates, and P_{UD} at forefoot segment was computed using data from anterior force plate.

Additionally, we calculated the COM power to quantify the total power of the whole body [25]. It can be calculated by the dot product of the GRF and COM velocity.

$$P_{COM} = F_{GRF} \bullet V_{COM} \quad (4)$$

Mechanical work of structures distal to the rearfoot, distal to the forefoot, ankle, knee, hip joints, and COM during stance phase were calculated by time integration of power.

2.4. Statistical analysis

Statistical analysis was performed using EZR 1.54 (R, open-source), with the significance level set at 5 %. The normality of the data distributions were assessed using the Shapiro–Wilk test. Participants' characteristics, spatiotemporal parameters, and mechanical work at structures distal to the rearfoot, distal to the forefoot, hip, knee, ankle, mid-tarsal joints, and COM were compared between groups using independent *t*-test.

3. Results

The results of the participants' characteristics and spatiotemporal parameters are shown in Table 1. Pronated foot had significantly lower maximum COM acceleration during stance compared to neutral foot. There was no significant difference in spatiotemporal parameters between groups.

The results of the mechanical work during walking of the neutral foot and pronated foot are shown in Table 2 and Fig. 1. For the mechanical work at the mid-tarsal joint, there was no significant difference between groups. On the other hand, pronated foot performed significantly greater negative work and net negative work at the structures distal to the rearfoot compared to neutral foot. Furthermore, pronated foot performed significantly greater net negative work at the structures distal to the forefoot compared to neutral foot.

For the mechanical work at the lower limb joints, pronated foot performed less positive work and net positive work at the ankle during walking compared to neutral foot. There was no significant difference in the mechanical work at the hip and knee between groups.

For the mechanical work at COM, pronated foot performed less positive during walking compared to neutral foot.

Table 1
Subject characteristics and spatiotemporal parameters of the neutral foot and pronated foot groups.

	Neutral foot (n = 10)	Pronated foot (n = 11)
Age [year]	22 ± 1	22 ± 1
Sex [male/female]	6/4	5/6
Body height [m]	1.68 ± 0.08	1.64 ± 0.08
Body mass [kg]	59.4 ± 10.5	62.0 ± 13.5
Investigate side [right/left]	3/7	4/7
FPI score [point]	2 ± 2	8 ± 2**
Walking speed [m/s]	1.27 ± 0.06	1.29 ± 0.05
Stance duration [s]	0.61 ± 0.03	0.60 ± 0.04
Step length [m]	0.40 ± 0.02	0.39 ± 0.02
Max COM acceleration [m/s^2]	1.91 ± 0.48	1.57 ± 0.27*

FPI: Foot Posture Index, Max: Maximum, COM: Center of mass
mean ± SD, *: $p < 0.05$, **: $p < 0.01$

Table 2
Mechanical work profiles during walking of the neutral foot and pronated foot.

		Neutral foot (n = 10)	Pronated foot (n = 11)	*p*-value	Effect size *d*
Mid-tarsal joint [J/kg]	Positive	0.099 ± 0.045	0.104 ± 0.027	0.744	0.08
	Negative	–0.084 ± 0.018	–0.085 ± 0.013	0.884	0.03
	Net	0.015 ± 0.049	0.020 ± 0.034	0.814	0.05
Distal to the Rearfoot [J/kg]	Positive	0.088 ± 0.038	0.077 ± 0.024	0.439	0.18
	Negative	–0.076 ± 0.019	–0.107 ± 0.019**	0.002	0.63
	Net	0.011 ± 0.045	–0.031 ± 0.031*	0.029	0.48
Distal to the Forefoot [J/kg]	Positive	0.014 ± 0.008	0.009 ± 0.006	0.117	0.35
	Negative	–0.088 ± 0.043	–0.122 ± 0.034	0.071	0.40
	Net	–0.073 ± 0.044	–0.112 ± 0.032*	0.039	0.45
Ankle [J/kg]	Positive	0.282 ± 0.043	0.247 ± 0.026*	0.043	0.45
	Negative	–0.087 ± 0.029	–0.099 ± 0.022	0.345	0.22
	Net	0.194 ± 0.044	0.148 ± 0.038*	0.023	0.49
Knee [J/kg]	Positive	0.085 ± 0.024	0.070 ± 0.023	0.187	0.30
	Negative	–0.096 ± 0.042	–0.094 ± 0.027	0.925	0.02
	Net	–0.011 ± 0.051	–0.024 ± 0.026	0.476	0.16
Hip [J/kg]	Positive	0.099 ± 0.034	0.124 ± 0.032	0.122	0.35
	Negative	–0.142 ± 0.069	–0.131 ± 0.058	0.714	0.09
	Net	–0.043 ± 0.087	–0.008 ± 0.085	0.382	0.20
COM [J/kg]	Positive	0.362 ± 0.045	0.316 ± 0.034*	0.021	0.50
	Negative	–0.252 ± 0.064	–0.253 ± 0.053	0.968	0.01
	Net	0.109 ± 0.072	0.062 ± 0.065	0.155	0.32

