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Short Communication

The Influence of High-Heeled Shoes on Strain and Tension Force of the Anterior Talofibular Ligament and Plantar Fascia during Balanced Standing and Walking

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Abstract

High-heeled shoes have the capability to alter the strain and tension of ligamentous structure between the foot and ankle, which may result in ankle instability. Contrarily, high-heeled shoes can also reduce the strain on plantar fascia, which may be beneficial to the treatment of plantar fasciitis. In this study, the influence of heel h eight on the strain and tension force of the anterior talofibular ligament (ATL) and plantar fascia were investigated.

A three-dimensional finite element model of coupled foot-ankle-shoe complex was constructed. Four heel heights were studied in balanced standing: (0-inch, 1-inch, 2-inch, and 3-inch). A 2 inch high-heeled shoe was used for the study during walking stance.

During balanced standing, the tension force on the ATL increased from 14.8N to 97.0N, with a six-fold increase of strain from 0 inches to 3 inches. Conversely, at 3 inches, the tension force and average strain on the fascia reduced from 151.0N (strain: 0.74%) to 59.6N (strain: 0.28%), and increased sharply to 278.3N (strain: 1.33%) despite it being less relative to standing. The walking simulation showed that the fascia tensed while the loading of ATL decreased during push off. The simulation outcome demonstrated the influence of heel height on the alteration of the ATL and plantar fascia strain, which has risk implications for ankle injury and also guidance for the treatment for plantar fasciitis.

Keywords:

Finite element analysis; High-heeled shoe; Foot and Ankle; Sprain ankle; plantar fasciitis

Introduction

Presently, high-heeled shoes (HHS) are more than just sensuous fashion; they can be seen as indispensable articles in the lives of many. The majority of females wear HHS, of which, nearly half of them wear HHS daily[1]. However, HHS are considered to be the major cause of foot pain and source of pathologies in women[2].The increase in heel height attenuates normal gait and posture, resulting in pain, discomfort and impaired foot functions[3]. HHS are also viewed as the major culprits for hallux valgus and calluses[3].

Ankle injuries, such as ankle sprains, are associated with an increased heel height, which predisposes the risk of inversion injury through excessive ankle plantarflexion and inversion[4, 5]. The altered ankle kinematics causes compensation at the knee joint, including significant increase in knee joint angle and abduction moment[6]. The overall change in gait kinematics produce muscle fatigue and imbalance in the gastrocnemius muscles, which eventually bring about ankle and walking instability[7, 8].

On the contrary, appropriate heel height is beneficial in the treatment of plantar fasciitis[9]. Decreased plantar fascia strain was demonstrated in cadaveric study[10] and finite element (FE) simulation[11].The reduced contact area between the heel and forefoot, together with the raised heel height, was believed to contribute to reduced fascia strain[10]. Besides, HHS significantly increases ankle plantarflexion angle, reduces postural stability, increases lower limb muscle forces and shifts plantar pressure anteriorly[3, 4]. In fact, the intrinsic influence of heel height on the ligamentous structure could provide insight to the mechanism of injury and treatment. While biomechanical information of the foot and ankle is difficult to obtain from experiments alone, researchers have identified that a validated computational model based on FE methods can yield realistic simulations of foot structures, thus providing pertinent biomechanical information of the foot and ankle [12].

This study will extend our previous work on the biomechanics of HHS during standing position [11, 13]. The objective of this study is to investigate the effect of heel height on the ligamentous structure, particularly the lateral ankle ligament and plantar fascia during balanced standing and walking stance via FE analysis. Based on the effects of HHS on ankle injury and treatment of plantar fasciitis, it was hypothesized that the strain and tension of the anterior lateral ankle ligament would increase while the strain and tension of the plantar fascia would decrease with the elevation of heel height.

Methods

Model Construction

The model construction in this study was reported in our previous work[11, 13]. The model was reconstructed from coronal MR images of the right foot in a neutral, non-weight-bearing condition fixed by an ankle-foot orthosis. The images were obtained at 1-mm interval using a 3.0-T MR scanner (Siemens, Erlangen, Germany). The subject was a healthy 28 year old female, who is 165 cm tall and has a mass of 54 kg. The geometry of 28 bony segments and encapsulated soft tissue were segmented by Mimics v14 (Materialise, Leuven, Belgium) and processed by Rapidform XOR2 (3D Systems Korea Inc., Seoul, Korea), as shown in Figure 1. 78 ligaments, 9 extrinsic muscles and the plantar fascia were included and modeled by connecting the corresponding attachment points on the bones. The insertion sites of ligaments and muscular structures were referenced to 3D anatomy atlas software: Interactive Foot and Ankle (Primal Picture Ltd., London, UK, 2001).

FE package, ABAQUS v6.11 (Dssault Systèmes, RI, USA) was used for mesh creation and subsequent analysis. The bony structures and encapsulated soft tissue were meshed into 4-noded tetrahedral elements (C3D4). Plantar fascia and ligaments were modeled as tension-only truss elements. The articular cartilage was modeled by assigning non-linear contact stiffness between joints[14], which was adopted from a cadaveric study[15]. The articular joints were assumed frictionless, while the coefficient of friction between the ground and encapsulated soft tissue was 0.6[16].

Load and Boundary Conditions

The superior surfaces of the encapsulated soft tissue, distal tibia and distal fibula were fixed. Ground reaction force (GRF) and inclination angle were assigned under the ground plate (Figure 2a). During balanced standing, a vertical GRF of half body weight (270 N) was applied at the inferior surface of foot supports.

The boundary and loading conditions of walking stance were determined from gait analysis of the same subject. Extrinsic muscles were assigned with different magnitudes of muscle forces detailed in our previous work[13]. With the assumption that the soleus and gastrocnemius predominate the propulsion torque during high-heeled gait[17, 18], the muscle force profile of barefoot walking was adopted in all heel height conditions except the Achilles tendon load[11]. The Achilles tendon forces were estimated based on a sensitivity analysis[11] on the center of pressure and previous EMG study [19]. The muscle force profiles for all conditions are presented in Table 1. The simulations were repeated in four height values: 0 inches, 1 inch, 2 inches and 3 inches in the standing condition. Walking stance was simulated only on the 2-inch HHS. The HHS consisted of a sole, heel, shankpiece and upper component[20].

Experimental Validation

The validation was conducted by comparing the plantar pressure distribution and arch deformation between experiments and simulations in standing position (Figure. 2b). From the FE analysis, the contact pressure between the plantar foot surface and the ground was extracted to calculate the center of pressure, and compared to the F-scan measurement. The validation process and findings were described in our previous work and acceptable agreement was demonstrated[11, 13]. To summarize, the maximum deviation of the center of pressure in all heel heights between FE predictions and measurements were less than 3 mm in the anterior-posterior direction and 2 mm in the medial-lateral direction.

Results

High-heeled Shoe Balanced Standing

Figure 3a displays the relationship between heel height and tension force in the ATL and total plantar fascia. In the ATL, the tension force increased from 14.8N to 97.0N with elevation in heel height from 0 inches to 3 inches. For plantar fascia, the tension force decreased to 59.6N for the 2-inch heel height and increased sharply to 278.3N with 3-inch heel height. The average strain of the plantar fascia reduced from 0.74% to 0.28%, and sharply increased to 1.33% at 3 inches. In the 2-inch condition, the strain and total tension force of plantar fascia was minimal in all simulated cases. In particular, the contribution of different plantar fascia rays for tension loading were different. Figure 3b shows the strain of each plantar fascia ray under different heel height conditions. The first and second ray sustained a larger portion of tension. The first ray sustained 36.2% of load for all five rays in the 0-inch heel height situation. On the contrary, the fifth ray sustained 8.1% in the 0-inch heel height situation.

High-heeled Shoe Walking

For 2-inch high-heeled walking, there was an apparent increase in the tensile strain and tension force of the plantar fascia from 42.7N to 258.4N. Conversely, the change of tension force of the ATL was small from heelstrike to midstance as it decreased at push off (Figure 4). The FE simulation also showed that the tension force of the calcaneofibular ligament (CFL) was negligible during high-heeled walking.

Discussion

Biomechanical knowledge of the foot and ankle is important for addressing foot biomechanics and the mechanism for foot and ankle injuries [12, 21].To overcome the limitations of in vivo experiments, comprehensive computational foot and shoe models can be used to estimate the internal stress and strain of the foot, providing further understanding on foot problems and evaluation on interventions[22].