COM: Center of mass
mean ± SD, *: $p < 0.05$, **: $p < 0.01$

4. Discussion

This study addressed the hypothesis that individuals with pronated foot exhibit 1) increased energy loss at distal foot structure due to the impaired spring-like function of the mid-tarsal joint, 2) increased active work at proximal lower limb joints, and 3) reduced walking efficiency. Contrary to our hypothesis, no differences were detected in the mid-tarsal joint work between groups. On the other hand, we found that pronated foot exhibited greater net negative work at structures distal to the forefoot. Additionally, pronated foot exhibited less net positive work at the ankle and COM compared to neutral foot. Based on the above findings, we conclude that individuals with pronated foot utilized the spring-like function at mid-tarsal joint by compensating with increased energy transfer from the MTP joint, which results in reduced energy efficiency at distal foot structure during walking. That energy

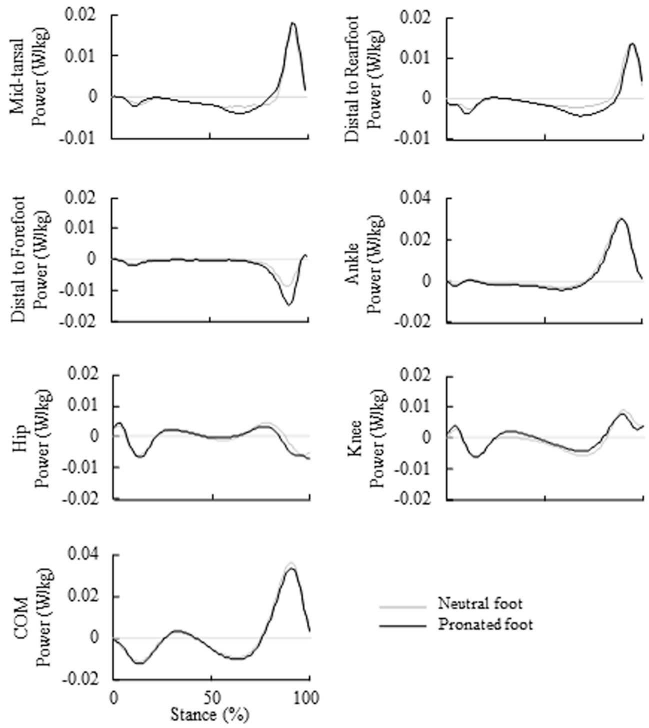

Fig. 1. Group mean the mid-tarsal joint, distal to the rearfoot, distal to the forefoot, ankle, hip, knee, and COM power for neutral and pronated foot during stance phase of walking.

inefficiency at distal foot structure may reduce positive work at the ankle and affect the walking efficiency in individuals with pronated foot.

It has been indicated that individuals with pronated foot have altered plantar structure compared with neutral foot [11,12], and we assumed that the spring-like function at the mid-tarsal joint would be impaired. However, contrary to our assumption, there is no differences in the mid-tarsal work between groups (Table 2). On the other hand, individuals with pronated foot performed greater net negative work at structures distal to the forefoot than those with neutral foot (Table 2). Most of the mechanical work performed by the structure distal to the forefoot generated around the late stance (Fig. 1), which could arise from the extension mobility of the MTP joints [26]. Therefore, increased net negative work at structure distal to the forefoot in pronated foot likely to be caused by the MTP joint. Taking this into consideration, our results may be explained by the kinetic coupling between the mid-tarsal joint and MTP joint. It has been reported that the induced tension resulting from the MTP joint extension during late stance may transfer energy from the MTP joint to the mid-tarsal joint, facilitating positive mid-tarsal power generation during push-off [27]. This relationship can also be comprehended by observing that positive power at the mid-tarsal joint and negative power at structure distal to the forefoot are almost synchronously generated (Fig. 1). Considering this relationship, our results can be interpreted that in individuals with pronated foot, disability of work generation at the mid-tarsal joint due to altered plantar structure is compensated by increasing the energy transfer from the MTP joint. Consequently, the apparent spring-like function at mid-tarsal joint is utilized by this compensation. However, individuals with pronated foot performed greater net negative work at structures distal to the rearfoot than those with neutral foot (Table 2), which means reduced energy efficiency at distal foot structure due to that compensation. Net work at structures distal to the rearfoot in neutral foot was nearly zero, indicating good energy recycling within the whole of the foot, whereas pronated foot had net negative work at structures distal to the rearfoot, indicating poor energy recycling within the whole of the foot.