Footwear can reshape the biomechanics of the foot. Both positive and negative influence of extraordinary footwear was documented in literatures [23-25]. HHS could be considered one of the abnormal designs that are commonly worn but believed to be deleterious. It was proposed that foot pathologies are related to intrinsic factors [26-28], while a quantitative evaluation of the extrinsic factors (HHS) is also required to facilitate better footwear design. In this study, the influence of high heels on the ligamentous structure and ankle instability was investigated. Our previous simulations overcame the challenges in the large deformation induced by HHS[11, 20]. Meanwhile, further interpretations and simulation on stance were carried out.

ATL strain and tension force

The ATL is the most important stabilizer of the talocrural joint. However, it is the ligament that undergoes the most damage in a lateral ankle sprain injury. The ATL prevents anterior displacement, as well as any excessive inversion and internal rotation of the talus relative to the tibia. Injuries occurs when the load exceeds the inversion restraint of ATL, especially under compressive loading[29]. Prolonged plantarflexion of the ankle causes tension in the ATL [30], predominantly from neutral position to 20° plantarflexion[31]. Our prediction showed that 3-inch heel height would facilitate 25.7°of ankle plantarflexion, in addition to the six-fold increase of predicted strain from 0- to 3-inch heel heights.

Plantar fascia strain and tension force

In this study, the predicted peak strain of plantar fascia reduced when the heel was elevated, but increased sharply from 2-inch to 3-inch heel heights during balanced standing. With respect to high-heeled walking, there was a gradual increase of fascia strain from heel strike to push off. Nevertheless the strain was relatively less compared to standing. The findings were in alignment with previous studies [9, 32]. The prediction of load sustained by fascia was 49.2% (applied load), which was comparable to 45% reported by Cheung et al.[32] during balanced standing on a flat support. The relationship between fascia strain and heel height was also shown in a cadaveric experiment [10].

A common strategy to treat plantar fasciitis is to reduce the strain in the plantar fascia by elevating the heel with shoe modifications or inserting arch insoles [9, 33, 34].The trend in fascia strain demonstrated in this study showed that an appropriate heel height would be necessary to reduce fascia strain. While in standing position, the predicted total plantar fascia tension force decreased by 77.3%, from 132.8N to 30.1N from 0-inch to 2-inch heel height during balanced standing, respectively. Reduced tensile strain in the plantar fascia may contribute to pain alleviation and reduced inflammation from plantar fasciitis, which is consistent with the treatment outcome of plantar fasciitis[9].

Limitations and Suggestions

The external validity of this study was limited due to the single-subject design. Also, there could be possible interactions between the foot anthropometry (such as foot length) and heel heights. Furthermore, the shank profile designs of the high-heeled shoes could produce different supporting forces to the plantar fascia and should be investigated in future studies.

Conclusion

Elevated heel height could significantly change foot biomechanics, especially the strain of the ATL and plantar fascia during balanced standing or walking. In this study, the strain and tension force of the ATL increased with the increase of heel height, while the strain and of plantar fascia decreased at moderate heel height.

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References:

[1] Yoon JY, An DH, Yoo WG, Kwon YR. Differences in activities of the lower extremity muscles with and without heel contact during stair ascent by young women wearing high-heeled shoes. J Orthop Sci. 2009;14:418-22.

[2] Riskowski J, Dufour AB, Hannan MT. Arthritis, foot pain and shoe wear: current musculoskeletal research on feet. Curr Opin Rheumatol. 2011;23:148-55.

[3] Cowley EE, Chevalier TL, Chockalingam N. The effect of heel height on gait and posture: a review of the literature. J Am Podiatr Med Assoc. 2009;99:512-8.

[4] Cronin NJ. The effects of high heeled shoes on female gait: A review. Journal of Electromyography & Kinesiology Official Journal of the International Society of Electrophysiological Kinesiology. 2014;24:258-63.

[5] Hong WH, Lee YH, Lin YH, Tang SF, Chen H. Effect of shoe heel height and total-contact insert on muscle loading and foot stability while walking. Foot & Ankle International. 2013;34:273-81.

[6] Simonsen EB, Svendsen MB, Nørreslet A, Baldvinsson HK, Heilskov-Hansen T, Larsen PK, et al. Walking on high heels changes muscle activity and the dynamics of human walking significantly. Journal of Applied Biomechanics. 2012;28:20-8.

[7] Gefen A, Megido-Ravid M, Itzchak Y, Arcan M. Analysis of muscular fatigue and foot stability during high-heeled gait. Gait & Posture. 2002;15:56–63.

[8] Kerr R, Arnold GP, Drew TS, Cochrane LA, Abboud RJ. Shoes influence lower limb muscle activity and may predispose the wearer to lateral ankle ligament injury. Journal of Orthopaedic Research. 2009;27:318–24.

[9] Marshall P. The rehabilitation of overuse foot injuries in athletes and dancers. Clinics in sports medicine. 1988;7:175-91.

[10] Kogler GF, Veer FB, Verhulst SJ, Solomonidis SE, Paul JP. The effect of heel elevation on strain within the plantar aponeurosis: in vitro study. Foot & Ankle International. 2001;22:433-9.

[11] Yu J, Cheung JT, Fan Y, Zhang Y, Leung AK, Zhang M. Development of a finite element model of female foot for high-heeled shoe design. Clinical Biomechanics. 2008;23 suppl 1:S31–S8.

[12] Cheung JT-M, Yu J, Wong DW-C, Zhang M. Current methods in computer-aided engineering for footwear design. Footwear Science. 2009;1:31-46.

[13] Yu J, Cheung JT, Wong DW, Cong Y, Zhang M. Biomechanical simulation of high-heeled shoe donning and walking. J Biomech. 2013;46:2067-74.

[14] Wong DW-C, Wang Y, Zhang M, Leung AK-L. Functional Restoration and Risk of Non-union of the First Metatarsocuneiform Arthrodesis for Hallux Valgus: A Finite Element Approach. Journal of biomechanics. 2015;48:3142-8.

[15] Athanasiou KA, Liu GT, Lavery LA, Lanctot DR, Jr SR. Biomechanical Topography of Human Articular Cartilage in the First Metatarsophalangeal Joint. Clinical Orthopaedics & Related Research.

1998;348:269-81.
[16] Zhang M, Mak AFT. In vivo friction properties of human skin. Prosthetics and orthotics international. 1999;23:135-41.
[17] Simonsen EB, Svendsen MB, Norreslet A, Baldvinsson HK, Heilskov-Hansen T, Larsen PK, et al. Walking on high heels changes muscle activity and the dynamics of human walking significantly. J Appl Biomech. 2012;28:20-8.
[18] Cronin NJ, Barrett RS, Carty CP. Long-term use of high-heeled shoes alters the neuromechanics of human walking. Journal of Applied Physiology. 2012;112:1054-8.
[19] Henderson PD, Piazza SJ. A biomechanical evaluation of standing in high-heeled shoes. Penn State McNair J. 2004;11:25-38.
[20] Luximon Y, Luximon A, Yu J, Zhang M. Biomechanical evaluation of heel elevation on load transfer - experimental measurement and finite element analysis. Acta Mechanica Sinica. 2012;28:232-40.
[21] Kirby KA. What future direction should podiatric biomechanics take? Clinics in podiatric medicine and surgery. 2001;18:719-23, vii.
[22] Wang Y, Wong DW, Zhang M. Computational Models of the Foot and Ankle for Pathomechanics and Clinical Applications: A Review. Annals of biomedical engineering. 2016;44:213-21.
[23] Sousa AS, Silva A, Macedo R, Santos R, Tavares JMR. Influence of long-term wearing of unstable shoes on compensatory control of posture: An electromyography-based analysis. Gait & posture. 2014;39:98-104.
[24] Sousa AS, Macedo R, Santos R, Tavares JMR. Influence of wearing an unstable shoe construction on compensatory control of posture. Human movement science. 2013;32:1353-64.
[25] Sousa A, Tavares JMR, Macedo R, Rodrigues AM, Santos R. Influence of wearing an unstable shoe on thigh and leg muscle activity and venous response in upright standing. Applied ergonomics. 2012;43:933-9.
[26] Wong DW, Zhang M, Yu J, Leung AK. Biomechanics of first ray hypermobility: An investigation on joint force during walking using finite element analysis. Med Eng Phys. 2014;36:1388–93.
[27] Yu J, Cheung JTM, Fan Y, Zhang Y, Leung AK, Zhang M. Development of a finite element model of female foot for high-heeled shoe design. Clinical Biomechanics (Bristol, Avon). 2008;23:S31-S8.
[28] Glasoe WM, Nuckley DJ, Ludewig PM. Hallux valgus and the first metatarsal arch segment: a theoretical biomechanical perspective. Physical therapy. 2010;90:110-20.
[29] Bahr R, Pena F, Shine J, Lew WD, Engebretsen L. Ligament force and joint motion in the intact ankle: a cadaveric study. Knee Surgery Sports Traumatology Arthroscopy Official Journal of the Esska. 1998;6:115-21.
[30] Renstrom P, Wertz M, Incavo S, Pope M, Ostgaard HC, Arms S, et al. Strain in the lateral ligaments of the ankle. Foot Ankle. 1988;9:59-63.
[31] Colville MR, Marder RA, Boyle JJ, Zarins B. Strain measurement in lateral ankle ligaments. Am J Sports Med. 1990;18:196-200.
[32] Cheung JT, Zhang M, Leung AK, Fan YB. Three-dimensional finite element analysis of the foot