For the lower limb joints proximal to the foot, individuals with pronated foot were found to perform lower net positive ankle work than those with neutral foot (Table 2). As most of positive power at ankle can be observed during late stance (Fig. 1), lower positive ankle work is likely to mean reduced push-off work at ankle. This result was contrary to our hypothesis that individuals with pronated foot have increased active work at proximal lower limb joints to maintain the steady walking speed. The lower positive work at the ankle in individuals with pronated foot may be explained by reduced energy efficiency at distal foot structure. The foot acts as a variable lever arm during walking, which can improve the mechanical advantage of the ankle. There are some evidence that adding stiffness to the foot through insoles altered ankle energetic behavior and soleus muscle-tendon mechanics [28,29]. Moreover, the Achilles tendon has been reported to be structurally connected with the plantar fascia and facilitate active force transmission between these structures [30–32]. Therefore, the foot structural properties may be closely related with power generation at the ankle during walking. Krupenevich et al. have indicated that the mechanical energy loss from distal foot structure contributes to reduce push-off power at the ankle in older adults [33].

Ankle push-off is known to mainly contribute to COM acceleration by increasing speed and kinetic energy of the trailing leg [34]. Individuals with pronated foot had lower positive COM work and maximum COM acceleration compared to those with neutral foot (Table 2), which is likely to be associated with less positive work at the ankle. The present findings may indicate that individuals with pronated foot cannot fully compensate for reduced energy efficiency through active work, even during steady walking, and describe poor walking efficiency in individuals with pronated foot. Our findings must advance our understanding of the impact of foot structure on walking efficiency, but there are several limitations. First, the present mechanical works were calculated throughout the stance phase, and differences in each phase of stance have not been examined. In the future, it is necessary to investigate the differences in mechanical work across each phase of stance. Second, we have not conducted a quantitative evaluation of the medial longitudinal arch. To accurately assess the form, it might have been necessary to combine the FPI with other quantitative foot assessments such as the Navicular Drop test. Third, we could not detect the difference in spatiotemporal parameters between groups, and how they compensated for insufficient acceleration of the COM was not determined. Future studies are warranted to clear this. Finally, subjects walked about 30–40 times before obtaining three successful trials. Therefore, the present results may include the effects of fatigue. However, there is no significant difference in total trial number between groups, and breaks were provided during measurements as needed. We believe that the effect of fatigue has been kept to a minimum.

5. Conclusion

Individuals with pronated foot have greater net negative work at structures distal to the forefoot and rearfoot, but no differences were detected in the mid-tarsal joint work between groups. Additionally, individuals with pronated foot have less net positive work at the ankle and COM during walking compared to neutral foot. These findings may indicate that individuals with pronated foot utilized the spring-like function at mid-tarsal joint by compensating with increased energy transfer from the MTP joint, which results in reduced energy efficiency at distal foot structure during walking. That energy inefficiency may reduce positive work at the ankle and affect the walking efficiency in individuals with pronated foot. Pronated foot has an impact on energetic behavior during walking, suggesting that it is important to evaluate foot posture for improving walking efficiency.