during standing - a material sensitivity study. J Biomech. 2005;38:1045-54.

[33] Gordon GM. Podiatric sports medicine. Evaluation and prevention of injuries. Clinics in Podiatry. 1984;1.

[34] Cole C, Seto C, Gazewood J. Plantar fasciitis: evidence-based review of diagnosis and therapy. American family physician. 2005;72:2237-42.

Tables

Table 1 Boundary, loading conditions and muscle load profiles of the subject weighing 54kg during balanced standing and stance in different heel heights.

	Balanced Standing				Heelstrike	Midstance	Push-off
Heel Height	0-inch	1-inch	2-inch	3-inch	2-inch	2-inch	2-inch
Tibial inclination	0°				-4°	0°	19°
Vertical GRF	270N				615 N	513N	648N
Achilles tendon force	202.5N	175.5N	216N	432N	405N	594N	756N
Other extrinsic muscles	EHL (10N) EDL (5N) PB (20N) PL (25N)				TA (80N) TP (30N)	TA (80N) PB (50N) PL (70N)	FHL (100N) FDL (25N) TP (80N) PB (80N) PL (100N)

GRF: Ground Reaction Force; EHL: Extensor Hallux Longus; EDL: Extensor Digitorum Longus; PB: Peroneus Brevis; PL: Peroneus Longus; TA: Tibialis Anterior; TP: Tibialis Posterior; FHL: Flexor Hallux Longus; FDL: Flexor Digitorum Longus

Figure Legends

Fig. 1 Finite element model of female foot and high-heeled shoe: a) Demonstration of the ATL and plantar fascia in the foot model; b) Demonstration of the foot model embedded in the encapsulated soft tissue aligned with the 2-inch high-heeled shoe during midstance; c) Display of the whole high-heeled shoe model, including the heel, support and upper, with the bony and ligamentous structure of the foot.

Fig. 2(a) boundary and loading condition during stance; (b) Demonstration of validation experiment of the same volunteer on a 2-inch heel support.

Fig. 3 Tension force and strain of ATL and plantar fascia (PL) during balanced standing on 0 to 3 inch heel height supports: a) tension force; b) strain.

Fig. 4 Tension force and strain of ATL and plantar fascia (PL) during 2-inch high-heeled walking: a) tension force; b) strain.

Figure 3

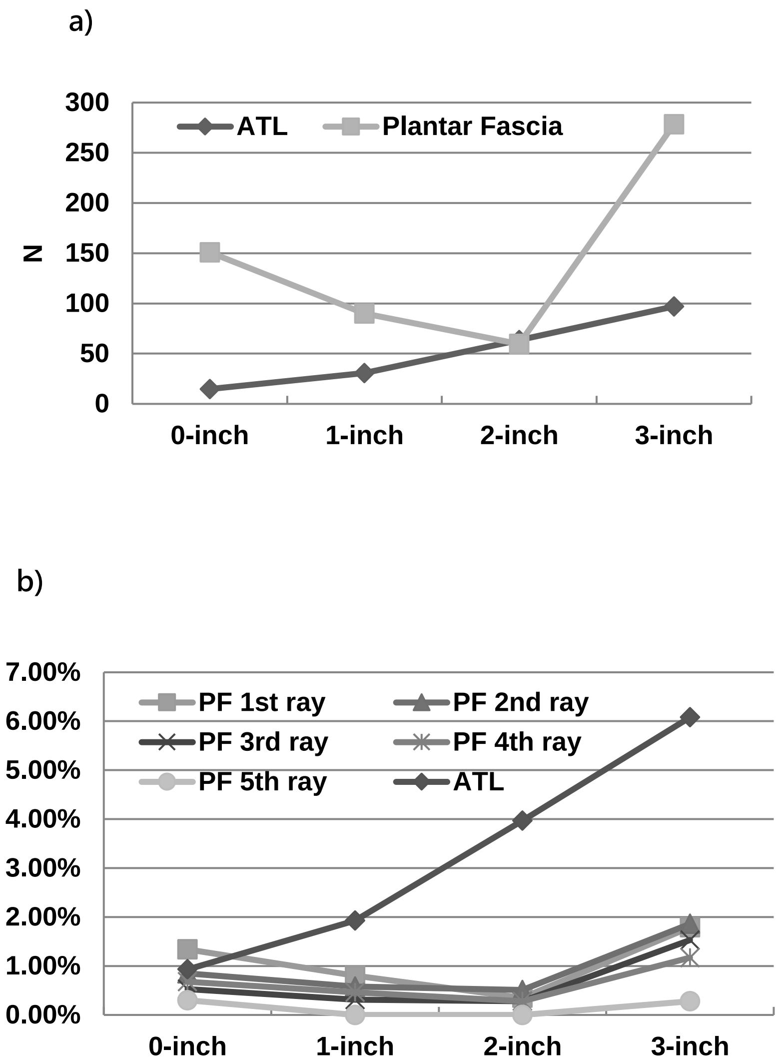
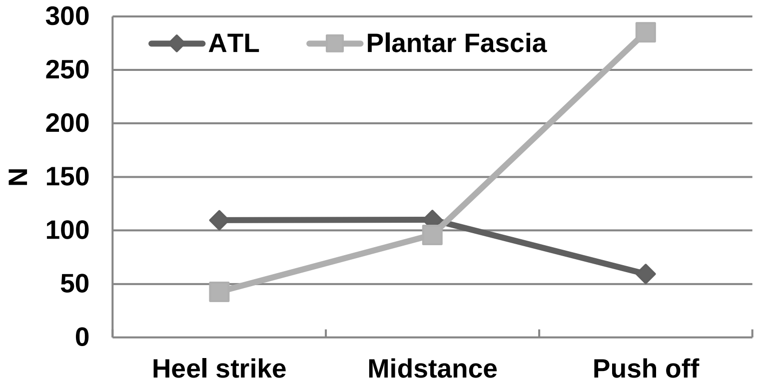

a)
ATL
Plantar Fascia
N
300
250
200
150
100
50
0
0-inch
1-inch
2-inch
3-inch
b)
PF 1st ray
PF 2nd ray
PF 3rd ray
PF 4th ray
PF 5th ray
ATL
7.00%
6.00%
5.00%
4.00%
3.00%
2.00%
1.00%
0.00%
0-inch
1-inch
2-inch
3-inch

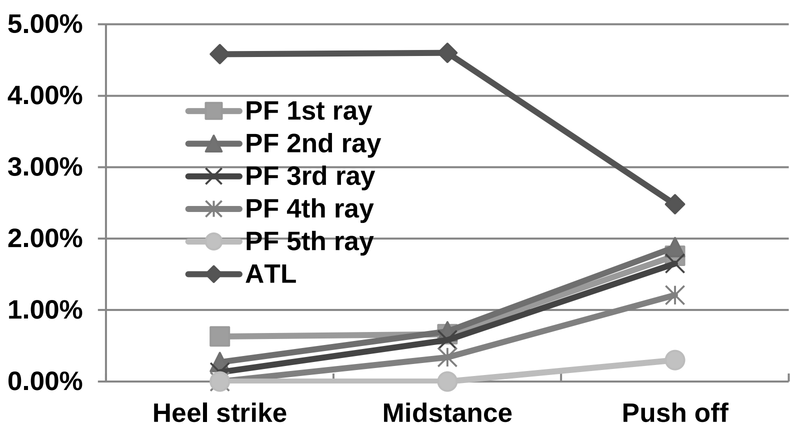
Figure 4

a)



300
250
200
150
100
50
0
N
ATL
Plantar Fascia
Heel strike
Midstance
Push off

b)



5.00%
4.00%
3.00%
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PF 1st ray
PF 2nd ray
PF 3rd ray
PF 4th ray
PF 5th ray
ATL
Heel strike
Midstance
Push off