Declaration of Competing Interest

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This study did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

[1] A.D. Kuo, The six determinants of gait and the inverted pendulum analogy: a dynamic walking perspective, Hum. Mov. Sci. 26 (2007) 617–656, https://doi.org/10.1016/j.humov.2007.04.003.
[2] K.E. Zelik, A.D. Kuo, Human walking isn't all hard work: evidence of soft tissue contributions to energy dissipation and return, J. Exp. Biol. 213 (2010) 4257–4264, https://doi.org/10.1242/jeb.044297.
[3] K.E. Zelik, K.Z. Takahashi, G.S. Sawicki, Six degree-of-freedom analysis of hip, knee, ankle and foot provides updated understanding of biomechanical work during human walking, J. Exp. Biol. 218 (2015) 876–886, https://doi.org/10.1242/jeb.115451.
[4] A.L. Hof, B.A. Geelen, J. Van den Berg, Calf muscle moment, work and efficiency in level walking; role of series elasticity, J. Biomech. 16 (1983) 523–537, https://doi.org/10.1016/0021-9290(83)90067-2.
[5] R.M. Alexander, Energy-saving mechanisms in walking and running, J. Exp. Biol. 160 (1991) 55–69, https://doi.org/10.1242/jeb.160.1.55.
[6] R.F. Ker, M.B. Bennett, S.R. Bibby, R.C. Kester, R.M. Alexander, The spring in the arch of the human foot, Nature 325 (1987) 147–149, https://doi.org/10.1038/325147a0.
[7] S.M. Stearne, K.A. McDonald, J.A. Alderson, I. North, C.E. Oxnard, J. Rubenson, The foot's arch and the energetics of human locomotion, Sci. Rep. 6 (2016) 19403, https://doi.org/10.1038/srep19403.
[8] L.A. Kelly, G. Lichtwark, A.G. Cresswell, Active regulation of longitudinal arch compression and recoil during walking and running, J. R. Soc. Interface 12 (2015) 20141076, https://doi.org/10.1098/rsif.2014.1076.
[9] R. Riddick, D.J. Farris, L.A. Kelly, The foot is more than a spring: human foot muscles perform work to adapt to the energetic requirements of locomotion, J. R. Soc. Interface 16 (2019) 20180680, https://doi.org/10.1098/rsif.2018.0680.
[10] P.O. McKeon, J. Hertel, D. Bramble, I. Davis, The foot core system: a new paradigm for understanding intrinsic foot muscle function, Br. J. Sports Med 49 (2015) 290, https://doi.org/10.1136/bjsports-2013-092690.
[11] S. Angin, G. Crofts, K.J. Mickle, C.J. Nester, Ultrasound evaluation of foot muscles and plantar fascia in pes planus, Gait Posture 40 (2014) 48–52, https://doi.org/10.1016/j.gaitpost.2014.02.008.
[12] S. Angin, K.J. Mickle, C.J. Nester, Contributions of foot muscles and plantar fascia morphology to foot posture, Gait Posture 61 (2018) 238–242, https://doi.org/10.1016/j.gaitpost.2018.01.022.
[13] S. Otman, O. Basgöze, Y. Gökce-Kutsal, Energy cost of walking with flat feet, Prosthet. Orthot. Int 12 (1988) 73–76, https://doi.org/10.3109/03093648809078203.
[14] H.S. Shin, J.H. Lee, E.J. Kim, M.G. Kyung, H.J. Yoo, D.Y. Lee, Flatfoot deformity affected the kinematics of the foot and ankle in proportion to the severity of deformity, Gait Posture 72 (2019) 123–128, https://doi.org/10.1016/j.gaitpost.2019.06.002.
[15] A.C. Redmond, J. Crosbie, R.A. Ouvrier, Development and validation of a novel rating system for scoring standing foot posture: the foot posture index, Clin. Biomech. 21 (2006) 89–98, https://doi.org/10.1016/j.clinbiomech.2005.08.002.
[16] N. Kito, K. Shinkoda, T. Yamasaki, N. Kanemura, M. Anan, N. Okanishi, et al., Contribution of knee adduction moment impulse to pain and disability in Japanese women with medial knee osteoarthritis, Clin. Biomech. 25 (2010) 914–919, https://doi.org/10.1016/j.clinbiomech.2010.06.008.
[17] D.A. Bruening, K.M. Cooney, F.L. Buczek, Analysis of a kinetic multi-segment foot model. Part I: model repeatability and kinematic validity, Gait Posture 35 (2012) 529–534, https://doi.org/10.1016/j.gaitpost.2011.10.363.
[18] D.A. Bruening, K.M. Cooney, F.L. Buczek, Analysis of a kinetic multi-segment foot model part II: kinetics and clinical implications, Gait Posture 35 (2012) 535–540, https://doi.org/10.1016/j.gaitpost.2011.11.012.
[19] K. Tokuda, M. Anan, M. Takahashi, T. Sawada, K. Tanimoto, N. Kito, et al., Biomechanical mechanism of lateral trunk lean gait for knee osteoarthritis patients, J. Biomech. 66 (2018) 10–17, https://doi.org/10.1016/j.jbiomech.2017.10.016.
[20] H. Okada, M. Ae, N. Fujii, Y. Morioka, Body segment inertia properties of Japanese elderly, Biomechanisms 13 (1996) 125–139.
[21] E. Hanavan. A mathematical model of the human body, AMRLTR-64–102, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, 1964.
[22] R. Chang, P.A. Rodrigues, R.E. Van Emmerik, J. Hamill, Multi-segment foot kinematics and ground reaction forces during gait of individuals with plantar fasciitis, J. Biomech. 47 (2014) 2571–2577, https://doi.org/10.1016/j.jbiomech.2014.06.003.
[23] F.L. Buczek, T.M. Kepple, K.L. Siegel, S.J. Stanhope, Translational and rotational joint power terms in a six degree-of-freedom model of the normal ankle complex, J. Biomech. 27 (1994) 1447–1457, https://doi.org/10.1016/0021-9290(94)90194-5.
[24] K.Z. Takahashi, T.M. Kepple, S.J. Stanhope, A unified deformable (UD) segment model for quantifying total power of anatomical and prosthetic below-knee structures during stance in gait, J. Biomech. 45 (2012) 2662–2667, https://doi.org/10.1016/j.jbiomech.2012.08.017.
[25] J.M. Donelan, R. Kram, A.D. Kuo, Simultaneous positive and negative external mechanical work in human walking, J. Biomech. 35 (2002) 117–124, https://doi.org/10.1016/S0021-9290(01)00169-5.
[26] K.Z. Takahashi, K. Worster, D.A. Bruening, Energy neutral: the human foot and ankle subsections combine to produce near zero net mechanical work during walking, Sci. Rep. 7 (2017) 15404, https://doi.org/10.1038/s41598-017-15218-7.
[27] L.R. Williams, S.T. Ridge, A.W. Johnson, E.S. Arch, D.A. Bruening, The influence of the windlass mechanism on kinematic and kinetic foot joint coupling, J. Foot Ankle Res. 15 (2022) 16, https://doi.org/10.1186/s13047-022-00520-z.
[28] S.F. Ray, K.Z. Takahashi, Gearing up the human ankle-foot system to reduce energy cost of fast walking, Sci. Rep. 10 (2020) 8793, https://doi.org/10.1038/s41598-020-65626-5.
[29] K.Z. Takahashi, M.T. Gross, H. van Werkhoven, S.J. Piazza, G.S. Sawicki, Adding stiffness to the foot modulates soleus force-velocity behaviour during human walking, Sci. Rep. 6 (2016) 29870, https://doi.org/10.1038/srep29870.
[30] S.W. Snow, W.H. Bohne, E. DiCarlo, V.K. Chang, Anatomy of the Achilles tendon and plantar fascia in relation to the calcaneus in various age groups, Foot Ankle Int. 16 (1995) 418–421, https://doi.org/10.1177/107110079501600707.
[31] C. Stecco, M. Corradin, V. Macchi, A. Morra, A. Porzionato, C. Biz, et al., Plantar fascia anatomy and its relationship with Achilles tendon and paratenon, J. Anat. 223 (2013) 665–676, https://doi.org/10.1111/joa.12111.
[32] R.E. Carlson, L.L. Fleming, W.C. Hutton, The biomechanical relationship between the tendoachilles, plantar fascia and metatarsophalangeal joint dorsiflexion angle, Foot Ankle Int. 21 (2000) 18–25, https://doi.org/10.1177/107110070002100104.
[33] R.L. Krupenevich, W.H. Clark, S.F. Ray, K.Z. Takahashi, H.E. Kashefsky, J.R. Franz, Effects of age and locomotor demand on foot mechanics during walking, J. Biomech. 123 (2021), 110499, https://doi.org/10.1016/j.jbiomech.2021.110499.
[34] K.E. Zelik, P.G. Adamczyk, A unified perspective on ankle push-off in human walking, J. Exp. Biol. 219 (2016) 3676–3683, https://doi.org/10.1242/jeb.140376.